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INTERGRANULAR CRACK PROPAGATION RATES IN SENSITIZED TYPE 304
STAINLESS STEEL IN AN OXYGENATED WATER ENVIRONMENT

by

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Final Report on EPRI Contract T117-1

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ABSTRACT

Intergranular stress-corrosion crack (IGSCC) propagation rates were measured in three heats of sensitized Type 304 stainless steel (SS) as a function of applied load and degree of sensitization in an environment of high-purity water with 8 ppm oxygen, using a fracture mechanics approach. Specimens were sensitized using controlled furnace heat treatments and the degree of sensitization was measured by the electrochemical potentiokinetic reactivation (EPR) method. Active-loading tests on standard 25.4-mm (1-in.)-thick compact tension specimens yielded IGSCC propagation rates ranging from $\sim 2 \times 10^{-10}$ to 1×10^{-9} m/s ($\sim 2 \times 10^{-5}$ to 2×10^{-4} in./h) over the range of stress intensities from 25 to 46 MPa $\sqrt{m}$ (22 to 41 ksi $\sqrt{in.}$). If the dependence of propagation rate on stress intensity is assumed to follow a power law, a least-squares fit of data yields $(da/dt) = 1.23 \times 10^{-8} K^{2.42}$ (in./h) for K in ksi $\sqrt{in.}$. Deflection-controlled tests on standard 12.7-mm-thick compact tension specimens yielded IGSCC propagation rates from 7×10^{-12} to 2×10^{-10} m/s (10^{-6} to 2×10^{-5} in./h) at effective average stress intensities in the range 21-26 MPa $\sqrt{m}$ (19-24 ksi $\sqrt{in.}$). Crack lengths were determined by compliance measurements using in-situ high-temperature clip gage or LVDT methods, optical metallography on the side faces of the specimen, and fractography of the cracked surface after completion of the tests. The optical metallography measurements did not provide useful estimates of crack lengths, because large variations in IGSCC propagation across the thickness of the specimens occurred. The effects of the degree of sensitization on the IGSCC propagation rate are obscured by the data scatter. However, it seems clear that these variables do not lead to order-of-magnitude changes in the crack propagation rate.

Intergranular Crack Propagation Rates in Sensitized Type 304 Stainless Steel in an Oxygenated Water Environment

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I. INTRODUCTION

This is the final report on a research program on the stress corrosion cracking of Type 304 stainless steel (SS) in an oxygenated water environment at Argonne National Laboratory (ANL), sponsored by the Electric Power Research Institute (EPRI) under Contract T117-1.

Intergranular stress-corrosion cracking (IGSCC) is an ongoing problem in boiling-water-reactor (BWR) components fabricated of Types 304 and 316 SS. These cracking incidents have caused expensive unscheduled downtimes and have reduced the operating capacities of the reactors.

In many cases analyses of fracture mechanics can be carried out to demonstrate that the reactor can continue to operate safely with these flaws for a period of time, e.g., until the next scheduled outage when repairs can be made more expeditiously and effectively. Clearly one important factor in these analyses is the rate of propagation of cracks in the oxygenated water environments of operating BWRs. The primary objective of this program has been to contribute to the development of a database on crack growth rate.

II. PROJECT DESCRIPTION

The goal of the present work was to determine IGSCC propagation rates in sensitized Type 304 SS in an oxygenated water environment as a function of applied load and degree of sensitization. The IGSCC growth rates were measured using a fracture mechanics approach. Since IGSCC and crack growth occur in the highly stressed region around the crack tip, the stress (or strain) distribution in this region, rather than the nominal net section stress, is of primary importance. In the classical linear-elastic fracture mechanics (LEFM) approach, the stress field near a crack tip can be characterized in terms of a single parameter, the stress intensity K , which is of the form

$$K = F\sigma a^{\frac{1}{2}} \quad (1)$$

where a is the crack length, σ is the applied nominal stress, and F is a geometrical factor that depends on the shape of the body. The LEFM approach assumes that the zone of plastic deformation near the crack tip is small in comparison with the crack size and other planar dimensions of the body. In this case, the elastic solution represents a reasonable approximation of the stress field near the crack tip, since the small zone of plastically deformed material at the crack tip is contained within the surrounding elastic material. This approach has been successfully applied to the analysis of stress corrosion cracking of high-strength aluminum and titanium alloys.^{1,2} Even in a low-strength, extremely tough material such as Type 304 SS the stress intensity factor should be a satisfactory parameter with

Table I. Chemical Composition of Type 304 SS (Weight %)

Heat No.		Si	Mn	C	P	S	Ni	Cr	Mo	Cu	B	O	N
10285	Vendor	0.51	1.64	0.058	0.032	0.006	8.40	18.25	0.41	0.26			
	ANL Check	0.59	1.58	0.06	0.028	0.011	8.48	18.37	0.38	0.27	<0.0004	0.0019	0.0847
16117	Vendor	0.40	1.67	0.060	0.022	0.010	8.85	18.13	0.30	0.22			
	ANL Check 1	0.42	1.66	0.06	0.027	0.012	9.06	18.41	0.26	0.24	0.0005	0.0008	0.0307
	ANL Check 2	0.44	1.70	0.07	0.032	0.014	8.75	18.02					
16429w	Vendor	0.56	1.70	0.078	0.027	0.010	8.94	18.20	0.23	0.23			
	ANL Check	0.58	1.70	0.07	0.027	0.011	9.11	18.29	0.20	0.24	0.0004	0.0007	0.0341

Fig. 1. IGSCC Test Loop.

which to characterize the stress state in the vicinity of the crack tip for loads that produce relatively small plastic zones compared to the specimen size.

A. Test Materials

Three heats of Type 304 SS plates (1/2 and 1-1/8 in. thicknesses) that met the ASTM A240 specification were tested. The plates were in the hot-rolled and annealed and pickled condition as received, and were furnace-sensitized before IGSCC tests were begun. The chemical composition and some mechanical properties of the materials are shown in Tables I and II.

B. Sensitization Treatments and Measurement of Degree of Sensitization (DOS)

Specimens were sensitized using controlled furnace heat treatments, and the DOS was measured using the electrochemical potentiokinetic reactivation (EPR) method.³ The heat treatments and the resulting EPR values for each specimen are summarized in Table III.

C. Test Environment

The test environment consisted of high-purity water containing 8 ppm dissolved oxygen at a temperature of 288°C and a pressure of 8.3 MPa (1200 psi). In terms of dissolved oxygen, this is a somewhat more severe environment than the normal steady-state BWR operating condition (288°C, 0.2 ppm dissolved oxygen). Typical room-temperature resistivity values were $1.6 \times 10^5 \Omega \cdot m$ for feed water and $3 \times 10^4 \Omega \cdot m$ for effluent; thus the impurity levels were somewhat lower than expected in an operating reactor. The desired dissolved oxygen concentration was obtained by sparging the feed water with a mixture of high-purity nitrogen and oxygen in a 79 to 21 volume ratio. The flow rate through the autoclave system was 0.2 ml/s (0.2 gph). At this flow rate, the maximum number of changes of the test environment in the autoclave per hour is 0.1 for the two-gallon autoclave (active-loading tests) and 0.2 for the one-gallon autoclave (deflection-controlled tests).

D. Test Facilities

A schematic of the high-temperature water test loop is shown in Fig. 1. The test loop consists of autoclaves, an Instron load frame, water pump, water-quality control and monitoring devices, high-temperature linear variable differential transformer (LVDT) monitors, and furnaces and controllers. The Instron machine was used for active-loading tests on 1TCT specimens. In the active-loading test chamber, up to three specimens were tested simultaneously using a series-loading arrangement as shown in Fig. 2. Wedges or bolt-loading jigs (Fig. 3) were used for deflection-controlled tests on 0.5TCT specimens.

E. Specimen Design

Standard 12.7-mm (0.5-in.-) and 25.4-mm (1-in.-) thick compact tension (0.5TCT and 1TCT) specimens were used. Similar specimen designs had been

Table II. Mechanical Properties of Type 304 SS

Heat No.	Tensile (psi)	Yield (psi)	Elong. (%)	Reduction of Area (%)	Hardness
10285	84,000	35,000	58	72	BHN 149
16117	83,700	38,700	65	64	RB 83-86
16429w	99,000	46,000	57	58	RB 83-84

Table III. Sensitization Heat Treatment and EPR Values

Heat No.	Specimen ID	Heat Treatment ^a	EPR ₂ (C/cm ²)	Heat No.	Specimen ID	Heat Treatment ^a	EPR ₂ (C/cm ²)	Heat No.	Specimen ID	Heat Treatment ^a	EPR ₂ (C/cm ²)
16117	A01	2	65	16429W	B00	2	66	10285	C01	4	18
	A02	2	73		B01	2	57		C02	4	19
	A03	2	72		B02	2	55		C04	5	4
	A04	1	36		B03	1	30		C05	4	14
	A05	1	31		B04	1	38		C08	3	15
	A06	1	28		B05	1	42		C10	4	14
	A07	2	64		B06	2	62				
	A08	1	25		B07	1	36				
	A11	3	23		B11	3	27				

^aHeat Treatment 1: 590°C/10-25 h (under $K_{IC} = 15-18 \text{ MPa}\sqrt{\text{m}}$, $R = 0.05$, 1 Hz) plus 1100°C/4 h slow cooling.

Heat Treatment 2: Heat Treatment 1 plus 700°C/4 h.

Heat Treatment 3: 700°C/15 min plus 500°C/24 h.

Heat Treatment 4: 600°C/24 h.

Heat Treatment 5: 600°C/4 h.

Fig. 2. Active-loading IGSCC Test Autoclave with Three Specimens Arranged in Series.

Fig. 3. Bolt-loading Jig.

successfully used in fatigue crack propagation studies.⁴ To restrict the crack growth to a single plane, semicircular side grooves were cut into both sides of the specimen to reduce the total thickness of the specimen by 10%. The specimens were fabricated such that the rolling direction of the plate was parallel to the load line of the specimen (T-L orientation ASTM E399-81). A detailed description of the specimen geometry is given in Figs. 4 and 5. The 0.5TCT specimens were used for deflection-controlled tests and 1TCT specimens were used for active-loading tests. Prior to IGSCC testing, the specimens were precracked by cyclic loading to a depth of ~3 mm from the machined notch.

F. Measurement of Crack Lengths

Optical metallography was used to measure crack lengths on the side faces of the specimens. However, it was difficult to resolve the intergranular crack tip from the grain boundaries, which were etched due to corrosion, particularly for tight cracks in unloaded specimens. It was also found by post-test examination that the shape of the crack front across the specimen thickness was usually not a straight line.

Because of the limitations of the optical measurements in many of the tests, additional determinations of the crack length were made by measuring the applied load and corresponding crack mouth opening displacement (COD), using the compliance relation between load, COD, and crack length. The load and COD were monitored continuously for the active-loading tests by a load cell and high-temperature clip gage or LVDT (Fig. 6). Analytical expressions for the compliance relation and stress intensity are available in the literature and are expressed as follows:^{5,6}

$$\left(\frac{BEV_x}{P} \right) = \left[\frac{x_o/w - x/w}{x_o/w + 0.25} \right] \left(\frac{BEV_o}{P} \right) \quad (2)$$

$$\begin{aligned} \left(\frac{BEV_o}{P} \right) = & \left(1 + \frac{0.25}{a/w} \right) \left(\frac{1 + a/w}{1 - a/w} \right)^2 [1.61369 + 12.6778 (a/w) \\ & - 14.2311 (a/w)^2 - 16.6102 (a/w)^3 + 35.0499 (a/w)^4 \\ & - 14.4943 (a/w)^5] \end{aligned} \quad (3)$$

$$\begin{aligned} \frac{K}{P} Bw^{\frac{1}{2}} = & \frac{2 + a/w}{(1 - a/w)^{(3/2)}} [0.886 + 4.646 (a/w) - 13.32 (a/w)^2 \\ & + 14.72 (a/w)^3 - 5.6 (a/w)^4] \end{aligned} \quad (4)$$

where

$$\frac{BEV_o}{P} = \text{Normalized compliance at the front face of the specimen}$$

$$\frac{BEV_x}{P} = \text{Normalized compliance at a distance } x \text{ from the load line}$$

Fig. 4. 1TCT Specimen Design. All dimensions in inches.

B = specimen thickness

E = Young's modulus

V = displacement

P = load

w = width of specimen (i.e., $w = 2$ for 1TCT)

and

a = crack length measured from load line.

In Fig. 7, the analytical compliance relation is compared with experimental results obtained from mock-up specimens with known crack lengths (i.e., EDM notches). There is good agreement between calculated and experimental results.

Fig. 7. Normalized Compliance vs Dimensionless Crack Length for 0.5TCT Specimen.

After completion of the crack growth rate tests the cracked surface can be exposed by impact loading after cutting through most of the uncracked ligament from the back side and chilling in liquid nitrogen. The final crack length can be directly measured on the fracture surface of the specimen. Since this measurement is unambiguous, it was often used to adjust compliance measurements to compensate for long-term drift. As noted previously, significant variations in crack propagation across the thickness of the specimen were usually observed, and the areal average was used to determine an overall crack length for comparison with the values obtained from the compliance measurements.

III. ACTIVE-LOADING TESTS

Active-loading IGSCC tests were performed using an Instron machine for six 1TCT specimens, which were fabricated from the 1-1/8-in.-thick plate (Heat 10285), in a high-purity water with 8 ppm oxygen at 288°C and 3.3 MPa (1200 psi). The specimens were sensitized by furnace heat treatments to EPR values from 4 to 19 C/cm² (Table III). In order to initiate sharp intergranular cracking, the specimens were cyclically loaded (triangular wave shape, $R = 0.08-0.5$, $f = 1.6-7.5$ cph, and K_{max} not exceeding the value planned for the subsequent constant load IGSCC tests) in the test environment. The cyclic loading conditions were chosen based on data by Kawakubo et al. which indicated that intergranular rather than transgranular cracking would be produced. The cyclic loading was continued until a positive indication of crack extension was detected, and then IGSCC tests under constant load were performed. The crack length in the specimen was continuously monitored by the compliance method using an in-situ high-temperature LVDT (Schaevitz Model 100XS-ZT) or clip gage (MTS Model 632.10-01). Upon completion of the active-load tests, the specimens were fractured, and the fracture surface was examined both macroscopically and by scanning electron microscopy (SEM).

Although six specimens were tested, two specimens (C01 and C08) are excluded from analysis because of instrumentation failures and difficulties during the crack growth experiments. Figures 8(a-d) show the fracture surfaces of the 1TCT specimens C02, C04, C05 and C10. Crack propagation occurred in all four specimens. The crack fronts are rather uneven. For specimen C10, the crack length at a side face (0.502 in.) is nearly three times longer than the crack length determined by the areal average (0.189 in.). The reasons for the reversed crack tunneling (or tunneling in some 0.5TCT deflection-controlled test specimens) are not clearly understood, although it can perhaps be attributed to the higher plastic strain rates at the free surface or greater access of the environment to the crack tip. Scanning electron microscopy of the fracture surfaces was used to determine the mode of cracking (intergranular or transgranular, etc.). Sometimes the appearance of the fracture surface could be correlated with different loading or environmental test histories. Figure 9 shows the fracture surface of specimen C04 at a low magnification in the SEM. Figures 10(a-e) show the five different regions indicated in Fig. 9 at higher magnification. Mixed-mode cracking (inter- and transgranular) is seen for the beginning portion [Fig. (a-c)] of the crack, which corresponds to the cracking under the initial cyclic loading. Intergranular cracking is observed for the region between (c) and (d) which corresponds to the constant-load portion of

Fig. 8(a-d). Fracture Surface of 1TCT Specimens C02, C04, C05 and C10 Showing Crack Propagation.

Fig. 9. SEM of Fracture Surface of Specimen C04.

the loading history. The ductile-failure mode observed at location (e) was produced by impact fracture of the remaining ligament of the specimen in air after completion of the IGSCC tests. Figure 11 is a higher magnification view of a portion of region (a) of Fig. 10 and shows striation marks that may have been generated by the initial cyclic loading (sawtooth waveform $f = 1.67$ cph, $R = 0.12$, $K_{max} = 26-30$ ksi $\sqrt{\text{in.}}$). Figure 12 is a SEM of the fracture surface near a side face. Striation markings indicate that this part of the crack was formed during the initial cyclic loading. However, the failure mode is predominantly intergranular, in contrast to the mixed mode (Fig. 10) observed at the specimen center for the same crack depth. Crack branching was commonly observed, as shown in Fig. 13.

Average crack propagation rates were determined by dividing the crack extension by the test time. While crack extensions were continuously monitored by the compliance method using Eqs. (2-4), the LVDT and clip gage measurements indicated long-term instrumentation drift. Crack lengths (initial and final crack length, and other demarcations) measured directly on the fracture surface were used to recalibrate and correct for drift. The correction factor for the drift was incorporated into the value of Young's modulus E [Eq. (2)] and linear interpolation with respect to test time was used. This procedure also compensates for the effect of crack branching on the determination of crack length.

The crack propagation rates determined for specimens C02, C04, C05 and C10 are summarized in Table IV and Figs. 14-16. Figures 14 and 15 show crack length versus test time for the specimens C05 and C10. Figure 16 shows crack propagation rates versus stress intensity. The propagation rate varies from $\sim 2 \times 10^{-10}$ to 1×10^{-9} m/s (2×10^{-5} to 2×10^{-4} in./h) over the range of stress intensities from 25-46 MPa $\sqrt{\text{m}}$ (22-41 ksi $\sqrt{\text{in.}}$).

Fig. 10(a-e). Higher Magnification SEMs of Fracture Surface of Specimen C04.

Fig. 11. SEM of Striated Fracture Surface of Specimen C04 [Region (a) of Fig. 10].

Fig. 12. SEM of Fracture Surface Near a Side Face of Specimen C04.

Fig. 13. SEM of Fracture Surface of Specimen C10 Showing Crack Branching.

Table IV. IGSCC Propagation in Active-loading 1TCT Specimens in High-purity Water with 8 ppm Oxygen at 288°C

Specimen ID	Heat No.	EPR ₂ (C/cm ²)	Grain Size ASTM No.	Stress Intensity MPa√m		Crack Propagation Rate	
				Initial	Final	(m/s)	(in./h)
C02	10285	19	5.0	31	33	1.6×10^{-10}	2.2×10^{-5}
C04	↓	4	4.8	34	36	2.4×10^{-10}	3.4×10^{-5}
C05		14	4.9	24	25	2.8×10^{-10}	3.9×10^{-5}
C10		14	5.1	41	46	1.1×10^{-9}	1.6×10^{-4}

Fig. 14. Crack Length vs Time for Specimen C05.

Fig. 15. Crack Length vs Time for Specimen C10.

Fig. 16. Crack Propagation Rates vs Stress Intensity from Active-loading IGSCC Tests.

Because the test load was constant, the stress intensity values increased as the cracks propagated. The initial and final stress intensities are noted in Table IV and Figs. 14-16. If the dependence of propagation rate on stress intensity is assumed to follow a power law ($da/dt = CK^n$), a least-squares fit yields

$$(da/dt) = 1.23 \times 10^{-8} K^{2.42} \text{ (in./h) for } K \text{ in ksi}\sqrt{\text{in.}} \quad (6)$$

The exponent $n = 2.42$ is close to the value obtained by other investigations. The effect of degree of sensitization appears to be less than the scatter of the crack growth rates at a given DOS.

IV. DEFLECTION-CONTROLLED TESTS

Eighteen 0.5TCT specimens were fabricated from $\frac{1}{2}$ -in.-thick plates of heats 16117 and 16429w. The specimens were precracked to a depth of about 2.5 mm (0.1 inch) from the root of the EDM notch by fatigue loading at 590°C in air with a stress intensity of 15-18 MPa $\sqrt{\text{m}}$ (14-16 ksi $\sqrt{\text{in.}}$) and $R = 0.05$ at 1 Hz. The specimens were then solution-heat-treated in a high-purity argon atmosphere for 4 h at 1100°C, followed by a slow cooling in the heat-treating chamber in order to relieve the plastic strains introduced by the fatigue precracking and to obtain a stable microstructure. The specimens were highly sensitized by this treatment ($EPR \sim 30-40 \text{ C/cm}^2$).² Four specimens from each heat were further sensitized ($EPR \sim 60-70 \text{ C/cm}^2$) by additional treatment at 700°C for 4 hours. One specimen from each heat was tested without a fatigue precrack and was given a low-temperature sensitization treatment (700°C/15 min plus 500°C/24 h) in the as-received condition. The heat treatment conditions and degree of sensitization (DOS) are summarized in Table III. Specimens were loaded to initial stress intensities in the range of 28-33 MPa $\sqrt{\text{m}}$ (25-30 ksi $\sqrt{\text{in.}}$) using wedges or bolt-loading jigs (Fig. 3), and then immersed in the test environment. Significant reductions in the initial stress intensities were observed when the specimens were removed from the environment for examination. This reduction in the stress intensities was first assumed to be due to slippage of the load-bearing wedge in the specimen or slack in the loading jig. Subsequent tests, however, suggested that the reduction is due primarily to plastic deformation in the specimens which occurs so rapidly that the specimen will experience the reduced stress intensity for most of the test period. At accumulated test times (total immersion times at 288°C and 8.3 MPa (1200 psi) under the test load) of 300, 1200, 1800, 1949, 2560, 3560, 4772, 5960, 8171, 9254, 10483, 10741 and 12968 h, the tests were interrupted in order to check crack propagation and stress intensities. Figure 17 shows the crack on a side face of specimen B01 at different test times. The intergranular nature of the crack is clearly seen in the figure. Crack branching occurred in most of the specimens (Fig. 18 for specimen B00).

The deflection-controlled specimens were not instrumented. Average crack propagation rates (increment of crack length divided by the immersion time) were estimated from optical measurements on the side face of the specimens, and have been reported previously. The raw data is reproduced in Table V. However, this method of estimating crack growth rate was found to be unreliable because of the large variations in crack length across the thickness of the specimen as shown in Fig. 19. Average crack propagation

Fig. 17. Crack Propagation in Specimen B01 During Testing Times of 4772, 5960, 8171 and 9254 h.

Fig. 18. Branching of IGSCC in Specimen B00.

Table V. Optical Measurements of Crack Propagation in Deflection-Controlled 0.5TCT Specimens

Specimen ID	Accumulated Test Time (h)												EPR ₂ (C/cm ²)	Heat No.	
	300	1200	1800	1949	2560	3560	4772	5960	8171	9254	10483	10741			12968
A01	Δa (in)					0.008	0.003	0.018	0.020	0.011	0.007			65	16117
	a (in)	0.577	0.577	0.577	0.577	0.585	0.588	0.606	0.626	0.637	0.644	NT	NT		
	K _I /K _{IC} (ksi√in)*	31/26	31/18	31/19	31/	31/	32/20	32/21	32/22	33/24	20/16				
	(da/dt) _{avg} (in/h)**					8.9×10 ⁻⁶	2.7×10 ⁻⁶	1.7×10 ⁻⁵	9.5×10 ⁻⁶	1.1×10 ⁻⁵	6.2×10 ⁻⁶				
A02	Δa (in)						0.014	0.018	0.005	0.017	0.008			73	16117
	a (in)	0.617	0.617	0.617	0.617	0.617	0.631	0.649	0.653	0.670	0.678	NT	NT		
	K _I /K _{IC} (ksi√in)*	32/15	32/18	32/16	32/	32/	32/21	32/23	33/20	33/23	20/15				
	(da/dt) _{avg} (in/h)**						1.3×10 ⁻⁵	1.7×10 ⁻⁵	2.2×10 ⁻⁶	1.8×10 ⁻⁵	6.8×10 ⁻⁶				
A03	Δa (in)					0.001	0.005	0.014						72	16117
	a (in)	0.578	0.578	0.578	0.578	0.579	0.584	0.598				NT	NT		
	K _I /K _{IC} (ksi√in)*	26/16	26/13	32/	31/	31/	31/20	32/22	NM	NM	NM				
	(da/dt) _{avg} (in/h)**						1.2×10 ⁻⁶	4.2×10 ⁻⁶	1.3×10 ⁻⁵						
A05	Δa (in)								0.004	0.003				31	16117
	a (in)	NT	NT	0.658	0.658	0.658	0.658	0.658	0.662	0.665	0.665	NM	NT		
	K _I /K _{IC} (ksi√in)*			24/	24/	NM	24/	24/19	24/20	24/20	24/20	20/16			
	(da/dt) _{avg} (in/h)**									1.9×10 ⁻⁶	3.1×10 ⁻⁶				
A07	Δa (in)									0.0003		NM	0.001	64	16117
	a (in)	0.594	0.594	NT	0.594	0.594	0.594	0.594	0.594	0.594	0.594	NM	0.595		
	K _I /K _{IC} (ksi√in)*	28/22	28/		33/	NM	33/	33/21	33/22	33/22	33/24	20/18	29/24		
	(da/dt) _{avg} (in/h)**										3.1×10 ⁻⁷		5.5×10 ⁻⁷		
A11	Δa (in)													23	16117
	a (in)	NT	NT	NT	NT	NT	NT	NT	NT	NT	NT		0.730		
	K _I /K _{IC} (ksi√in)*												31/19		
	(da/dt) _{avg} (in/h)**														
B00	Δa (in)			0.002	NM	0.003	0.009	0.020	0.006	0.024	NM	0.037		66	16429W
	a (in)	0.624	0.624	0.626	NM	0.629	0.638	0.658	0.664	0.688	NM	0.725	NM		
	K _I /K _{IC} (ksi√in)*	32/19	32/17	32/20	32/	32/	32/	32/23	33/24	34/19	35/	21/17			
	(da/dt) _{avg} (in/h)**			4.1×10 ⁻⁶		5.0×10 ⁻⁶	9.6×10 ⁻⁶	1.8×10 ⁻⁵	5.5×10 ⁻⁶	1.2×10 ⁻⁵		1.7×10 ⁻⁵			

Δa = crack propagation,
 a = crack length; average of optical measurements at side face of the specimen.
 K_I = initial stress intensity
 K_F = final stress intensity
 $(da/dt)_{avg}$ = average propagation rate over a test period. A 100-h reinitiation time was assumed.
 NM = not measured.
 NT = not tested.
 $*1 \text{ ksi}/\sqrt{\text{in.}} = 1.099 \text{ MPa}/\sqrt{\text{in.}}$
 $*1 \text{ in.}/\text{h} = 7.056 \times 10^{-6} \text{ m/s.}$

Fig. 19. Fracture Surface of Deflection-controlled Test Specimen B07. Large variation in crack propagation across the thickness is visible.

rates were recalculated by an alternative method. A power law for the dependence of crack propagation rates on stress intensities was assumed [Eq. (6)].¹⁰ This was integrated to give a relation between the measured initial and final crack lengths and the applied stresses:

$$(da/dt) = D\sigma^{2.42}a^{1.21} \quad (7)$$

$$\int_{t_0}^{t_f} a^{-1.21} da = D \int_{t_0}^{t_f} \sigma^{2.42} dt$$

$$a^{-0.21} \Big|_{t_0}^{t_f} = 0.21 D \sum_{i=1}^n (\sigma_i^{2.42} \Delta t_i) \quad (8)$$

where

a_{t_0} = initial crack length,

a_{t_f} = final crack length,

σ_i = stress for each test period,

and

Δt_i = time for crack propagation during each test period.

Areal averages were used for crack length on the fracture surface. It was further assumed that a reinitiation time of 100 hours is required for crack propagation after each interruption of the test for examination.¹¹ Assuming

that the power law exponent $n = 2.42$ [see Eq. (6)], Eq. (8) was used to calculate D . Equation (8) was used further to calculate crack lengths for each test period, and K values were calculated from Eq. (4). An effective stress intensity for the overall test, defined as $\bar{K}$, was then calculated.

$$\bar{K} = \left[\frac{\sum (K_i^{2.42} \Delta t_i)}{\sum \Delta t_i} \right]^{\frac{1}{2.42}} \quad (9)$$

Thirteen deflection-controlled specimens that had shown appreciable crack propagation were analyzed. The results are summarized in Table VI and Fig. 20. Propagation rates vary from 7×10^{-12} to 2×10^{-10} m/s (10^{-6} to 2×10^{-5} in./h) at the effective average stress intensities in the range 21–26 MPa $\sqrt{m}$ (19–24 ksi $\sqrt{in.}$). Any effects of degree of sensitization and heat-to-heat variability are obscured by the data scatter.

Table VI. IGSCC Propagation in Deflection-controlled 0.5TCT Specimens in High-purity Water with 8 ppm Oxygen at 288°C

Specimen ID	Heat No.	EPR ₂ (C/cm ²)	Grain Size (ASTM No.)	Crack Length ^a (in.)		Effective Average Stress Intensity ^b ksi $\sqrt{in.}$	Average Propagation Rate	
				Initial	Final		(in./h)	(m/s)
A01	16117	65	1.7	0.608	0.716	22	1.2×10^{-5}	8.5×10^{-11}
A02		73	1.5	0.649	0.737	22	9.4×10^{-6}	6.6×10^{-11}
A03		72	1.5	0.611	0.713	22	1.1×10^{-5}	7.8×10^{-11}
A05		31	1.3	0.689	0.711	21	2.5×10^{-6}	1.8×10^{-11}
A07		64	1.8	0.598	0.615	23	1.5×10^{-7}	1.1×10^{-11}
A11		23	6.6	0.730	0.732	19	9.3×10^{-5}	6.6×10^{-10}
B00	16429w	66	2.7	0.669	0.870	24	2.1×10^{-5}	1.5×10^{-10}
B01		57	3.8	0.657	>0.799	21	$>1.2 \times 10^{-5}$	$>8.5 \times 10^{-11}$
B02		55	3.7	0.654	0.762	24	1.2×10^{-5}	8.5×10^{-11}
B05		42	3.2	0.657	0.666	21	1.1×10^{-6}	7.8×10^{-12}
B06		62	4.0	0.601	0.651	24	4.3×10^{-6}	3.0×10^{-11}
B07		36	3.9	0.611	0.661	23	4.7×10^{-6}	3.3×10^{-11}
B11		27	5.7	0.625	0.670	19	2.1×10^{-5}	1.5×10^{-10}

^aFractography.

^b1 ksi $\sqrt{in.}$ = 1.099 MPa $\sqrt{m}$.

Fig. 20. Crack Propagation Rates vs Stress Intensity from Deflection-controlled Tests.

V. SUMMARY

1. Three heats of Type 304 SS that had been furnace-sensitized showed IGSCC in high-purity water with 8 ppm oxygen at 288°C and 8.3 MPa (1200 psi).

2. Average IGSCC propagation rates versus stress intensity for the active-loading and for the deflection-controlled loading specimens are plotted in Fig. 21. A relatively large data scatter is observed. The scatter for the deflection-controlled specimens can be attributed in part to the poor load control inherent in this type of test and in part to the use of optical techniques to measure crack lengths in a situation where the crack fronts are very irregular. However, even in the active-loading tests, with good control of the load and compliance measurements of the crack length, the data scatter between nominally identical tests is in the order of a factor of two. However, the propagation rates are within the proposed upper bound of the crack growth rate curve given in the technical supplement to the new ASME Section XI Appendix on the evaluation of circumferential flaws in austenitic piping.¹² In Fig. 11, it appears that IGSCC propagation rates decrease rapidly below a stress intensity of $22 \text{ MPa}\sqrt{\text{m}}$ ($20 \text{ ksi}\sqrt{\text{in.}}$), but no such conclusion can be drawn since the effective test loads for the deflection-controlled specimens were centered around $22 \text{ MPa}\sqrt{\text{m}}$ ($20 \text{ ksi}\sqrt{\text{in.}}$), and the apparent rapid decrease may merely reflect the data scatter of more than an order of magnitude.

3. A large variation in IGSCC propagation across thickness of 1TCT and 0.5TCT test specimens was observed. Consequently optical measurements of IGSCC length at the side faces often did not provide useful estimates of crack length.

4. Effects of degree of sensitization and heat-to-heat variation on the IGSCC propagation rate could not be assessed because of the large data scatter. However, it seems clear that these variables do not lead to order-of-magnitude changes of crack propagation rate.

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Fig. 21. Crack Propagation Rates vs Stress Intensity from Active-loading Tests and Deflection-controlled Tests.

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