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A SURVEY OF THE EFFECT OF HEAT-TO-HEAT
VARIATIONS UPON THE FATIGUE-CRACK PROPAGATION
BEHAVIOR OF TYPES 304 AND 316 STAINLESS STEELS

HANFORD ENGINEERING DEVELOPMENT LABORATORY
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by

Lee A. James
May 1975

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ABSTRACT

The fatigue-crack growth behavior of four heats of annealed Type 304 stainless steel and three heats of annealed Type 316 stainless steel were studied at elevated temperature using the techniques of linear-elastic fracture mechanics. It is estimated that a factor of 1.5 applied above and below the mean data line would provide upper and lower bounds that would account for heat-to-heat variations. In addition, the three heats of Type 316 represented three different melt practices: air-melt, vacuum-arc-remelt, and double-vacuum-melt processes. No effect on fatigue-crack growth behavior was noted due to melt practice.

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INTRODUCTION

The analytical techniques of linear elastic fracture mechanics (LEFM) are enjoying ever increasing usage in the prediction of in-service lifetimes for nuclear structural components subject to cyclic loadings⁽¹⁾. At the same time, considerable progress has been made in experimentally characterizing the effect of various operating parameters (e.g. temperature, cyclic frequency, stress ratio, surrounding environment, thermal aging, neutron irradiation, etc.) upon the fatigue-crack growth behavior of two of the most frequently used materials: Types 304 and 316 stainless steels.

The experimental program at HEDL has systematically investigated the effect of one parameter at a time (e.g. temperature) by varying that parameter while holding the values of all other parameters (e.g. cyclic frequency, stress ratio, etc.) constant. In order to eliminate any possibility of heat-to-heat variations obscuring comparisons between the results of the studies on the effects of the various parameters, the tests at HEDL were mainly performed on a single heat of Type 304 (herein called "Heat A") and a single heat of Type 316 (herein called "Heat E"). The objective of this study is to survey the results of fatigue-crack propagation tests conducted on other heats of these materials, both at HEDL as well as at other laboratories around the world, to determine if there is a significant effect due to heat-to-heat variations. A secondary objective is to survey the effect of melt practice (e.g. air-melt, vacuum-arc-remelt, or double-vacuum-melt) upon the crack propagation behavior of Type 316 stainless steel.

EXPERIMENTAL PROCEDURE

Four heats of Type 304 stainless steel (including one heat of Type 304L) and three heats of Type 316 stainless steel (including one heat of Type 316H) have been tested at HEDL. The identification of these heats is shown in Table I. The chemical composition and room temperature mechanical properties are given in Tables II and III, respectively.

The specimen dimensions and major test parameters are listed in Table IV. With the exception of Specimen 287 (which was tested on a Baldwin-Tate-Emery testing machine), all of the specimens were tested on a MTS feedback-controlled electro-hydraulic testing machine using load as the control parameter. Elevated temperature tests were conducted in an air-circulating furnace and temperatures were controlled to within $\pm 2^\circ\text{F}$ ($\pm 1^\circ\text{C}$). The cyclic frequency for the elevated temperature tests was 40 cpm (0.667 Hz), and the stress ratio ($R = K_{\min}/K_{\max}$) was 0.05 for most of the tests. The majority of the specimens have been reported upon previously, and the references for these prior reports are given in Table IV. More detailed information concerning the experimental procedure for these tests may be found in these references.

RESULTS AND DISCUSSION

Heat-to-Heat Variations

One of the biggest advantages to employing LEFM techniques in structural analyses is that the fatigue-crack growth rate (da/dN), as determined experimentally for a given material and set of conditions (temperature, frequency, environment, etc.) in terms of the stress intensity factor (K), represents a true material property independent of the size, shape, and method of loading of the test specimen. This also means that the results obtained using relatively simple laboratory specimens may be directly applied quantitatively in the analysis of relatively complex structural components (e.g. see Ref. 1). In contrast the more traditional "S-N" fatigue tests (stress or strain versus cycles to failure), where the relationship obtained is a function of both the material behavior as well as the test specimen geometry, is more difficult to apply directly in the analysis of complex structural components.

TABLE I

IDENTIFICATION OF HEATS INVESTIGATED

<u>Heat Identification</u>	<u>Material</u>	<u>Producer</u>	<u>Heat Number</u>	<u>Melt Practice</u>	<u>Condition</u>
Heat A	Type 304	Allegheny Ludlum	55697	Air-Melt	Annealed 1 hr @ 2000°F, water quenched
Heat B	Type 304	Allegheny Ludlum	335074	Air-Melt	*
Heat C	Type 304	G.O. Carlson Co.	600414-1A	Air-Melt	Annealed 2 hr 23 min @ 2000-2050°F, water quenched
Heat D	Type 304L	Eastern Stainless Steel Co.	V50035	Unknown	Annealed 1/2 hr @ 1950°F, water quenched
Heat E	Type 316	Allegheny Ludlum	65808	Air-Melt	Annealed 1/2 hr @ 2000°F, water quenched
Heat F	Type 316H	Cameron Iron Works	55320	Vacuum-Arc-Remelt	Annealed 3/4 hr @ 1850°F, forced air cooled
Heat G	Type 316	Carpenter Technology	89335	Double-Vacuum-Melt	Annealed 1 hr @ 1950°F, water quenched

* Material was annealed, but exact annealing conditions are unknown.

TABLE II
CHEMICAL COMPOSITION (PERCENT BY WEIGHT)

Heat Ident.	C	Mn	P	S	Si	Cr	Ni	Cu	Mo	Pb	Ca	Sn	Ti	Al	Ta	Cb	Co	Fe	B	Ce	Il	Total Rare Earths
Heat A	0.053	0.87	0.019	0.010	0.49	18.25	9.51	0.21	0.18	<0.001	0.11	0.006	<0.01	*	*	*	*	Bal.	*	*	0.030	<0.001
Heat B	0.05	1.80	0.027	0.022	0.50	18.58	9.13	*	*	*	*	*	*	*	*	*	0.13	Bal.	*	*	*	*
Heat C	0.064	1.42	0.019	0.015	0.68	18.79	9.48	*	*	*	*	*	0.015	*	0.004	0.008	0.077	Bal.	*	*	*	*
Heat D	0.024	1.70	0.020	0.014	0.61	18.00	9.32	0.17	0.44	*	*	*	*	*	*	*	0.15	Bal.	*	*	*	*
Heat E	0.060	1.72	0.012	0.007	0.40	17.30	13.30	0.065	2.33	0.0014	*	0.013	0.003	0.012	*	*	0.030	Bal.	0.005	0.0006	0.048	0.0010
Heat F	0.075	1.55	0.02	0.018	0.25	16.75	12.80	*	2.30	*	*	*	<0.02	*	<0.01**	<0.01**	*	Bal.	*	*	0.116	*
Heat G	0.05	1.61	0.017	0.010	0.50	16.63	13.63	0.15	2.52	*	*	*	*	*	*	*	0.21	Bal.	0.0006	*	0.028	*

* Not determined

** Cb + Ta

TABLE III

ROOM TEMPERATURE MECHANICAL PROPERTIES

<u>Heat Identification</u>	<u>0.2% Yield Strength</u>	<u>Tensile Strength</u>	<u>Percent Elongation</u>	<u>Percent R.A.*</u>	<u>Hardness</u>	<u>Grain Size ASTM</u>
Heat A	39,600 psi 273 MPa	77,050 psi 531 MPa	65.0	60.7	R _B = 73.2	4-5
Heat B	39,350 psi 271 MPa	77,000 psi 531 MPa	65.5	72.2	BHN = 160	3-4
Heat C	37,000 psi 255 MPa	82,000 psi 565 MPa	57.0	*	R _B = 85.3	*
Heat D	39,300 psi 271 MPa	90,750 psi 626 MPa	67.4	*	R _B = 82.5	*
Heat E	44,100 psi 304 MPa	82,100 psi 566 MPa	68.0	63.4	BHN = 163	4
Heat F	47,100 psi 325 MPa	90,400 psi 623 MPa	52.0	65.9	R _B = 83.3	5-6
Heat G	43,000 psi 296 MPa	81,500 psi 562 MPa	54.3	72.5	BHN = 143	7-8

* Not determined

TABLE IV
SPECIMEN DIMENSIONS AND MAJOR TEST PARAMETERS

Heat Ident.	Specimen Number	Test Temp. (°F)	Crack Orientation**	Frequency (f)	Stress Ratio (R)	"W" (in.)	"B" (in.)	Max. Load (lb.)	Specimen Type	Data Reference
A	283	75	T-L	400 cpm	0.004	4.915	0.493	22,535	SEN	2
A	284	75	T-L	180	0.002	4.910	0.496	45,000	SEN	2
A	287	75	L-T	2	0	4.910	0.491	45,750	SEN	2
A	288	75	L-T	400	0.004	4.950	0.491	22,480	SEN	2
A	294	75	L-T	60	0.050	2.000	0.494	1,700	CT	2
A	324	75	*	240	0.050	---	---	1,500	TDCB	3
A	61	1000	S-L	40	0.050	2.004	0.499	1,150	CT	4
A	73	1000	L-T	40	0.050	1.154	0.300	800	CT	4
A	78	1000	L-T	40	0.050	1.155	0.300	800	CT	4
A	303	1000	L-T	40	0.050	2.000	0.496	1,400	CT	4
B	337	1000	*	40	0.050	1.497	0.518	1,200	CT	4
C	345	1000	*	40	0.050	2.001	0.492	1,400	CT	4
D	150	1000	T-L	40	0.050	2.001	0.477	1,250	CT	5
E	355	75	T-L	300	0.050	2.003	0.504	1,800	CT	6
E	364	75	L-T	600	0.050	2.000	0.495	1,650	CT	6
E	354	1000	T-L	40	0.050	2.000	0.512	1,400	CT	6
E	356	1000	L-T	40	0.050	1.998	0.501	1,200	CT	6
E	363	1000	L-T	40	0.050	1.999	0.499	1,200	CT	6
E	361	1200	T-L	40	0.050	2.000	0.499	1,250	CT	6
E	362	1200	L-T	40	0.050	1.998	0.491	1,100	CT	6
F	192	1000	Circum.	40	0.050	2.003	0.304	750	CT	7
F	197	1000	Axial	40	0.050	2.002	0.308	750	CT	7
G	385	75	*	300	0.050	2.001	0.525	1,900	CT	***
G	386	1000	*	40	0.050	1.499	0.525	1,300	CT	***
G	387	1200	*	40	0.050	1.502	0.525	1,250	CT	***

* Not determined

** See ASTM E399-74 for crack orientation system.

*** Not previously reported.

An excellent example of the specimen-independence that results when crack growth rates (da/dN) are expressed in terms of K is shown in Figure 1. Results are shown for annealed Type 304 stainless steel tested at room temperature using nine different specimen designs. The specimens used, and the K -solutions for each specimen, are shown in Figures 2 and 3. Considering the wide variety of specimens employed, and the obviously different mathematical relationships for K for the different specimens, the agreement shown in Figure 1 is quite impressive. Because several heats of annealed Type 304, tested in various laboratories around the world, are also represented in Figure 1, this plot is also somewhat indicative of the type of data scatter that might be expected for several heats of material. The total scatter on da/dN is a factor of 3.8 as shown in Figure 1. However, it should be pointed out that the tests shown were conducted under similar but not identical conditions (e.g. temperature, cyclic frequency, stress ratio, relative humidity, etc.). For example, the data from Reference 2 show a small effect of cyclic frequency for Type 304 tested at room temperature. Similarly, there is a definite effect of stress ratio upon the crack growth behavior of Type 304 at room temperature⁽¹³⁾, as well as an effect of relative humidity at room temperature⁽¹²⁾. In fact, relative humidity at room temperature can influence da/dN in Type 304 by a factor of 2 or more⁽¹²⁾. Therefore, while Figure 1 is quite impressive from the standpoint of specimen correlation, the factor of 3.8 on da/dN is probably higher than what would be observed if the same specimens from the different heats had been tested under identical conditions of temperature, cyclic frequency, stress ratio and relative humidity--in other words, a statistically meaningful survey of heat-to-heat variations.

Several other studies have been conducted on the crack growth behavior of Type 304 at room temperature⁽¹⁴⁻¹⁸⁾ tested under conditions similar to those in Figure 1. Although the results are not plotted, they generally fall within the scatter bands established in Figure 1.

The four heats of Type 304 tested at 1000°F (538°C) and shown in Figure 4 are probably more indicative of the scatter associated with heat-to-heat variations since all secondary variables (e.g. temperature, frequency, stress ratio, loading waveform, relative humidity) were held constant. A linear

Figure 1. Fatigue-crack propagation behavior of several heats of annealed Type 304 stainless steel at room temperature as determined from nine different specimen designs. See Figures 2 and 3 for specimens used. [Neg. L-324-1]

Figure 2. Specimens employed to generate the data shown in Figure 1.
[Neg. L-324-2]

SC
SURFACE-CRACKED

$$K = \frac{\sigma \sqrt{\pi a}}{\int_0^{\pi/2} \left[1 - \left(\frac{b^2 - a^2}{b^2} \right) \sin^2 \theta \right]^{1/2} d\theta}$$

CT
A.S.T.M. COMPACT TENSION

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

DCB
DOUBLE-CANTILEVER BEAM

$$K = \frac{P}{B} \sqrt{4 \left[\frac{3a^2}{h^3} + \frac{1}{h} \right]}$$

TDCB
TAPERED DOUBLE-CANTILEVER BEAM

$$K = \frac{P}{B} \sqrt{4 \left[\frac{3a^2}{h^3} + \frac{1}{h} \right]} \\ = \text{constant}$$

Figure 3. Specimens employed to generate the data shown in Figure 1.
[Neg. L-324-7]

Figure 4. Fatigue-crack propagation behavior of four heats of annealed Type 304 stainless steel tested at 1000°F (538°C). [Neg. L-331-2]

regression analysis using the data for Specimens 61, 73, 78, 303, 337, 345 and 150 (70 data points, not all of which are plotted for reasons of clarity) yields the relationship*

$$\log \left(\frac{da}{dN} \right) = -17.4824 + 2.91652 \log (\Delta K) \quad \text{Eq. [1]}$$

or

$$\frac{da}{dN} = 3.293 \times 10^{-18} (\Delta K)^{2.917} \quad \text{Eq. [2]}$$

Scatter bands are drawn through the data using the slope of 2.917 from Equation [2]. This slope is approximately equal to the value of 3.06 previously determined⁽²³⁾ for similar tests on Type 304 conducted at 1000°F (538°C). It will be seen that the total scatter band is a factor of 2.75 on da/dN. This factor can be put into the proper perspective by briefly reviewing the results of a recent round-robin crack growth testing program conducted by ASTM Committee E-24.04-01 (Ref. 19). The purpose of this round-robin testing program was to establish on a statistical basis the variability normally encountered in crack growth testing. To accomplish this, 78 specimens were tested in a uniform fashion by a total of 15 laboratories in the United States and England. A single plate of very uniform, environmentally-insensitive steel (10Ni-8Co-1Mo steel) was used. In general, it was found that the inter-laboratory variability was a factor of about 3 to 1 (on da/dN at a given ΔK), and the intralaboratory variability was a factor of about 2 to 1.

Since the average intralaboratory variability for a single heat is a factor of about 2.0, the results from Figure 4 (all of which were tested in the same laboratory) imply that at least part of the data scatter observed may indeed be due to heat-to-heat variations. One might conclude that the variation due to heat-to-heat differences might, for this case, be about a factor of 1.375 or 2.75/2.0 times the normal expected experimental scatter for a single heat.

The crack growth behavior of four heats of Type 316 stainless steel tested (two at HEDL and two elsewhere) at room temperature are shown in Figure 5. The scatter on crack growth rate is a factor of 3.3 but, as was the case for Type 304 tested at room temperature (Figure 1), this factor may not be truly

*The units of da/dN and K are inch/cycle and psi√in, respectively.

Figure 5. Fatigue-crack propagation behavior of four heats of annealed Type 316 stainless steel tested at room temperature. [Neg. L-324-3]

representative of heat-to-heat variations because of minor differences in test temperature, cyclic frequency, stress ratio and relative humidity. Other data exist for Type 316 tested under similar conditions at room temperature (17,24-26), and although not plotted these data would generally fall within the scatter bands established in Figure 5.

The crack growth behavior at 1000°F (538°C) for three heats of Type 316 (all tested at HEDL) is shown in Figure 6. A linear regression analysis using the data for Specimens 354, 356, 363, 192, 197 and 386 (75 data points, not all of which are plotted for reasons of clarity) yields the relationship*

$$\log \left(\frac{da}{dN} \right) = -15.8375 + 2.53012 \log (\Delta K) \quad \text{Eq. [3]}$$

or

$$\frac{da}{dN} = 1.454 \times 10^{-16} (\Delta K)^{2.530} \quad \text{Eq. [4]}$$

Scatter bands are drawn through the data using the slope of 2.530 from Equation [4]. The total scatter band on da/dN is a factor of 2.6 for these data. This factor is only slightly lower than the factor of 2.75 for Type 304 tested under identical conditions (Figure 4).

Limited data for two heats of Type 316 tested at 1200°F (649°C) are shown in Figure 7. The scatter band on da/dN is a factor of 2.1, and this fairly low factor is probably due to the limited number of specimens and heats represented.

Although not included in the present study, three heats of annealed Incoloy 800** (an austenitic stainless steel) were tested at temperatures ranging between 75°F (24°C) and 1200°F (649°C)⁽²⁷⁾. The total variation in da/dN at a given temperature ranged between factors of approximately 2.0 to 3.0, in excellent agreement with the results for Types 304 and 316 from the present study.

*The units of da/dN and K are inch/cycle and $\text{psi}/\sqrt{\text{in}}$, respectively.

**Incoloy 800 is a registered trademark of the International Nickel Company. However, the general specifications for this material may be found in ASME Specification SB-409.

Figure 6. Fatigue-crack propagation behavior of three heats of annealed Type 316 stainless steel (representing three different melt practices) tested at 1000°F (538°C). [Neg. L-331-1]

Figure 7. Fatigue-crack propagation behavior of two heats of annealed Type 316 stainless steel tested at 1200°F (649°C). [Neg. L-324-6]

It therefore appears that the total scatter factor for testing several heats of Types 304 and 316 lies somewhere between 2.0 and 3.0; most likely approaching the latter. It should be pointed out, however, that due to the limited data available the results were not analyzed statistically. The factors of 2.0 to 3.0 should therefore be regarded as estimates, although it is felt that statistically-derived factors would probably fall within this range. Therefore, a reasonable tentative estimate for upper-bound behavior for design purposes in order to account for normal testing variability and heat-to-heat variations, might be to multiply the nominal values obtained experimentally from a single heat by a factor of 1.5.

Melt Practice Variations

The three heats of Type 316 stainless steel tested at HEDL (see Table I) were from three different melt practices: air-melt, vacuum-arc-remelt, and double-vacuum-melt processes. Hence, this provided an excellent opportunity to survey any possible effects on fatigue-crack propagation behavior due to melt practice. The results shown in Figures 5-7 seem to indicate no observable effect due to the various melt practices employed.

SUMMARY AND CONCLUSIONS

The results of this study may be summarized as follows:

- Fatigue-crack growth data for annealed Type 304 stainless steel tested at room temperature using nine different specimen designs showed excellent correlation considering the varying conditions of cyclic frequency, stress ratio, and relative humidity between the tests. The excellent correlation between nine different specimen designs, several heats of material, and between a number of laboratories around the world is yet another example of the specimen-independence that results when fatigue tests are characterized in terms of fracture mechanics parameters.
- Four heats of annealed Type 304 stainless steel were tested at 1000°F (538°C) under identical test conditions. The total scatter on the fatigue-crack growth rate was a factor of 2.75. This was the largest scatter factor observed for tests run under identical

conditions, and this probably resulted from the fact that these results represented the largest number of specimens and material heats. Therefore, it is suggested that a factor of 1.5 applied above the mean data line for a single heat of material, and a factor of 1.5 applied below the mean data line, would probably adequately account for expected heat-to-heat variations and provide upper bound and lower bound curves, respectively, for analysis purposes.

- Three heats of annealed Type 316 stainless steel tested at 1000°F (538°C) exhibited a total scatter on crack growth rate of a factor of 2.6. Each of these heats represented a different melt practice: air-melt, vacuum-arc-remelt, and double-vacuum-melt processes. There was no observable difference in the results among the three melt practices. Therefore, it is concluded that melt practice does not have an appreciable effect on fatigue-crack growth behavior in annealed Type 316 stainless steel.

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