82034

Crack Initiation in CERT Tests on Type 304 Stainless Steel in Pure Water*

*PETER L. ANDRESEN**

Abstract

Crack initiation has been determined for Type 304 stainless steel in constant extension rate stress corrosion cracking tests. Tests have been conducted at 125, 200, and 288 C in pure water environments containing 1.8, 0.2, and 0.2 ppm of dissolved oxygen, respectively. In addition to the temperature/oxygen variable, the influence of surface condition (shot peened and wet ground) and sensitization heat treatment (600 C/24 hours and welded plus 500 C/24 hours or 400 C/ 10 days) has been examined. At 288 C, crack initiation in strongly sensitized specimens occurs at less than 20% of life. At lower temperature and/or less degree of sensitization, crack initiation occurs later in life. Shot peening reduces the strain to initiation, particularly at 125 C where there is a marked contrast to the wet ground condition. In general, variations in strain to initiation may not be strongly reflected in strain to failure. The limited results of other investigations were found to support the findings of this study.

TABLE 1 — Chemical Composition of 304 Stainless Steel

No.	C	Co	Cr	Cu	Mn	Mo	Ni	P	S	Si
78	0.076	0.13	18.62	0.20	1.75	0.24	8.32	0.021	0.025	0.58
114	0.07	0.12	18.38	0.18	1.68	0.22	8.6	0.025	0.017	0.60
116	0.051	0.26	18.8	0.25	1.7	0.23	9.5	0.028	0.013	0.48

Introduction

Susceptibility to stress corrosion cracking (SCC) of stainless steels and related materials in high temperature pure water environments have led to the widespread investigation of the chemical, metallurgical, and mechanical factors which contribute to SCC susceptibility. Many of these studies have resulted from intergranular stress corrosion cracking failures of stainless steel piping in the recirculation lines of boiling water reactors.[1,2] Numerous investigations[3] have employed constant extension rate techniques using smooth tensile specimens as an accelerated yet accurate and consistent measure of susceptibility. Additionally, constant extension rate testing (CERT) usually acts to promote crack initiation.[4,5]

The object of this investigation is to provide some understanding of the initiation process in constant extension rate testing, and to determine the effects on crack initiation of the environment (oxygen/temperature combinations), the surface condition (wet ground and shot peened), and heat treatment (furnace sensitization and two welded plus low temperature sensitization (LTS) conditions).

Experimental

Constant extension rate tests were performed on Instron Model 1131 or 1125 tensile machines. Influent water was channeled to the bottom of the compression tube within which the specimen was secured and exited at the upper portion of the compression tube to the remaining volume of the autoclave. This helped to ensure that the oxygen concentration experienced by the specimen was close to the inlet value. Oxygen concentration in the deionized water (conductivity <0.2 micromhos/cm) was controlled by continuous bubbling of the appropriate argon/oxygen mixture. A flow rate of 20 cc/minute at 10.3 MPa (1500 psi) was maintained through the one liter Type 316 stainless steel autoclaves, with the solution preheated by a coaxial heat exchanger. Analytical facilities for pH (Beckman Model 940B), conductivity (Beckman Solumeter), and dissolved oxygen concentration (Beckman Models 7001 and 7002) were used on influent and effluent Lines, and were regularly verified using colorimetric techniques. A similar system is described in more detail in Reference 5.

Type 304 stainless steel was used in this investigation, and the compositions are presented in Table 1 along with the experiment identification number. Specimens for experiment numbers 78 (heat C-17882) and 114 (heat 48898) were solution annealed at 1100 C for 30 minutes and water quenched. They were then centerless, wet ground (using a 100 grit wheel) to 6.35 mm diameter by 38 mm gage length (Figure 1), encapsulated in quartz tubes evacuated to 10^{-6} torr, and furnace sensitized to 600 C for 24 hours. The gage section of specimens for experiment number 114 were then shot peened with size 550 ceramic shot at 0.012 intensity to provide a hardened surface layer. This hardened layer fails mechanically at $\sim 2\%$ strain, resulting in shear cracks of $\sim$ 50 micron depth. This approach has been used to diminish the time required for crack initiation,[3] as well as to simulate conditions which occur when welds are ground severely.

---

*Submitted for publication May, 1981; revised September, 1981.

*Corporate Research and Development Center, General Electric Company, Schenectady, New York.

0010-9312/82/000015/$3.00/0

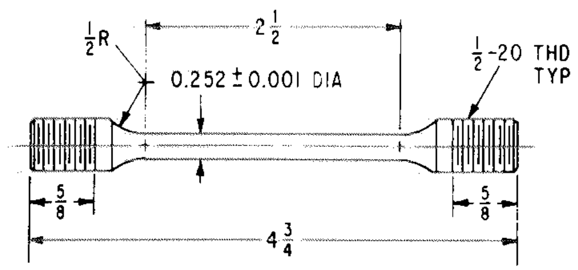

FIGURE 1 — Schematic of test specimen. Dimensions in inches.

Specimens for experiment number 116 (heat TH6656) were machined from a 254 mm diameter pipe weld so that the weld was centered in the gage section. The final machining step involved wet, centerless grinding. Specimens were encapsulated in quartz tubes evacuated to 10^{-6} torr and heat treated either at 500 C for 24 hours or 400 C for 10 days.

Specimens were tested under three oxygen/temperature conditions: (1) 1.8 ppm oxygen and 125 C; (2) 0.2 ppm oxygen and 200 C; and (3) 0.2 ppm oxygen and 288 C. Most of the tests were conducted at a nominal strain rate of 2×10^{-5} minute^{-1}, although some were conducted at 1.33×10^{-5} minute^{-1}.

Several techniques for monitoring crack initiation were investigated. Sophisticated acoustic emission equipment (Dunegan-Endevco Model 3000 series system, including models 302A, 303, 402, 502 920, 921, and 922 modules) was employed to identify crack initiation *in-situ*, without test interruption. These attempts involved tests at 288 C in a miniature autoclave, from which a long rod-type specimen with a reduced gage section extended. The acoustic emission system operated successfully at gains in excess of 90 db, yet it was not capable of detecting the early stages of cracking.

Ultrasonic techniques were also investigated. The grain size and acoustic attenuation of the stainless steel prevented measurements of the required accuracy, especially for very small flaws in relatively long specimens. Even in a more compact experimental sample, a flaw depth of 0.5 mm could not be consistently detected.

Potential drop techniques were also investigated, although a preflaw must be introduced on the surface in order for this technique to perform satisfactorily. It was felt that crack initiation from a flawed surface would not adequately represent the smooth sample behavior.

The technique which was finally employed involved periodic interruption of the test and visual (stereoscopic) inspection of the sample surface at 20X to 50X. Cracks of face length 0.5 mm and shorter were consistently dete anywhere on the surface. Assuming a thumbnail crack having the same radius of curvature as the specimen, would correspond to a crack penetration of less than 0.03 In fact, however, this technique is extremely time consur and crack detection is limited by the degree of patience p ticed in the selection and implementation of the interrup interval. Evidence of cracking obtained by visual examina of the surface was often confirmed by metallographic exa ation.

Tests were interrupted by slowly unloading the speci and cooling the autoclave. Continuation of the test occurre the reverse order, with specimens preloaded to approxima 90% of the load on interruption. Measurements of "mac strain" (crosshead speed times time) and specimen reduc in area and elongation were made at each interruption, the latter used in this report.

Most samples were interrupted many times until initia was observed. To ensure that the unloading and reloa

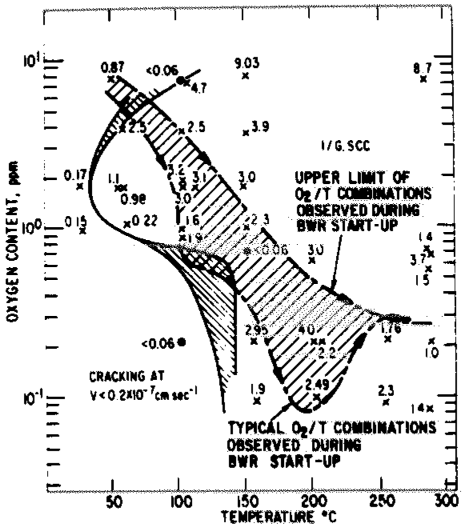

FIGURE 2 — Estimate of oxygen temperature combinations giving SCC of sensitized 304 stainless steel in high purity water. Superscript numbers denote average crack propagation rate in cm/second (x10^{-7}) and line denotes best estimate (with shaded area being uncertainty Ir isovelocity line for 2×10^{-8} cm/second). Data obtainec in constant extension rate tests on shot peened specimens sensitized at 600 C for 24 hours, strained at 2.1×10^{-7} second^{-1}. From Reference 5.

TABLE 2 — Summary of Test Conditions

Test Temperature	Specimen	Heat Treatment	Surface Condition	Strain Rate Min^{-1}
288 C (0.2ppm O_2)	78AJ,K	600 C/24 hours	AM	2×10^{-5}
	114BW,X,Z	600 C/24 hours	SP	1.33×10^{-5}
	116A13	500 C/24 hours	AM	2×10^{-5}
	116A15	400 C/10d	AM	2×10^{-5}
200 C (0.2 ppm O_2)	78AT,U	600 C/24 hours	AM	2×10^{-5}
	116A10,12	500 C/24 hours	AM	2×10^{-5}
	116A14	400 C/10d	AM	2×10^{-5}
125 C (1.8 ppm O_2)	78AC,D,H	600 C/24 hours	AM	1.33×10^{-5}
	114BS,T,U,V	600 C/24 hours	SP	1.33×10^{-5}

AM = As-machined (wet ground)
SP = Shot peened

TABLE 3 — Summary of Results of Test Interruption

Test Temperature	Specimen	%ε No Crack	%ε Crack	Crack Size[1]	Initiation Estimate %ε	Initiation Estimate % of Life
288 C	78AJ,K	2.2	3.5	small	3	20
	114BW,X,Z	—	4.7	small	4	15
	116A13	3.8	5.9	small	5	30
	116A15	7.4	12	large	9	50
200 C	78AT,U	3.7	5.3	small	5	24
	116A10,12	5.2	9.8	small	9	40
	116A14	27	36	small[2]	36	99
125 C	78AC,D,H	20	26	small[2]	25	95
	114BS,T,U,V	—	3	med	2	20

[1] Size range; small < 0.06 mm, medium < 0.2 mm.
[2] Very small IG crack; ductile failure.

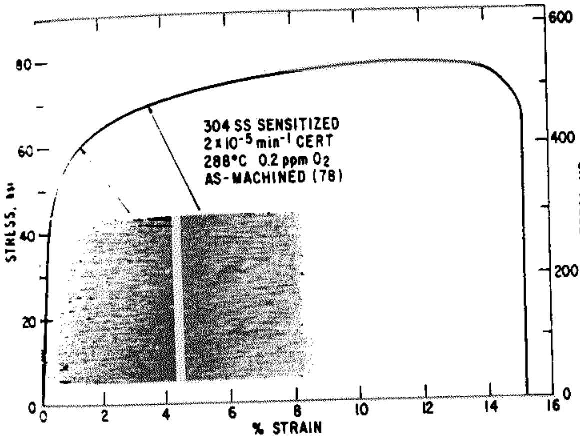

FIGURE 3 — Stress-strain behavior of as-machined, sensitized (600 C/24 hour) Type 304 stainless steel tested under CERT conditions at 288 C at 0.2 ppm oxygen. Arrows and accompanying photographs show the initiation of cracking.

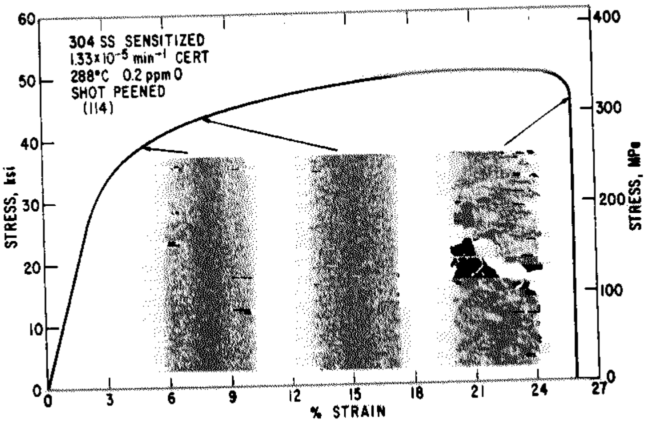

FIGURE 4 — Stress-strain behavior of shot peened, sensitized (600 C/24 hour) Type 304 stainless steel tested under CERT conditions at 288 C at 0.2 ppm oxygen. Arrows and accompanying photographs show the initiation of cracking.

method inherent in test interruption did not strongly influence crack initiation, some additional specimens were tested and interrupted only once to confirm the results obtained by repeated interruption. The results of these latter tests always agreed closely with the previous data. Determination of the probable time to initiation between observations was based on experience and the size of the first cracks observed. Accuracy of the results is limited by the interruption interval employed, specimen and test variations, and the statistical nature of the initiation process. Nonetheless, agreement between duplicate experiments was within approximately ± 20% of the strain to initiation.

Results and Discussion

A summary of the test conditions is shown in Table 2. The choice of the oxygen/temperature combinations which were employed in this investigation were guided by the conditions present during a normal BWR start up. At 200 and 288 C, the use of 0.2 ppm oxygen is in keeping with reactor measurements. At 125 C, the water chemistry in a BWR is changing quite rapidly, and hydrogen peroxide is present as a result of the radiolytic combination of oxygen and water. The choice of the 1.8 ppm oxygen concentration was based on work[5] which has shown that this concentration of oxygen represents a peak in crack growth rate (Figure 2).

The strain to crack initiation and its fraction of the failure strain as measured by interrupted CERT tests are summarized in Table 3. Selected stress-strain behavior is shown in Figures 3 through 8 for the three temperatures studied. Representative photographs showing initiating cracks are overlayed with arrows to identify the strain at which the test was interrupted and the photographs taken. Test interruption and stereoscopic examination often occurred at more frequent intervals than are indicated in these figures. Complete documentation of the development of cracking was not done in all cases. The initial evidence of cracking was confirmed during subsequent interruptions to ensure that crack initiation had been properly identified and that cracks continued to propagate. This practice also demonstrated that, for shot peened samples, mechanical shear cracks which formed on initial straining (at a level of several percent strain) did not result in immediate intergranular propagation. Thus, it is not generally accurate to compute average crack propagation rates based on the strain required to initiate shear cracks in the shot peened layer. A similar phenomenon was not observed in the other types of specimens examined in this study, where cracks continued to grow once initiated.

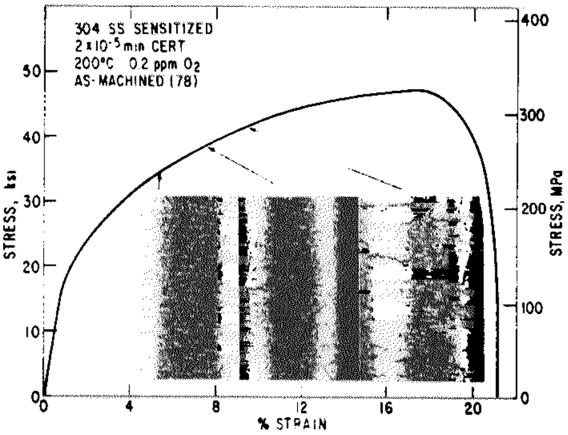

FIGURE 5 — Stress-strain behavior of as-machined, sensitized (600 C/24 hour) Type 304 stainless steel tested under CERT conditions at 200 C at 0.2 ppm oxygen. Arrows and accompanying photographs show the initiation of cracking.

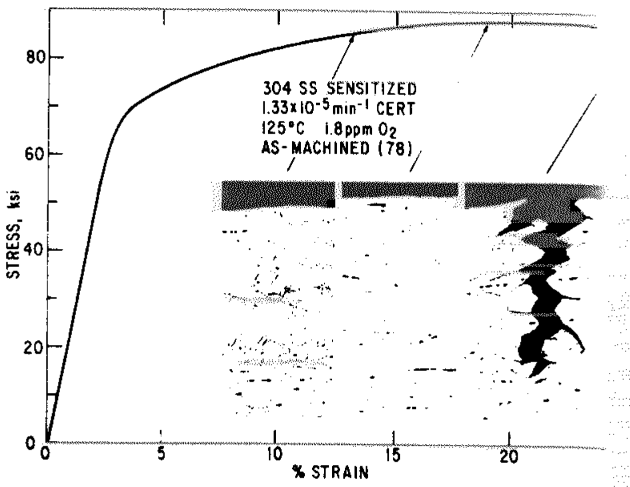

FIGURE 7 — Stress-strain behavior of as-machined, s sitized (600 C/24 hours) Type 304 stainless steel tes under CERT conditions at 125 C at 1.8 ppm oxygen. rows and accompanying photographs show the Init tion of cracking.

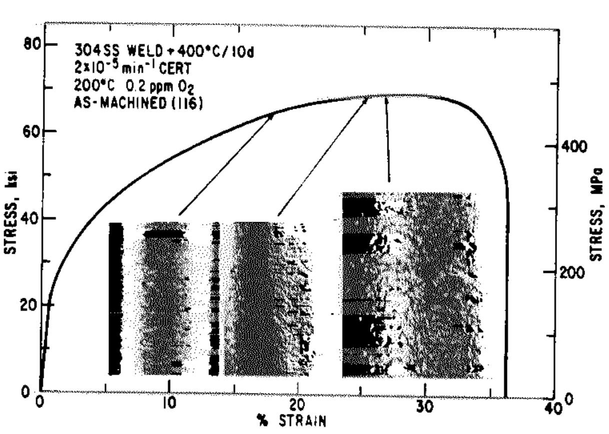

FIGURE 6 — Stress-strain behavior of as-machined, welded and low temperature sensitized (400 C/10 days) Type 304 stainless steel tested under CERT conditions at 200 C at 0.2 ppm oxygen. Arrows and accompanying photographs show the initiation of cracking.

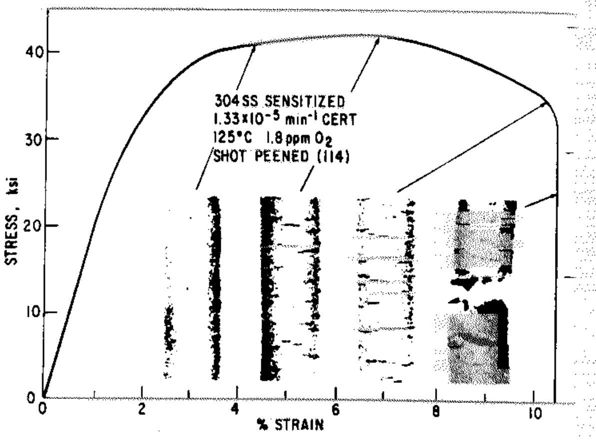

FIGURE 8 — Stress-strain behavior of shot peened, se sitized (600 C/24 hours) Type 304 stainless steel teste under CERT conditions at 125 C at 1.8 ppm oxygen. A rows and accompanying photographs show the initiatio of cracking.

The effect of temperature on initiation is shown graphically in Figure 9. Note that the oxygen concentration at 200 and 288 C was maintained at 0.2 ppm, while at 125 C, it was 1.8 ppm. In all cases, the percentage of life to initiation increased as temperature decreased. For the two closed points representing initiation at approximately 100% of life, failure occurred by ductile rupture, although in both cases there were one or more small intergranular cracks outside of the necked region. At any temperature, the strain to initiation for the various materials examined also parallels the percentage of life to initiation. Points representing the percentage of life to initiation are used as a basis for the curves, primarily since this helps to normalize any test-to-test and sample-to-sample variations.

This data compares well with that of Staehle, *et al*[6] who have conducted limited interrupted CERT testing on sensitized Type 304 stainless steel at a strain rate of 10^{-6} second^{-1} (6 × 10^{-5} minute^{-1}) and at a dissolved oxygen concentration of 8 ppm. In one test conducted at 250 C, no cracking was observed at 2% strain, while intergranular cracks of medium size (~1 mm surface length) were observed at 9% strain. Strain to failure was not reported, but is estimated to be 20% based on the data of this and other[7] studies. In another test[6] conducted at 121 C, no cracking was observed at 12% strain, whil tergranular cracks were observed at 23% strain. Strai failure values listed varied widely at 33% and 49%. Since 33% value is similar to the strain to failure measured in thi vestigation, it will be used below.

Assuming that at 250 C, the initiation reporte Reference 6 occurred at (approximately) 7%, then initiatio curred at 35% of life. At 121 C, initiation occurred at (app mately) 20%, indicating that initiation takes place at 60 life. The 250 C result compares favorably with (although s what higher than) the results obtained in this investigatio 121 C, the trend is toward a higher value, and is general keeping with the findings of this work. At this low temperature, there is a high degree of sensitivity to sur condition, as will be discussed. The surface condition was specified in Reference 6, and may readily have been a m susceptible condition than the wet ground condition use this investigation, although it was less susceptible than shot peened condition.

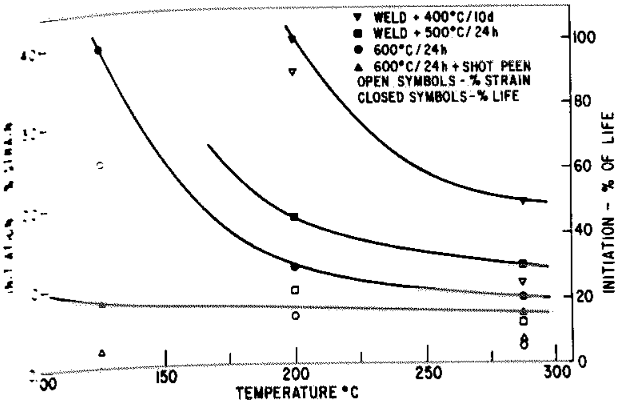

FIGURE 9 — The effect of temperature on crack initiation showing that initiation occurs at lower strains and percentages of life at higher temperatures. Note that the oxygen concentration changes from 0.2 ppm for the tests at 200 and 288 C to 1.8 ppm for the 125 C tests.

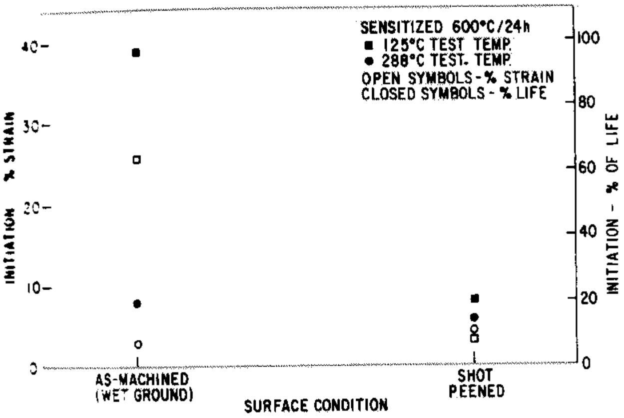

FIGURE 10 — The effect of surface condition on crack initiation indicating that shot peening dramatically affects initiation at lower temperatures. At 288 C, however, shot peening does not significantly influence crack initiation response.

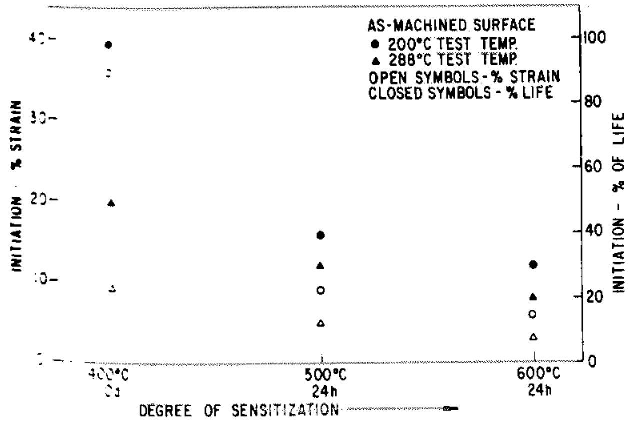

FIGURE 11 — The effect of the degree of sensitization on crack initiation showing that for the lower temperature sensitization treatments crack initiation occurs later in life.

The effect of surface condition is shown in Figure 10. Comparing the two types of samples sensitized at 600 C for 24 hours, it can be seen that, at 288 C, shot peening only mildly accelerates initiation over the as-machined (wet ground) surface (Figures 9 and 10). However, at 125 C, the difference in strain to initiation is dramatic, with the as-machined sample (wet ground surface) being almost completely resistant to crack initiation, and the shot peened sample exhibiting crack initiation at nearly the same percentage of life as was observed at 288 C. Clearly, at lower temperatures, shot peening greatly accelerates crack initiation, presumably as a result of the surface "precracks" which form as the hardened surface layer is strained.

Note that the determination of crack initiation in this study was based on growth of intergranular cracking as determined by surface examination and confirmed by metallographic cross section. The appearance of small mechanical shear cracks has been shown to occur at low strains on shot peened surfaces,[8] although growth of intergranular cracks was not observed in this study until later in life. Nonpropagating stress corrosion cracks have been discussed by Parkins[9] and Ford,[10] although in both instances, loading conditions (*e.g.*, constant load) or alloy environment system are different in response than the system under study. For example, Ford[10] has shown that when carbon or low alloy steels are tested in high temperature water at low frequency or constant load, corrosion products prevent solution access to the crack tip and cracks cease to propagate. Ford[11] has also shown that this will not occur in sensitized stainless steel under similar conditions and that the conditions used in this study are conducive to stable crack growth.

The degree of sensitization also effects the strain to initiation, and Figure 11 presents the results on an arbitrary scale of degree of sensitization, although other workers[7] have shown that this general trend in sensitization is observed using the standard ASTM measures of sensitization. It is important to recognize that the specimens sensitized at 500 and 400 C were machined from welded 254 mm diameter pipe, and that these heat treatments (known as low temperature sensitization[12]) enhance sensitization by accelerating the diffusion of chromium to preexisting carbides. If carbide "seeding" had not occurred as a result of welding, heat treatments of this duration would result in no observable increase in sensitization over the solution annealed condition. Previous work[7] has also shown that strain to failure in CERT indicates that the 500 C/24 hour heat treatment is more severe than the 400 C/10 day treatment. Crack initiation and failure always occurred in the heat affected zone.

Figure 11 shows that strain to initiation increases monotonically with decreasing temperature of heat treatment. In agreement with previous results on the effects of surface condition, variations in degree of sensitization are less significant at 288 C than at lower temperatures. As the temperature of heat treatment is lowered, the concentration of chromium in thermodynamic equilibrium with the chromium in the $M_{23}C_6$ carbide decreases; that is, the "level" of chromium depletion increases. However, at the same time, the width of the depleted region becomes narrower as a result of the steeper diffusion gradient which develops at lower temperatures. This has been examined experimentally and theoretically in Reference 7. It would seem, therefore, that in the temperature range examined, initiation of cracking is more sensitive to the width of chromium depleted region (for example, the width at which the chromium concentration is below 12%) than it is to the depth of the concentration trough. Presumably, the deep, narrow trough formed at 400 C after a 10 day heat treatment is too narrow to be fully "visible" to the 200 or 288 C test environment.

The strain to initiation does not influence the strain to failure in an additive fashion. For example. at 288 C, there is a difference in strain to initiation of 6% between samples 78J,K (600 C/24 hours) and 116A16 (400 C/10 days). However the strain to failure differs only about 3%, an indication that crack propagation occurs more rapidly at the higher stresses/strains present in the latter sample.

The effects of heat-to-heat variability have not been examined for the three heats employed in this study. Variation in IGSCC susceptibility between 13 heats of Type 304 stainless steel tested in CERT was reported by Clarke, *et al.*[13] However, their tests were conducted on alloys ranging in carbon content from 0.040% to 0.070% and were tested in the as-received (mill annealed) conditions and following a low temperature sensitization (LTS) treatment at 500 C for 24 hours. A wide variation exists in the microstructure as a result of "mill annealing", and this can be magnified by the LTS treatment, during which no new carbides nucleate and increased sensitization occurs only as a result of carbide growth. By contrast, in this investigation two of the alloys were very similar in composition and were tested in the furnace annealed condition followed by a 600 C heat treatment for 24 hours. The third alloy was sensitized by welding followed by LTS. These heat treatments yield a far more consistent and predictable degree of sensitization than the mill annealed condition. Additionally, heat-to-heat variations would be expected to affect tests at lower temperatures more than at higher temperatures,[14] and, therefore, tests on the welded + LTS material (#116) were limited to 200 and 288 C. Any remaining effects of heat-to-heat variation were minimized by normalizing the observed behavior using a life-to-initiation parameter.

Very little quantitative work has been published on crack initiation in CERT with which to compare the results of this investigation. Several workers have made qualitative determinations of crack initiation. Povich[8] conducted CERT studies on stainless steels in high temperature water and found that shot peening promotes susceptibility to IGSCC of furnace sensitized Type 304, hypothesizing that initiation at relatively low levels of strain during the test may account for the detrimental effects of peening, a supposition which is clearly supported in this study.

Matsushima, *et al*,[15] studied the effect of surface preparation on the initiation of SCC in 300 C water containing 600 ppm chloride, apparently under constant load conditions. They made the qualitative determination that initiation occurred more readily on mechanically polished surfaces than on chemically or electrochemically polished surfaces. They proposed that the surface condition affects initiation through its influence on the surface film established during polishing. They observed that the oxide films grown in high temperature water on the chemically or electrochemically polished specimens were dense and adherent, in contrast to the porous and nonadherent oxide on mechanically polished specimens.

Solomon has also observed the beneficial effects of electropolishing in CERT tests.[16] The electropolished surfaces failed at higher strains and usually resulted in the formation of only a single crack, in contrast to mechanically polished samples where many cracks formed along the gage section.

Andresen, *et al*,[17] have observed crack initiation in annealed and sensitized 304 stainless steel in water containing 100 ppm chloride at temperatures from 150 to 290 C. They found that transgranular cracking initiated from pits which developed at potentials above a threshold value for annealed material. Above the yield stress, there was essentially no effect of strain rate, with initiation time in constant load and CERT tests being similar. However, initiation in sensitized material was not associated with pitting and, in the chloride environment, occurred readily at stresses as low as half of the yield stress and at potentials substantially below the threshold value for annealed material.

Conclusions

1. The condition of the specimen surface plays an important role in influencing crack initiation behavior in Type 304 stainless steel. Shot peening (and presumably any treatment which inflicts heavy cold work on the sample surface) promotes crack initiation. Intergranular stress corros cracking proceeds from mechanical shear cracks in the s peened surface at low percentages of life, although initiat of IGSCC does not immediately follow the appearance of shear cracks.

2. The degree of sensitization affects crack initiati both in terms of strain to initiation and percentage of life to itiation. Crack initiation is apparently influenced by the wic (at a given concentration) of the chromium deleted zone mc than the minimum concentration of chromium.

3. CERT tests tend to become initiation limited as severity of the environment (temperature) and/or mater (degree of sensitization, surface condition) decreases.

4. The effect of increasing temperature is to dramatica reduce the strain to initiation, particularly for the mc marginal conditions of lower degrees of sensitization and le susceptible surface conditions.

5. The results of this investigation are in general agre ment with the limited data available in the literature.

Acknowledgments

Acknowledgment is gratefully extended to Duane Broecker who performed the experiments described in th paper.

References

1. M. J. Fox, An Overview of Intergranular Stress Corrosic Cracking in BWR's, Proceedings: Seminar on Counte measures for Pipe Cracking in BWR's, Paper No. 1, Ele tric Power Research Institute, Palo Alto, California (198
2. H. H. Klepfer, *et al.*, Investigations of Cause of Crackir in Austenitic Stainless Steel Piping, General Electr Report NEDC 21000-1, p. 1 and pp. 9-39, July (1975).
3. G. M. Ugiansky and J. H. Payer, Editors. Stress Corrosic Cracking: The Slow Strain Rate Technique, ASTM STP 66 Philadelphia, (1979).
4. R. B. Diegle and W. K. Boyd, The Role of Film Ruptu During Slow Strain Rate Stress Corrosion Cracking Tes ing, Stress Corrosion Cracking: The Slow Strain Ra Technique, ASTM STP 665, Philadelphia, p. 26 (1979).
5. F. P. Ford and M. J. Povich, The Effect of Oxygen/Temper ture Combinations on the Stress Corrosion Susceptibilit of Sensitized Type 304 Stainless Steel in High Purit Water, Corrosion Vol. 35, No. 12, p. 569 (1979).
6. R. W. Staehle, J. A. Begley, A. K. Agrawal, F. H. Beck an J. B. Lumsden, Corrosion and Corrosion Cracking Materials for Water Cooled Reactors, Progress Report fc Period July 1 to December 31, 1977, Contract RP311- Electric Power Research Institute, Palo Alto Californi (1978).
7. P. L. Andresen, H. D. Solomon, and D. F. Taylor, Bas Studies on the Variabilities of Fabrication Related Sens tization Phenomena in Stainless Steels, Final Report Cor tract RP-1072-1, Electric Power Research Institute, Pal Alto, California, (1981).
8. M. J. Povich, Constant Strain Rate Studies on Stainles Steel in High Temperature Aqueous Environments, Corro sion Vol. 24, p. 162 (1978).
9. R. N. Parkins, Development of Strain-Rate Testing and It Implications, Stress Corrosion Cracking: The Slow Strai Rate Technique, ASTM STP 665, Philadelphia, p. 26 (1979
10. F. P. Ford, BWR Environmental Cracking Margins for Ca bon Steel Piping, EPRI Contract RP 1248-1, Task 2, Fina Report, November (1981).
11. F. P. Ford, Mechanisms of Environmentally-Enhance Cracking in Alloy/Environment Systems Peculair to Powe Generation Industries, EPRI Contract RP 1332-1, Fina Report, October (1981).
12. M. J. Povich, Low Temperature Sensitization of Type 30 Stainless Steel, Corrosion Vol. 34, p. 60 (1978).
13. W. L. Clarke, R. L. Cowan, and W. L. Walker, Comparativ Methods for Measuring Degree of Sensitization in Stair

less Steel, Intergranular Corrosion of Stainless Alloys, ASTM STP 656, Philadelphia, p. 99 (1978).

4. P. E. Manning, The Effect of Environmental Variables on the Pitting Corrosion Behavior of Single and Duplex Phase 304L Stainless Steel, Ph.D. Thesis, Rensselaer Polytechnic Institute, December (1978).

5. S. Matsushima, T. Ishihara, and G. Ito, Effect of Surface Preparation on Stress Corrosion Cracking of Stainless Steels in High Temperature Water, Corrosion Engineering, Vol. 26, No. 7, p. 367 (1977).

16. H. D. Solomon, Private Communication, General Electric Corporate Research and Development Center, Schenectady, New York, November (1980).

17. P. L. Andresen and D. J. Duquette, The Effects of Dissolved Oxygen, Chloride Ion and Applied Potential on the SCC Behavior of Type 304 Stainless Steel in 290 C Water, Corrosion Vol. 36, No. 8, p. 409 (1980).

Discussion

Comparative Corrosion Tests on Steel Plates Rolled from Continuously Cast Slabs and Rolled from Mold Cast Ingots*

The following is a discussion of the paper entitled "Comparative Corrosion Tests on Steel Plates Rolled from Continuously Cast Slabs and Rolled from Mold Cast Ingots," by Ake Josefsson and Kaarina Lounamaa, published in *Corrosion*, Vol. 37, p. 279 (1981) May.

DISCUSSION by G. Wranglén, Royal Institute of Technology, Dept. of Applied Electrochemistry and Corrosion Science, Stockholm 70, Sweden.

In the above paper, it is shown that continuously cast steel (CCS), "reheated according to normal routine," (A) does not corrode faster, and (B) does not contain a higher relative frequency of *active* sulfides, as revealed by the microcorrosion test (MCT), than ingot cast steel (ICS).

Although Josefsson and Lounamaa take pains to quote two early and preliminary accounts by this writer of the widely known Soviet ice-breaker case, where the heat affected zone (HAZ) in CCS on one side of the welds did corrode rapidly whereas the HAZ in ICS on the other side of the same welds did not corrode at all, they fail to mention that in a more detailed study, presented in 1971 and published in 1974,[1] I reached the same conclusions (A) and (B), stated above, which were then repeated in a paper presented in 1974 and published in 1975.[2]

Generally speaking, MnS inclusions in carbon steel have been shown to initiate: (a) Surface rusting of polished steel, which may be mitigated by removal of surface sulfides by acid pickling[3] or by adding Ce, forming sparingly soluble Ce-oxysulfides;[4] and (b) various forms of localized attack such as pitting in both acid[5] and neutral[6] solutions, weld corrosion,[7] hydrogen[8-10] and stress corrosion cracking,[10,11] and corrosion fatigue.[12]

In these respects, some MnS inclusions are more active and hence induce attack more rapidly than others.

On the other hand, it has been known for 50 years that the general corrosion of carbon steel during extended exposure in sea water is under cathodic control and therefore not influenced by minor variations in composition and structure. Naturally, this also applies to slag inclusions. It is equally well known, however, that localized corrosion in or along welds is strongly dependent upon both composition and structure.[7] It, therefore, does not seem justified, from tests relating to general corrosion in water, to state that the MCT is "entirely devoid of prognostic value as a criterion for corrosion resistance," particularly since several other authors[7,11,12] have found the MCT to be relevant in explaining various forms of localized corrosion. Indeed, in one investigation,[7] intense corrosion of the HAZ in 3% NaCl could be predicted by the MCT but not with polarization curves.

Recently, the MCT, by using dry instead of wet polishing,[13] has been extended to water soluble sulfides, such as CaS and MgS, which have been found to strongly accelerate the corrosion of both carbon[14] and stainless steel,[15] as well as of nodular cast iron.[13]

References

1. G. Wranglén. Localized Corrosion, NACE-3, p. 462, 476, Houston (1974).
2. G. Wranglén. Sulfide Inclusions in Steel, ASM-6, p. 361, 443, Metals Park (1975).
3. D. Twigg and R. H. Bingham. Corrosion, Vol. 34, p. 365 (1978).
4. H. Shimada, et al. Corrosion, Vol. 33, p. 196 (1977).
5. L. Felloni, et al. Brit. Corr. J., Vol. 13, p. 167 (1978).
6. L. J. Gainer and G. R. Wallwork. Corrosion, Vol. 35, p. 435 (1979).
7. R. Strφmmen. Int. Inst. Welding, Ann. Assemby, Tel Aviv, 1975.
8. P. H. Pumphrey. Corrosion, Vol. 36, p. 537 (1980).
9. B. E. Wilde, et al. Corrosion, Vol. 36, p. 625 (1980).
10. T. Taira, et al. Corrosion, Vol. 37, p. 5 (1981).
11. J. G. Parker. Sulfide Inclusions in Steel, ASM-6, p. 403, Metals Park (1975).
12. G. P. Ray and R. A. Jarman. Brit. Corr. J., Vol. 15, p. 226 (1980).
13. J. Berendson and G. Wranglén. Corrosion Sci., Vol. 20, p. 937 (1980).
14. G. Eklund. Localized Corrosion, NACE-3, p. 477, Houston (1974).
15. N. Kinoshita, et al. Sulfide Inclusions in Steel, ASM-6, p. 422, Metals Park (1975).

REPLY by Ake Josefsson, Svenskt Stal AB, Borlange, Sweden and Kaarina Lounamaa, Rautaruukki Oy Helsingki, Finland.

Thanking Professor Wranglén for his discussion, we apologize for not having noted the modifying statements in his later pub-

---

*Submitted for publication July, 1981.

0010-9312/82/000017/$3.00/0