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ABSTRACT

Fatigue tests in sodium were conducted to investigate the influence of a high-temperature sodium environment on the low-cycle fatigue behavior of Types 304 and 316 stainless steel. The effects of testing in a sodium environment as well as long-term sodium exposure were investigated. The fatigue tests were conducted at 600 and 700°C in sodium of controlled purity, viz., ~1 ppm oxygen and 0.4 ppm carbon, at a strain rate of $4 \times 10^{-3} s^{-1}$. The fatigue life of annealed Type 316 stainless steel is substantially greater in sodium than when tested in air; however, the fatigue life of annealed Type 304 stainless steel is altered much less when tested in sodium. A 1512-h preexposure to sodium had no significant effect on the fatigue life of Type 316 stainless steel tested in sodium. However, a similar exposure substantially increased the fatigue life of Type 304 stainless steel in sodium.

INTRODUCTION

The austenitic stainless steels are of interest as containment and structural materials in the Liquid-Metal Fast-Breeder Reactor (LMFBR). For these applications, much of the stainless steel in contact with sodium at elevated temperatures will be subjected to a variety of stress conditions that can limit its performance. Although extensive fatigue data in support of the LMFBR program have been obtained in air at room and elevated temperatures[1-4], little data exists for the effects of the sodium environment on the fatigue behavior of austenitic stainless steels.

It has been shown that the testing environment can have a significant effect on the elevated-temperature fatigue life and fatigue-crack propagation rate of certain materials[5-10]. Typically these data have been obtained from tests in air, argon, or vacuum, and the enhanced crack-growth rates of specimens tested in oxidizing environments have been attributed to "wedging" caused by oxides that formed at the crack tip. The oxygen potential in reactor sodium is much lower than the oxygen potentials of other typical test environments and no oxides will form on stainless steel in sodium. Therefore, enhanced crack-growth rates caused by an oxide "wedging" effect are not expected for stainless steel tested in a sodium environment. However, carbon is known to migrate in stainless steel-sodium heat-transport systems as a result of chemical activity gradients produced by both temperature and compositional differences. Data in the literature in-indicate that the mechanical properties of austenitic stainless steels are strongly dependent on the carbon concentration[11-14]. The problem is further complicated since, under most conditions, carbon concentration gradients will be established in the stainless steel during the lifetime of the components. Crack initiation and propagation in the material may be influenced by the sodium environment as well as the carburization and thermal aging that occur during long-term exposure of the steels.

The purpose of the present investigation is to determine the effects of a high-temperature sodium environment on the low-cycle fatigue behavior of AISI Types 304 and 316 stainless steel under conditions pertinent to LMFBR applications. Data obtained at one strain rate under slightly carburizing conditions are presented.

EXPERIMENTAL PROCEDURE

The facilities for fatigue testing in sodium (FFTS), which consist of 20-kip MTS closed-loop servo-controlled hydraulically-actuated fatigue machines with associated sodium loops, have been described previously[15]. The recirculating sodium loops provide a well-characterized sodium environment for fatigue testing at temperatures to 750°C. The specimens are inserted into the fatigue fixture, which is then lowered into the sodium test vessel at the selected temperature. The sodium is continuously circulated during this period to maintain the desired sodium purity.

The specimen stress is determined by a fatigue-rated load cell attached to the actuator. Since direct measurement of the specimen strain in the sodium environment was not considered feasible, the tests were conducted in a stroke-control mode by means of a standard resistive-type extensometer located on the upper portion of the fixture in an ambient temperature region. The extensometer measures the sum of the elongation in the fixture, the specimen gauge section, and the transition region of the specimen. Hourglass specimens with identical geometry, except for the gauge section, were used as a reference to determine the amount of elongation in the fixture and the transition region of the specimens as a function of load at each test temperature. The measured displacement obtained with an hourglass specimen was subtracted from the measured displacement of a test specimen under identical loading conditions to determine the strain in the gauge section of the test specimens. The fatigue tests were conducted at a strain rate of $4 \times 10^{-3} s^{-1}$ with a fully-reversed triangular waveform and a zero mean strain.

The compositions of the Types 304 and 316 stainless steel, identified as heats 9T2796 and V87210, are given in Table I. The fatigue test specimens with a 0.508-cm-dia by 1.27-cm-gauge length were fabricated from 1.6-cm-dia rods that had been solution annealed for 30 min in argon at 1025°C and water quenched. These samples are referred to hereafter as the annealed condition. A number of these specimens have been exposed to recirculating sodium at temperatures of 600 and 700°C for periods of 1512 and 5012 h in a sodium exposure loop, which has been described previously[14]. The oxygen concentration in sodium during these exposures was 1.0 ppm and the carbon concentration in sodium was maintained at 0.4 ppm. The carbon concentrations in the two steels were not altered significantly by the exposures at 700°C since the initial carbon levels were almost in equilibrium with sodium containing ~0.4 ppm carbon. After the 1512-h exposure at 600°C, the carbon profile in the Types 304 and 316 stainless steel varied from 0.3 and 0.4 wt%, respectively, at the surface to the initial concentration in the steels at a depth of 0.01 cm. The 5012-h exposures at 600°C produced a profile depth of 0.02 cm.

RESULTS AND DISCUSSION

The low-cycle fatigue data on Types 316 and 304 stainless steel in sodium are listed in Tables II and III. Values for the total strain range $\Delta\varepsilon_t$, plastic strain range $\Delta\varepsilon_p$, cyclic stress range at half the fatigue life $\Delta\sigma_{\frac{1}{2}N_f}$, fatigue life N_f, and time to failure t_f are listed for the materials in the annealed and sodium exposed (~1500 and ~5000 h at 600°C and ~1500 h at 700°C) conditions. The relationship between total and plastic strain range and the fatigue life of annealed Types 316 and 304 stainless steels in sodium at 600°C is shown in Figs. 1 and 2, respectively. The dashed curves in both figures represent comparative data obtained in air for the two steels[2,3,16]. For Type 316 stainless steel at 600°C, the ratio of fatigue life in sodium to that in air increases by factors of

Table II. Low-Cycle Fatigue Data on Type 316 Stainless Steel Obtained in a Sodium Environment.

Specimen No.	Matl. Condition*	Temp., °C	$\Delta\varepsilon_t$ (%)	$\Delta\varepsilon_p$ (%)	$\Delta\sigma_{\frac{1}{2}N_f}$ (MPa)	N_f Cycles	t_f min
C-67	1	600	1.65	1.11	686	1,017	172
C-74	1	"	1.50	0.91	676	1,874	248
C-57	1	"	1.10	0.63	599	7,738	648
C-59	1	"	1.10	0.60	599	6,411	538
C-52	1	"	1.08	0.61	601	8,232	699
C-54	1	"	1.08	0.59	602	7,826	665
C-55	1	"	1.06	0.60	605	6,878	579
C-56	1	"	0.77	0.37	512	26,917	1561
C-63	1	"	0.76	0.36	509	27,115	1571
C-72	1	"	0.69	0.31	471	57,170	2927
C-34	2	"	1.61	1.17	579	1,279	168
C-33	2	"	1.16	0.76	546	4,843	408
C-35	2	"	1.11	0.69	523	6,087	510
C-36	2	"	0.88	0.52	464	17,603	1021
C-37	2	"	0.81	0.44	436	36,250	2102
C-38	2	"	0.75	0.38	422	43,247	2212
C-71	1	700	1.36	0.94	464	1,835	237
C-69	1	"	0.94	0.59	437	5,777	482
C-68	1	"	0.81	0.46	424	13,690	911
C-73	1	"	0.77	0.40	398	23,065	1363
C-25	4	"	1.42	1.09	459	1,353	175
C-27	4	"	0.89	0.62	420	7,122	556
C-26	4	"	0.72	0.43	398	19,898	994
C-30	4	"	0.70	0.46	418	12,166	727

*Conditions: (1) Solution annealed, (2) 1512 h in 600°C sodium, and (4) 1512 h in 700°C.

Table I. Compositions of Austenitic Stainless Steels

Material	Heat	Concentration, wt%											
		C	N	P	S	Cr	Ni	Mn	Si	Mo	Ti	Cu	Co
Type 304	9T2796	0.046	0.038	0.026	0.012	17.7	9.3	1.17	0.47	0.33	0.03	0.02	0.10
Type 316	V87210	0.058	0.007	0.026	0.011	16.7	13.9	1.43	0.46	2.84	0.04	0.06	0.03

Table III. Low-Cycle Fatigue Data on Type 304 Stainless Steel Obtained in a Sodium Environment.

Specimen No.	Matl. Condition*	Temp., °C	$\Delta\varepsilon_t$ (%)	$\Delta\varepsilon_p$ (%)	$\Delta\sigma_{\frac{1}{2}N_f}$ (MPa)	N_f Cycles	t_f min
A-61	1	600	1.86	1.43	602	418	71
A-93	1	"	1.48	1.02	597	624	85
A-65	1	"	1.38	0.83	495	1,275	109
A-63	1	"	1.33	0.82	515	1,152	98
A-96	1	"	1.05	0.59	544	1,975	202
A-71	1	"	0.95	0.56	481	1,950	123
A-92	1	"	0.82	0.49	497	4,293	363
A-91	1	"	0.80	0.43	468	7,066	605
A-77	1	"	0.72	0.44	513	2,563	220
A-73	1	"	0.70	0.38	433	5,856	349
A-70	1	"	0.52	0.23	353	30,628	1306
A-104	1	"	0.46	0.15	407	25,783	1320
A-10	2	"	1.67	1.19	595	545	74
A-14	2	"	1.36	0.93	535	2,402	246
A-08	2	"	1.24	0.73	471	3,649	312
A-09	2	"	1.01	0.55	460	8,015	678
A-15	2	"	0.67	0.38	411	31,036	1422
A-80	3	"	1.48	0.99	517	996	118
A-79	3	"	1.28	0.85	505	1,441	120
A-84	3	"	1.02	0.60	477	4,819	403
A-81	3	"	0.85	0.47	454	7,644	522
A-83	3	"	0.55	0.23	392	31,309	1555
A-74	1	700	1.72	1.34	463	368	47
A-106	1	"	1.02	0.68	430	1,321	136
A-105	1	"	0.91	0.52	406	2,024	171
A-97	1	"	0.52	0.24	377	13,282	773
A-68	4	"	1.16	0.81	410	1,303	119
A-61	4	"	0.99	0.62	379	3,463	343
A-85	4	"	0.65	0.36	384	6,533	380
A-87	4	"	0.53	0.24	355	21,123	1054

*Conditions: (1) Solution annealed, (2) 1512 h in 600°C sodium, (3) 5012 h in 600°C sodium, and (4) 1512 h in 700°C sodium.

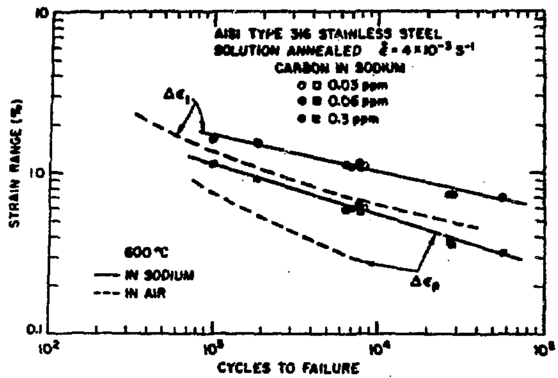

Fig. 1. Plot of Total and Plastic Strain Ranges Versus Cycles to Failure for Type 316 Stainless Steel Tested in Sodium and Air at 600°C.

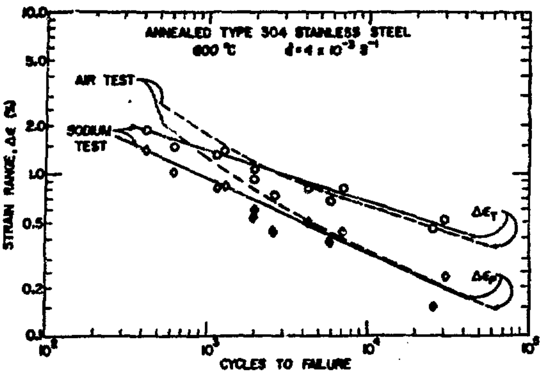

Fig. 2. Plot of Total and Plastic Strain Ranges Versus Cycles to Failure for Type 304 Stainless Steel Tested in Sodium and Air at 600°C.

2 to 6 as the total strain range decreases from 1.5 to 0.7%, which indicates the environmental effect is more pronounced at the longer lifetimes. These observations are in qualitative agreement with elevated temperature crack-growth behavior of stainless steel in sodium and air[10]. However, the fatigue life of annealed Type 304 stainless steel in sodium at 600°C is essentially the same as that in air for total strain ranges from 0.5 to 1.0% and somewhat less than that in air at higher strain ranges (Fig. 2). Although no explanation for the difference in the environmental effect on the two steels can be given at this time, the microstructure and fracture surfaces are being analyzed in an attempt to rationalize this behavior.

Figures 3 and 4 show the effect of temperature on the fatigue life of the two steels tested in sodium. The fatigue life at 600°C is ~50% greater than that at 700°C for both materials, which is similar to the temperature dependence in an air environment.

The effect of long-term sodium exposure on the fatigue life of the two steels is shown in Figs. 5 through 8. The fatigue life of Type 316 stainless steel, in Figs. 5 and 7, was not altered significantly by the 1512-h exposure at either 600 or 700°C for the strain ranges investigated. Since the 700°C exposure did not result in carburization or decarburization of the material, the specimens were essentially subjected to thermal aging. Cheng et al.[1] reported that aging of Type 316 stainless steel had little effect on fatigue life in air at 650°C, which may explain the results in Fig. 6. Carburization of the surface of the steel during the 600°C sodium exposure did not influence the life significantly; however, small increases in the plastic strain were observed for the preexposed specimens.

In contrast to the results for Type 316 stainless steel, preexposure to sodium increased the fatigue life

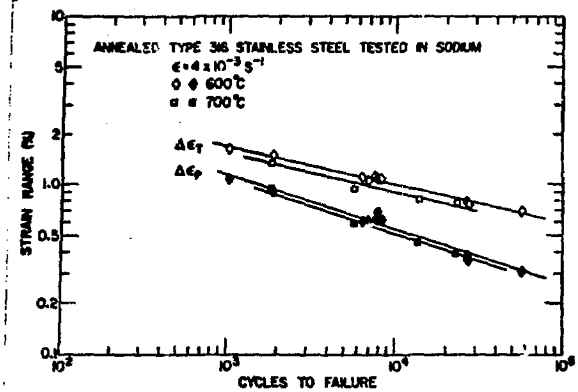

Fig. 3. Fatigue Data Obtained on Annealed Type 316 Stainless Steel Tested in Sodium at 600 and 700°C.

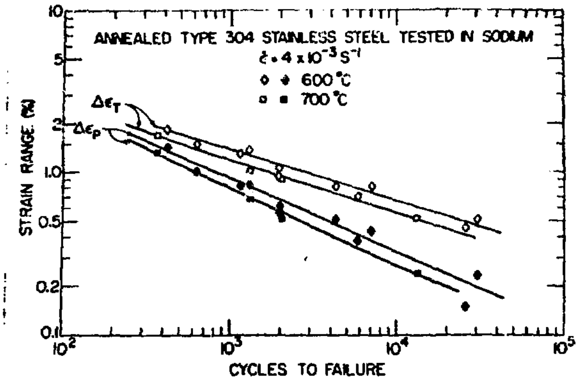

Fig. 4. Fatigue Data Obtained on Annealed Type 304 Stainless Steel Tested in Sodium at 600 and 700°C.

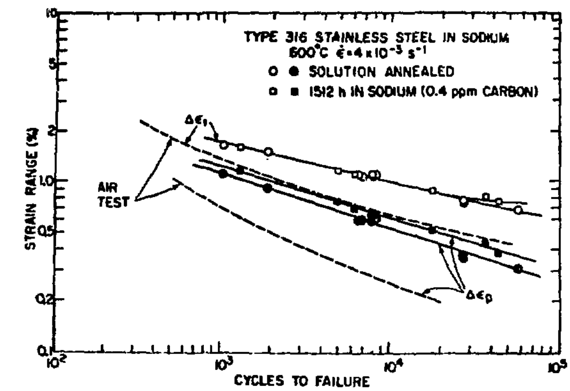

Fig. 5. Fatigue Data Obtained in Sodium at 600°C on Type 316 Stainless Steel in the Annealed and Sodium-exposed Conditions.

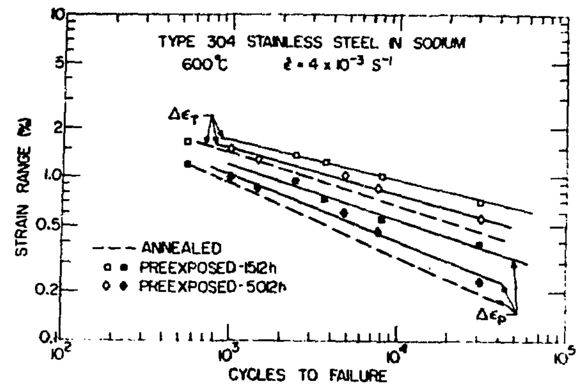

Fig. 6. Fatigue Data Obtained in Sodium at 600°C on Type 304 Stainless Steel in the Annealed and Sodium-exposed Conditions.

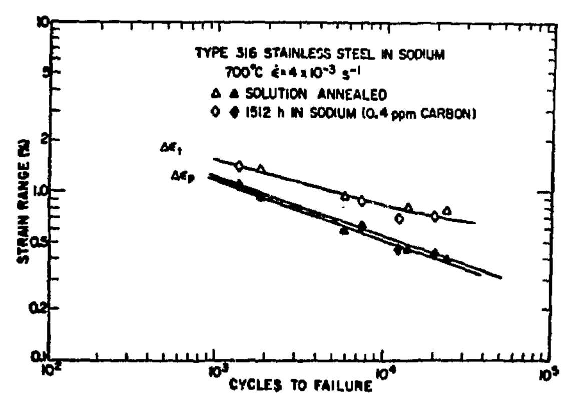

Fig. 7. Fatigue Data Obtained in Sodium at 700°C on Type 316 Stainless Steel in the Annealed and Sodium-exposed Conditions.

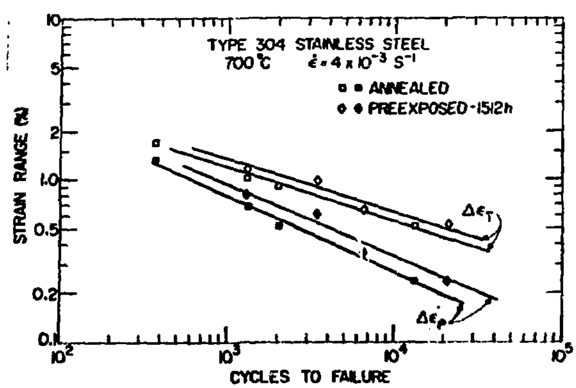

Fig. 8. Fatigue Data Obtained in Sodium at 700°C on Type 304 Stainless Steel in the Annealed and Sodium-exposed Conditions.

of Type 304 stainless steel at both 600 and 700°C (Figs. 6 and 8, respectively). As in the previous case, the 700°C exposure was primarily an aging process since the carbon concentration in the material remained constant. The modest increase in lifetime produced by exposure at 700°C, i.e., 30 to 50%, is in agreement with the effect of aging reported for Type 304 stainless steel[1,2]. The 1512-h sodium exposure at 600°C increased the fatigue life of Type 304 stainless steel by factors of 2 and 4 for total strain ranges of 1.4 and 0.7%, respectively. This increase is substantially greater than the 50% increase in fatigue lifetime for aged material tested in air[1,2]. Therefore, much of the increase can be attributed to the surface carburization of the material. The Type 304 stainless steel was also exposed to sodium for 5012 h at 600°C before testing in sodium. As indicated in Fig. 7, the fatigue lifetime decreases with an increase in the exposure time. This may be related to the greater depth of carburization that occurred during the longer exposure.

The cyclic stress-strain response of the two steels is shown in Figs. 9 and 10. The cyclic stresses for the annealed materials in sodium at 600°C are in agreement with the stresses obtained in air tests at the same temperature. In contrast to the data of Weeks et al.[2] for Type 316 stainless steel aged for 1000 h at 565°C and tested in air at this temperature, considerable softening of the Type 316 stainless steel occurred during the 1512-h exposure to sodium. At 700°C the stresses in preexposed Type 316 stainless steel were only slightly lower than in the annealed material. Apparently substantial aging occurs at 700°C during exposure to sodium for the thermal equilibration period just before fatigue testing. This conclusion is also supported by the much lower strain-hardening exponent for the annealed material, i.e., 0.15 at 700°C in comparison with a value of 0.31 at 600°C. Sodium-exposed Type 304 stainless steel exhibited less softening than Type 316 stainless steel at 600°C, and only a slight reduction in the cyclic stress occurred in both materials after the 1512-h sodium exposure at 700°C.

SUMMARY

Types 304 and 316 stainless steel exhibit different low-cycle fatigue behavior in a sodium environment. At a total strain range of ~1% and a strain rate of $4 \times 10^{-3} s^{-1}$, the fatigue life of annealed Type 316 stainless steel at 600°C was a factor of four greater in sodium than in air. Under similar conditions the fatigue life of annealed Type 304 stainless steel tested in sodium did not differ significantly from the reported lifetime in air. The fatigue lifetimes in sodium for both steels at 600°C were ~50% greater than their respective lifetimes at 700°C; similar to results obtained in an air environment. The fatigue lifetime of Type 316 SS tested in sodium was not influenced significantly by a 1512-h exposure to sodium at either temperature; however, a substantial increase in fatigue life of Type 304 stainless steel was produced by a 1512-h exposure to sodium at 600°C. A modest increase in fatigue life of Type 304 stainless steel resulted from

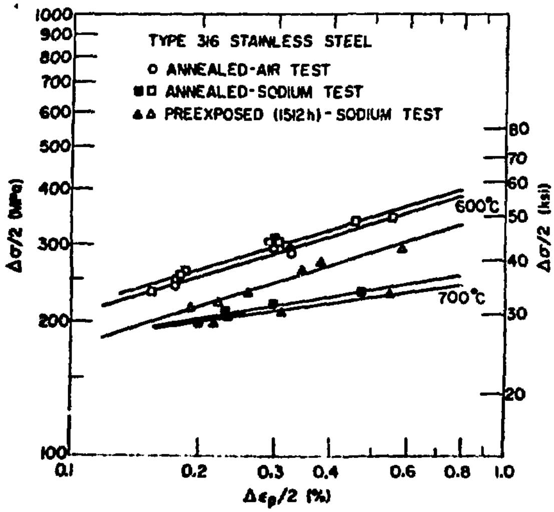

Fig. 9. Cyclic Stress-strain Response for Type 316 Stainless Steel Tested in Sodium at 600 and 700°C in the Annealed and Sodium-exposed Conditions.

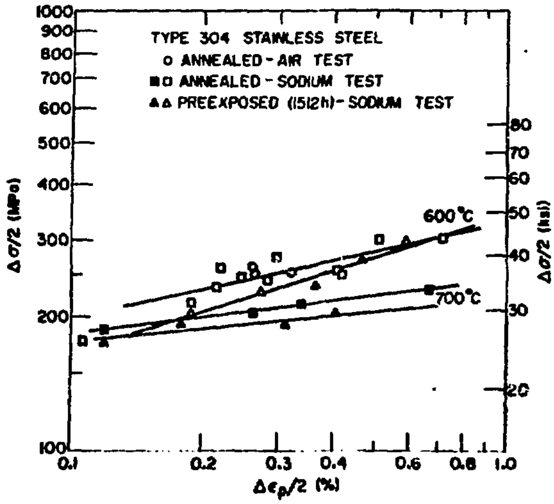

Fig. 10. Cyclic Stress-strain Response for Type 304 Stainless Steel Tested in Sodium at 600 and 700°C in the Annealed and Sodium-exposed Conditions.

the 700°C exposure. Lower cyclic stresses were observed for both steels after the 600°C sodium exposure. The 700°C sodium exposure had almost no effect on the cyclic stress response. An increase in the exposure time of Type 304 stainless steel to sodium from ~1500 to 5000 h at 600°C reduced fatigue life.

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