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THE EFFECT OF TEMPERATURE ON
THE FATIGUE-CRACK PROPAGATION
BEHAVIOR OF A-286 STEEL

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Prepared for the U.S. Energy Research and Development
Administration under Contract No. E(45-1)-2170

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Printed in the United States of America
Available from
National Technical Information Service
U.S. Department of Commerce
5285 Port Royal Road
Springfield, Virginia 22161
Price: Printed Copy \$4.50; Microfiche \$2.50

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L. A. James

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January, 1976

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ABSTRACT

The techniques of linear-elastic fracture mechanics were used to characterize the effect of temperature upon the fatigue-crack growth behavior of A-286 steel in an air environment over the temperature range of 75°-1000°F (24°-538°C). In general, the fatigue-crack growth rate increased with increasing temperature. Two material forms were tested: 0.5 inch thick strip material and 1.5 inch diameter bar. Two different crack orientations were tested in each product form. In general, no significant differences in crack growth behavior were noted between product forms nor between the different crack orientations.

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By

L. A. James

INTRODUCTION

A-286 is a precipitation-hardenable austenitic stainless steel that is being utilized or considered for structural applications in current LMFBR designs. These components will be subjected to cyclic loading fluctuations at elevated temperatures during the reactor lifetime, and hence there is the potential for subcritical extensions of cracks or crack-like flaws. The techniques of linear-elastic fracture mechanics have been shown to be quite valuable in estimating the extension of such cracks in reactor components.⁽¹⁾ A number of parameters are known to influence the fatigue-crack growth behavior of austenitic stainless steels (e.g., temperature, cyclic frequency, stress ratio, environment, etc.). The present report deals with the effect of temperature upon the fatigue-crack growth behavior of A-286 steel.

EXPERIMENTAL PROCEDURE

Two different product forms of A-286 were investigated in this study. One heat of material (designated "Heat A" in Table I) was in the form of 0.5 inch strip, while the other heat (designated "Heat B" in Table I) was in the form of 1.5 inch diameter bar. Both heats of material were tested in the precipitation-hardened condition. The chemical analyses and mechanical properties of these heats are given in Tables II and III, respectively. Considerable additional work has been done on characterizing

TABLE I
HEAT IDENTIFICATION

<u>HEAT IDENTIFICATION</u>	<u>PRODUCER/ HEAT NO.</u>	<u>PURCHASE SPECIFICATION</u>	<u>HEAT TREATMENT</u>	<u>PRODUCT FORM</u>
A	Carpenter Steel/ K-58139-2	AMS 5525C	1800°F for 30 min., Water Quenched, Aged 16 hours at 1325°F, Air Cooled	0.5 x 6.0 in. wide strip
B	TELEDYNE/8790	ASME SA-453, Grade 660, Cond. B	1800°F for 1 hour, Water Quenched, Aged 16 hours at 1325°F, Air Cooled	1.5 in. dia. bar

TABLE II
CHEMICAL ANALYSES (percent by weight)

HEAT	ANALYSIS TYPE	C	Mn	Si	P	S	Cr	Ni	Mo	Cu	V	Ti	Al	B	Fe
A	Ladle	.04	1.23	.50	.014	.003	14.45	25.74	1.31	.12	.26	2.23	.25	.005	Bal.
A	Check	.04	1.27	.53	.015	.002	14.04	25.80	1.30	.08	.26	2.17	.19	.004	Bal.
B	Ladle	.055	1.47	.53	.006	.008	14.50	26.00	1.35	*	.32	2.20	.34	.005	Bal.
B	Check	.057	1.51	.50	.006	.006	14.46	26.35	1.37	*	.33	2.24	.38	.005	Bal.

* Not reported.

TABLE III
MECHANICAL PROPERTIES

HEAT	TEST TEMP.	0.2% OFFSET YIELD	ULTIMATE	TOTAL ELONG.	UNIFORM ELONG.	RED. IN AREA	HARDNESS	SITE SEQUENCE NUMBER****
A**	75°F 24°C	100,000 psi 689 MPa	159,500 psi 1,100 MPa	23.4%	19.4%	43.9%	R _C = 34.7	H02086
A**	600°F 316°C	96,500 psi 665 MPa	144,300 psi 995 MPa	20.0%	16.7%	44.7%	*	H02087
A**	1000°F 538°C	94,700 psi 653 MPa	132,200 psi 911 MPa	18.6%	15.7%	50.4%	*	H02085
B***	75°F 24°C	136,400 psi 940 MPa	168,300 psi 1,160 MPa	19.0%	15.1%	46.3%	R _C = 32.5	H02001
B***	600°F 316°C	113,500 psi 783 MPa	156,100 psi 1,076 MPa	15.4%	12.7%	40.2%	*	H02017
B***	800°F 427°C	105,700 psi 729 MPa	147,700 psi 1,018 MPa	14.8%	11.4%	43.1%	*	H02018
B***	1000°F 538°C	111,300 psi 767 MPa	129,700 psi 894 MPa	22.9%	3.7%	50.0%	*	H02019

* Not reported

** Strain rate = 3×10^{-4} sec⁻¹

*** Strain rate = 3×10^{-5} sec⁻¹

**** HEDL LMFBR Fuel Cladding Information Center

the effect of several parameters (e.g. temperature, thermal aging, strain rate, neutron irradiation) upon the tensile behavior of these two heats, and this is reported in Reference 2.

ASTM "Compact Specimens"⁽³⁾ were used for the crack growth tests in this study. The specimens are shown in Figure 1, and the specimen dimensions are summarized in Table IV along with the major test parameters. It will be noted in Figure 1 that four different specimen orientations* were employed: L-T and T-L orientations in the strip material, and R-C and R-L orientations in the rod material.

The specimens were fatigue tested using an MTS servo-controlled electro-hydraulic testing machine operating in load control. The stress ratio ($R = K_{\min}/K_{\max}$) was 0.05 for all tests. The cyclic frequency was 40 cpm (0.667 Hz) for all tests except those conducted at room temperature where a frequency of 180 cpm (3 Hz) was employed. The loading waveform was sinusoidal or a "sawtooth" for all tests. Elevated temperature tests were conducted in an air-circulating furnace, and temperatures were controlled to within $\pm 2^{\circ}\text{F}$ ($\pm 1^{\circ}\text{C}$).

Crack lengths were determined periodically throughout each test using a travelling microscope. The fatigue-crack growth rate (da/dN) was calculated by dividing each increment of crack extension (Δa) by the number of fatigue cycles producing that increment (ΔN). The stress intensity factor (K) was calculated using the average crack length for each increment, and the expressions in either Equations [1]⁽³⁾ or [2]⁽⁴⁾:

* See Reference 3 for the ASTM crack orientation system used in this study.

(Neg. 741264-1)

FIGURE 1. Arrangement of Fatigue-Crack Growth Specimens.

TABLE IV
TEST PARAMETERS AND SPECIMEN DIMENSIONS

<u>SPECIMEN NUMBER</u>	<u>HEAT</u>	<u>TEST TEMP.</u>	<u>CRACK ORIENT.</u>	<u>"W"</u>	<u>"B"</u>	<u>MAX. LOAD</u>
219	A	75°F 24°C	T-L	1.999 in. 50.77 mm	0.486 in. 12.34 mm	1300 lb. 5783 N
222	A	75°F 24°C	L-T	2.000 in. 50.80 mm	0.484 in. 12.29 mm	1300 lb. 5783 N
256	B	75°F 24°C	R-C	0.804 in. 20.42 mm	0.401 in. 10.19 mm	700 lb. 3114 N
221	A	600°F 316°C	T-L	2.002 in. 50.85 mm	0.487 in. 12.37 mm	1350 lb. 6005 N
224	A	600°F 316°C	L-T	1.997 in. 50.72 mm	0.484 in. 12.34 mm	1350 lb. 6005 N
260	B	600°F 316°C	R-L	1.151 in. 29.24 mm	0.300 in. 7.62 mm	800 lb. 3559 N
257	B	600°F 316°C	R-C	0.795 in. 20.19 mm	0.403 in. 10.24 mm	800 lb. 3559 N
218	A	800°F 427°C	T-L	2.001 in. 50.83 mm	0.488 in. 12.40 mm	1400 lb. 6228 N
223	A	800°F 427°C	L-T	1.999 in. 50.77 mm	0.487 in. 12.37 mm	1300 lb. 5783 N
261	B	1000°F 538°C	R-L	1.153 in. 29.28 mm	0.290 in. 7.37 mm	800 lb. 3559 N
220	A	1000°F 538°C	T-L	2.000 in. 50.80 mm	0.486 in. 12.34 mm	1300 lb. 5783 N
225	A	1000°F 538°C	L-T	2.001 in. 50.83 mm	0.487 in. 12.37 mm	1350 lb. 6005 N

$$K = \frac{P}{B \sqrt{W}} \left[29.6 \left(\frac{a}{W}\right)^{0.5} - 185.5 \left(\frac{a}{W}\right)^{1.5} + 655.7 \left(\frac{a}{W}\right)^{2.5} - 1017.0 \left(\frac{a}{W}\right)^{3.5} + 638.9 \left(\frac{a}{W}\right)^{4.5} \right] \quad \text{Eq. [1]}$$

$$\left(0.3 < \frac{a}{W} < 0.7 \right)$$

$$K = \frac{P}{2B} \left[\frac{w+a}{(w-a)^{1.5}} \right] \left[4.0 + \frac{w-a}{w+a} \right] \quad \text{Eq. [2]}$$

$$\left(\frac{a}{W} > 0.7 \right),$$

where P = applied load and a = crack length. The stress intensity factor range (ΔK) was calculated from Equation [3]

$$\Delta K = K_{\max} (1-R) \quad \text{Eq. [3]}$$

and the results were then plotted as $\log (da/dN)$ as a function of $\log (\Delta K)$.

RESULTS AND DISCUSSION

Fatigue-crack growth tests were conducted at test temperatures of 75°F (24°C), 600°F (316°C), 800°F (427°C) and 1000°F (538°C), and the results are shown in Figures 2-5. Also shown, for purposes of comparison, are scatter bands^(5,6) for 20% cold-worked Type 316 stainless steel which was tested under identical conditions. The cold-worked Type 316 had a 0.2% yield strength approximately equal to that of the A-286 strip material.

The results for the tests conducted at room temperature are shown in Figure 2. It will be noted that both product forms of the A-286 steel exhibit essentially identical crack growth behavior, and that there is no observable effect of crack orientation upon the crack growth behavior. In addition, the crack growth behavior of the A-286 steel is quite similar to that of the cold-worked Type 316 stainless steel. The data for both materials suggests a slope transition at the lower values of ΔK , and similar transitions have been noted in the behavior of other stainless steels⁽⁷⁾ as well as nickel-base alloys⁽⁸⁾.

The crack growth behavior at 600°F (316°C) is shown in Figure 3. Four crack growth orientations were tested and three of the orientations (T-L, L-T, and R-C) exhibited behavior that was quite similar to one another. The fourth orientation (R-L) exhibited crack growth rates significantly higher than the other orientations, especially at the higher values of ΔK . However, post-test examination of the fracture surfaces of this specimen suggested that the crack front had progressed unevenly across the specimen, and this may have influenced the apparent crack growth rates observed for Specimen 260. Additional specimens with this crack

(Neg. 754823-5)

FIGURE 2. Fatigue-Crack Growth Behavior of A-286 Steel in Air at 75°F (24°C).

(Neg. 754823-4)

FIGURE 3. Fatigue-Crack Growth Behavior of A-286 Steel in Air at 600°F (316°C)/

orientation were unavailable for duplicate testing, and therefore the behavior of Specimen 260 must remain in question. The other three specimens tested at 600°F (316°C) behaved quite similarly to the cold-worked Type 316 stainless steel tested under identical conditions.

Specimens from Heat A (strip material) were tested at 800°F (427°C), and the results are shown in Figure 4. Little or no effect of crack orientation is noted between the two specimens, and the crack growth behavior is quite similar to that of the cold-worked Type 316 stainless steel except at the lowest levels of ΔK .

Both heats of material were tested at 1000°F (538°C) and the results are given in Figure 5. Little or no difference is noted between the behavior of the two heats, nor is there any apparent effect of crack orientation. Again, the crack growth behavior is similar to that observed in the cold-worked Type 316 stainless steel except for some difference at the highest levels of ΔK . The transition to a steeper slope at the lower levels of ΔK that was previously noted at the lower test temperatures is also quite pronounced.

The results of this study are summarized in Figure 6. The curves shown represent the average crack growth behavior at each test temperature. With the exception of the tests at 600°F (316°C) and 800°F (427°C), which behaved similarly to one another, the fatigue-crack growth rate increases with increasing test temperature. This is in agreement with similar observations^(5,7,8) when other alloy systems are tested in an air environment at elevated temperatures.

(Neg. 754823-2)

FIGURE 4. Fatigue-Crack Growth Behavior of A-286 Steel in Air at 800°F (427°C).

(Neg. 754823-1)

FIGURE 5. Fatigue-Crack Growth Behavior of A-286 Steel in Air at 1000°F (538°C).

(Neg. 754823-3)

FIGURE 6. Summary Curve of the Effect of Temperature Upon the Fatigue-Crack Growth Behavior of A-286 Steel in an Air Environment.

SUMMARY AND CONCLUSIONS

The results of this study may be summarized as follows:

- The crack propagation properties of two different product forms of A-286 steel (0.5 in. thick strip and 1.5 in. dia. bar) were evaluated at four test temperatures (75°, 600°, 800°, and 1000°F) and in general, the fatigue-crack growth behavior of the two types was similar.
- With the possible exception of one test conducted at 600°F (316°C), little or no effect of crack orientation on crack propagation rates was noted for the four different orientations studied: L-T, T-L, R-C, and R-L.
- The fatigue-crack growth behavior of A-286 steel at each test temperature was similar to that of 20% cold-worked Type 316 stainless steel tested under similar conditions.
- In general, the fatigue-crack growth rate increased with increasing test temperature, and this is in agreement with other observations for different alloy systems tested in an air environment.

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