5/2/80

DR. 1128

HEDL-TME 80-9
UC-79b,h

EFFECT OF HEAT TREATMENT AND HEAT-TO-HEAT VARIATIONS IN THE FATIGUE-CRACK GROWTH RESPONSE OF ALLOY 718

MASTER

PART 1: MACROSCOPIC OBSERVATIONS

Hanford Engineering Development Laboratory

DO NOT MICROFILM
COVER

HANFORD ENGINEERING DEVELOPMENT LABORATORY
Operated by Westinghouse Hanford Company
P.O. Box 1970 Richland, WA 99352
A Subsidiary of Westinghouse Electric Corporation
Prepared for the U.S. Department of Energy
under Contract No. DE-AC14-76FF02170

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency Thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

DISCLAIMER

Portions of this document may be illegible in electronic image products. Images are produced from the best available original document.

NOTICE

This report was prepared as an account of work sponsored by the United States Government. Neither the United States nor the U.S. DOE, nor any of their employees, nor any of their contractors, subcontractors, or their employees, makes any warranty expressed or implied, or assumes any legal liability or responsibility for the accuracy, completeness or usefulness of any information, apparatus, product or process disclosed, or represents that its use would not infringe privately-owned rights.

Printed in the United States of America
Available from
DOE Technical Information Center
P.O. Box 62
Oak Ridge, TN 37830
Price: Printed Copy \$4.50

EFFECT OF HEAT TREATMENT AND HEAT-TO-HEAT VARIATIONS IN THE FATIGUE-CRACK GROWTH RESPONSE OF ALLOY 718

PART 1: MACROSCOPIC OBSERVATIONS

Hanford Engineering Development Laboratory

**L.A. James
W.J. Mills**

April 1980

DISCLAIMER

This book was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

MASTER

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

HANFORD ENGINEERING DEVELOPMENT LABORATORY
Operated by Westinghouse Hanford Company
P.O. Box 1970 Richland, WA 99352
A Subsidiary of Westinghouse Electric Corporation
Prepared for the U.S. Department of Energy
under Contract No. DE-AC14-76FF02170

EFFECT OF HEAT-TREATMENT AND HEAT-TO-HEAT VARIATIONS IN THE
FATIGUE-CRACK GROWTH RESPONSE OF ALLOY 718 —
PART 1: MACROSCOPIC OBSERVATIONS

By

Lee A. James and William J. Mills

ABSTRACT

The fatigue-crack growth behavior of seven heats of Alloy 718 was studied at five different test temperatures. These seven heats represented at least four different producers, four different product forms, two melt practices, and most of the heats were tested in two different heat-treated conditions. Heat-to-heat variations were noted; these were most obvious in material given the conventional heat-treatment.

CONTENTS

	<u>Page</u>
Abstract	iii
Figures	vi
Tables	vii
I. INTRODUCTION	1
II. EXPERIMENTAL PROCEDURE	3
III. RESULTS AND DISCUSSION	9
A. PRECIPITATION HEAT-TREATED MATERIAL	9
B. ANNEALED MATERIAL	19
C. CRACK GROWTH EQUATIONS	19
IV. CONCLUDING REMARKS	25
V. REFERENCES	27

FIGURES

<u>Figure</u>	<u>Page</u>
1. Fatigue-Crack Growth Behavior of Heat-Treated Alloy 718 Tested in an Air Environment at 24°C	10
2. Fatigue-Crack Growth Behavior of Heat-Treated Alloy 718 Tested in an Air Environment at 316°C	11
3. Fatigue-Crack Growth Behavior of Heat-Treated Alloy 718 Tested in an Air Environment at 427°C	12
4. Fatigue-Crack Growth Behavior of Heat-Treated Alloy 718 Tested in an Air Environment at 538°C	13
5. Fatigue-Crack Growth Behavior of Heat-Treated Alloy 718 Tested in an Air Environment at 649°C	14
6. Fatigue-Crack Growth Behavior of Annealed Alloy 718 Tested in Air at 24°C	20
7. Fatigue-Crack Growth Behavior of Annealed Alloy 718 Tested in Air at 316°C	21
8. Fatigue-Crack Growth Behavior of Annealed Alloy 718 Tested in Air at 538°C	22

TABLES

<u>Table</u>	<u>Page</u>
1. Identification of Material Heats	4
2. Chemical Composition (Percent by Weight)	5
3. Heat-Treatments for Alloy 718	6
4. Average Mechanical Properties	7
5. Values for Regression Analyses	15

EFFECT OF HEAT-TREATMENT AND HEAT-TO-HEAT VARIATIONS IN THE
FATIGUE-CRACK GROWTH RESPONSE OF ALLOY 718 —

PART 1: MACROSCOPIC OBSERVATIONS

(AF-15-10-15) ;

I. INTRODUCTION

Alloy 718 is a precipitation-hardened nickel-base superalloy that is employed in structural applications in the nuclear, aerospace, and petrochemical industries where high strength, creep resistance, and corrosion resistance at elevated temperatures are important design considerations. An important aspect in assessing the structural integrity of such applications is the estimation of in-service extension of cracks and crack-like flaws, either real or hypothetical. Linear-elastic fracture mechanics (LEFM) techniques are the analytical tool most frequently employed in conducting in-service crack extension calculations.

Knowledge of the fatigue-crack propagation (FCP) behavior of the structural alloy is a prerequisite to conducting crack growth analyses. Alloy 718 is a complex alloy involving the precipitation of several phases, and differences in FCP behavior have been noted arising from different precipitation heat-treatments⁽¹⁻⁴⁾ as well as from heat-to-heat variations.^(3,4) Although such differences have been noted, the underlying reasons for the differences between material heats is not well understood. Therefore, the objective of this paper is to describe the effect of heat-treatment upon the crack growth behavior of several heats of Alloy 718 using LEFM techniques, while the objective of a companion paper⁽⁵⁾ is to discuss the microstructural factors that influence that behavior.

Blank Page

II. EXPERIMENTAL PROCEDURE

Seven different heats of Alloy 718 were employed in this study. These heats, identified in Table 1, represented at least four different producers, and at least two different melt practices: vacuum-induction-melting followed by vacuum-arc-remelting (VIM-VAR), and vacuum-induction melting followed by electroslag-remelting (VIM-ESR). The vacuum-induction-melting followed by electroflux-remelting (VIM-EFR) process is essentially equivalent to the VIM-ESR process. In addition, the seven heats represented several different product forms: round bar, rectangular bar, plate, and a forging. The chemical compositions of these seven heats are detailed in Table 2.

The objective of this study was to characterize heat-to-heat variations in the FCP behavior of Alloy 718, and also to investigate the response of the different heats of material to different precipitation heat-treatments. Therefore, two precipitation heat-treatments were employed: the "conventional" (ASTM A637) heat-treatment, and a "modified" heat-treatment (developed at the Idaho National Engineering Laboratory⁽⁶⁾). These heat-treatments are given in Table 3. In addition, limited testing was done on one heat (Heat B) in the annealed condition. Average tensile properties are given in Table 4.

All of the specimens employed were of the standard ASTM Compact Specimen design (see ASTM E647-78T). Specimen dimensions, depending upon the particular heat of material, were either $W = 50.8$ mm and $B = 12.7$ mm (Heats B, E, F, G), or $W = 38.1$ mm and $B = 8.89$ mm (Heat D), or $W = 29.3$ mm and $B = 7.62$ mm (Heats A and C), where W denotes the width and B denotes the thickness. All tests were conducted in an air environment (relative humidity at room temperature was 40-60%). Elevated temperature tests were conducted in an air-circulating furnace where temperatures were controlled to within about $\pm 1^\circ\text{C}$.

The specimens were tested on a feedback-controlled electrohydraulic testing machine using load as the control parameter. The stress ratio ($R = K_{\min}/K_{\max}$) was 0.05 for all tests. A sinusoidal waveform at a cyclic frequency of

TABLE 1
IDENTIFICATION OF MATERIAL HEATS

<u>Heat Identification</u>	<u>Producer Heat No.</u>	<u>Product Form</u>	<u>Melt Practice</u>	<u>Purchase Spec.</u>
A	Teledyne Allvac H-673	15.9 x 41.3 mm Bar	VIM-VAR	RDT M2-15T Amend. 3
B	Cabot-Stellite 2180-9-9104*	12.7 mm Plate	VIM-VAR	AMS 5597
C	Cabot-Stellite 2180-1-9327	12.7 mm Plate	VIM-ESR	AMS 5596C
D	Unknown	76.2 mm Dia. Bar	Unknown	Unknown
E	Huntington 52C9EK	12.7 mm Plate	VIM-EFR	AMS 5596C
F	Cartech 84221	157.5 cm Dia. x 50.8 mm Thick Forging**	VIM-VAR	RDT M2-15T Amend. 3
G	Cabot-Stellite 2180-6-9457	12.7 mm Plate	VIM-ESR	RDT M5-21T

*Results first reported in Reference 12.

**Open die upset forging.

TABLE 2
CHEMICAL COMPOSITION (PERCENT BY WEIGHT)

Heat Ident.	C	Mn	Fe	S	Si	Cu	Ni	Cr	Al	Ti	Co	P	Mo	B	Nb&Ta	Nb	Ta
A	.04	.19	Bal.	.002	.10	<.01	53.80	17.65	.56	1.00	.02	.003	3.08	.005	5.26	5.24	.02
B	.05	.19	Bal.	.003	.09	<.01	53.00	17.95	.46	.95	.07	.003	3.16	.003	5.17	*	*
C	.04	.08	Bal.	<.005	.07	.02	51.60	18.30	.52	1.01	.12	<.005	3.10	.004	5.26	*	*
D	.04	.15	17.97	.005	.15	.10	53.06	18.50	.62	.95	.09	*	3.06	*	5.29	*	*
E	.07	.08	18.19	.007	.17	.11	53.44	18.11	.49	1.08	.03	*	3.00	*	5.10	*	*
F	.041	.05	18.18	.005	.08	.01	53.33	18.28	.53	.93	.10	<.005	3.01	.0029	5.23	5.16	.07
G	.05	.29	19.18	.002	.15	.02	52.19	18.24	.55	1.06	.05	.005	3.05	.003	5.16	*	*

*Not determined.

TABLE 3
HEAT-TREATMENTS FOR ALLOY 718

Conventional Heat-Treatment (per ASTM A637)

Annealed at 954°C, air cooled to room temperature

Aged 8 hours at 718°C, furnace cooled to 621°C and held at 621°C for a total aging time of 18 hours

Air cooled to room temperature

Modified Heat-Treatment (Developed by Idaho National Engineering Laboratory)

Solution annealed 1 hour at 1093°C, cooled to 718°C at 55°C/hour

Aged 4 hours at 718°C, cooled to 621°C at 55°C/hour

Aged 16 hours at 621°C, air cooled to room temperature

Mill-Annealed (Heat B only)

Annealed at 1066°C and air-cooled

TABLE 4
AVERAGE MECHANICAL PROPERTIES

Test Temp. (°C)	Mat'l. Cond.*	Heats Tested	No. of Tests	0.2% Yield Strength		Ultimate Strength		Total Elong.	
				Mean (MPa)	Std. Dev. (MPa)	Mean (MPa)	Std. Dev. (MPa)	Mean (%)	Std. Dev. (%)
24	ANN	B, C, E, G	4	359.6	38.26	819.0	42.51	53.00	5.87
24	CHT	A, B, C, E, F, G	20	1113.4	49.84	1373.2	64.84	20.50	2.69
24	MHT	A, C, E, F, G	10	978.8	45.66	1317.8	11.36	17.91	2.94
316	CHT	A, C, E	3	996.1	-----	1251.4	-----	20.97	-----
316	MHT	A, E	2	921.5	-----	1203.5	-----	17.00	-----
427	CHT	A, C, E, F, G	12	1000.6	55.76	1234.3	60.37	18.03	3.41
427	MHT	A, C, E, F, G	10	864.3	40.07	1178.7	25.23	16.07	2.04
538	CHT	A, C, E, F, G	12	966.2	54.21	1216.0	68.97	16.78	3.36
538	MHT	A, C, E, F, G	10	853.6	30.80	1155.9	27.12	16.69	2.58
649	CHT	A, C, E, F, G	10	916.0	47.50	1071.4	73.62	17.86	7.51
649	MHT	A, E	2	827.7	-----	916.7	-----	8.15	-----

*ANN = Annealed

CHT = Conventional Heat-Treatment

MHT = Modified Heat-Treatment

40 cpm (0.667 Hz) was employed for all tests, except for those at room temperature where frequency is not expected to be an important variable.

Crack lengths were determined optically using a traveling microscope. Fatigue-crack growth rates (da/dN) were calculated using the "secant method",⁽⁷⁾ and the stress intensity factor (K) was calculated using the standard expression found in ASTM E647-78T. The results were expressed as logarithmic plots of da/dN as a function of ΔK , where $\Delta K = K_{\max} - K_{\min}$.

III. RESULTS AND DISCUSSION

A. PRECIPITATION HEAT-TREATED MATERIAL

Tests were conducted at temperatures of 24, 316, 427, 538 and 649°C. The results for the two different precipitation heat-treatments (conventional and modified) at each of these temperatures are shown in Figures 1-5, respectively. The format in each of these figures is the same: results for the conventional heat-treatment on the left, and those for the modified treatment on the right. It will be noted that not all seven material heats were tested at every temperature in both heat treatments, but at least five heats are represented at each condition. Linear (or in some cases, bilinear) least square regression lines were fitted through various groupings of data, as shown in Figures 1-5. The regression constants are given in Table 5.

Although a comparison of the crack growth data at all five test temperatures has not been plotted, review of the trends exhibited in Figures 1-5 would show that, in general, crack growth rates at a given K-level increase with increasing temperature. This observation, of course, has been made many times on Alloy 718,^(1-4,8,9) as well as with most other structural alloys tested in an air environment at elevated temperatures.

A second observation that may be made from the data in Figures 1-5 is that, in general, at a given test temperature, the material given the modified heat treatment exhibits lower crack growth rates than material given the conventional treatment. Again, this has been observed in several previous studies.⁽¹⁻⁴⁾ However, it will be noted that the degree of improvement gained when the modified heat treatment is employed varies considerably from heat to heat, and these differences are the main thrust of this paper and its companion paper.⁽⁵⁾

The results of an extensive ASTM round-robin test program on fatigue-crack growth rate testing suggested that a total scatter of da/dN of a factor of two was normal for intralaboratory room temperature tests on a single

FIGURE 1. Fatigue-Crack Growth Behavior of Heat-Treated Alloy 718 Tested in an Air Environment at 24°C. (Neg. 7903336-1)

FIGURE 2. Fatigue-Crack Growth Behavior of Heat-Treated Alloy 718 Tested in an Air Environment at 316°C. (Neg. 7902646-11)

FIGURE 3. Fatigue-Crack Growth Behavior of Heat-Treated Alloy 718 Tested in an Air Environment at 427°C. (Neg. 7902646-10)

FIGURE 4. Fatigue-Crack Growth Behavior of Heat-Treated Alloy 718 Tested in an Air Environment at 538°C. (Neg. 7902646-9)

FIGURE 5. Fatigue-Crack Growth Behavior of Heat-Treated Alloy 718 Tested in an Air Environment at 649°C. (Neg. 7902646-8)

TABLE 5
VALUES FOR REGRESSION ANALYSES^(a)
(SEE EQUATION (2))

Material Heats	Condition	Test Temp. (°C)	A=Intercept	n=Slope	Data Pairs	Std. Error ^(b)	Corr. Coeff.	Range of Validity
B	Annealed	24	-88.5370	19.2614	12	0.2225	0.9556	15,500 < ΔK < 20,030
B	Annealed	24	-22.9351	4.0112	30	0.0727	0.9880	20,030 < ΔK < 53,900
A	Conv. H.T.	24	-19.7840	3.3126	14	0.0471	0.9923	15,670 < ΔK < 35,430
A	Conv. H.T.	24	-28.3391	5.1932	7	0.0288	0.9982	35,430 < ΔK < 63,260
B,C,E,F,G	Conv. H.T.	24	-21.6448	3.6625	151	0.1285	0.9832	10,100 < ΔK < 61,980
A,C,D,E,F,G	Mod. H.T.	24	-21.2658	3.5094	143	0.1673	0.9723	10,950 < ΔK < 73,340
B	Annealed	316	-77.5161	16.7037	3	0.0818	0.9977	16,340 < ΔK < 20,680
B	Annealed	316	-24.6870	4.4621	16	0.0639	0.9895	20,680 < ΔK < 40,710
A	Conv. H.T.	316	-19.8180	3.3497	17	0.0714	0.9934	12,960 < ΔK < 47,300
B,C,E,F,G	Conv. H.T.	316	-20.8135	3.5091	116	0.1222	0.9850	11,660 < ΔK < 73,950
A,C,E,F,G	Mod. H.T.	316	-20.8822	3.4675	127	0.2964	0.9208	11,860 < ΔK < 80,960
A	Conv. H.T.	427	-19.3011	3.2572	19	0.0602	0.9952	12,840 < ΔK < 49,230
C,E,F,G	Conv. H.T.	427	-19.8483	3.3361	110	0.1056	0.9850	11,580 < ΔK < 63,290
A,C,E,F,G	Mod. H.T.	427	-19.2534	3.1300	125	0.1375	0.9763	11,860 < ΔK < 69,620
B	Annealed	538	-20.6367	3.5822	15	0.0647	0.9908	15,470 < ΔK < 39,290
A	Conv. H.T.	538	-15.1032	2.3008	21	0.0683	0.9879	11,940 < ΔK < 31,750
C	Conv. H.T.	538	-13.8986	1.9632	13	0.0842	0.9696	29,510 < ΔK < 94,110
B,E,F,G	Conv. H.T.	538	-18.5383	3.0679	113	0.0740	0.9920	11,340 < ΔK < 68,700
A,C,D,E,F,G	Mod. H.T.	538	-16.3204	2.4996	158	0.0934	0.9821	11,060 < ΔK < 58,790
A	Conv. H.T.	649	-15.2496	2.4941	13	0.0727	0.9766	14,120 < ΔK < 36,310
B,C,E,F,G	Conv. H.T.	649	-15.7324	2.5241	113	0.1597	0.9239	14,200 < ΔK < 61,070
A,C,E,F,G	Mod. H.T.	649	-17.7130	2.9521	113	0.1516	0.9588	11,480 < ΔK < 48,630

(a) Units: da/dN = inch/cycle, ΔK = psi/ $\sqrt{\text{in}}$
Conversion to SI Units: (inch/cycle)(25.4) = mm/cycle
(psi/ $\sqrt{\text{in}}$)(1.099 x 10⁻³) = MPa/ $\sqrt{\text{m}}$

(b) Standard error of estimate on log(da/dN)

well-behaved heat of material.⁽⁷⁾ Results for individual heats in the present study generally exhibited total scatter considerably less than a factor of two. It should be remembered, however, that only in a very few cases (e.g., see Figures 1a, 4a and 4b) were more than one specimen from a single heat tested under identical conditions. The results of Reference 10 suggest that slightly greater scatter (six specimens from a single heat of Type 304 SS exhibited a factor of 2.75) is associated with elevated temperature testing; presumably because of the increased difficulty of determining crack lengths at elevated temperatures.

Hence, one might infer from the results of References 7 and 10 that total scatter in excess of a factor of 2.0 at room temperature, and a factor of about 2.75 at elevated temperatures, would indicate the existence of a heat-to-heat variation. However, it has not been established that these variability factors apply to Alloy 718 tested at room and elevated temperatures.

The heat-to-heat variations in FCP behavior is quite apparent when reviewing the results of Figures 1-5. In general, one heat (Heat A) displayed crack growth behavior in the conventionally-treated condition that was sufficiently different from that of the other heats to warrant a separate description. Only at 538°C (Figure 4a), does Heat A appear to exhibit FCP rates which are generally similar to those of the other heats. For this reason, regression analyses for conventionally-treated Heat A were computed separately from those for the other heats where results were usually combined into a single regression line. Unlike the conventionally-treated material, there is no consistent trend in the results for material given the modified heat-treatment. Hence, a single regression line was employed for all heats of modified heat-treated material.

Considerable scatter, of presently unknown origin, is also evident in the results of the other heats (Heats B-G) in both heat-treated conditions over the entire temperature range tested. However, unlike the case for Heat A in the conventionally-treated condition, there are no obvious consistent

trends; a given heat may exhibit relatively high crack growth rates at one temperature and relatively low rates at another. Also, the total scatter varies from one test temperature to another. For example, for the cases where the data from Heats B-G are fitted with a single regression line, the total scatter factors (on da/dN) at 24, 316, 427, 538, and 649°C are approximately 3.9, 2.9, 1.9, 2.4, and 4.0, respectively, for conventionally-treated material, and 5.5, 3.8, 4.0, 3.7, and 4.1, respectively, for material given the modified treatment. This shows that there is somewhat greater variability in the results for the modified heat-treatment. This may also be seen in Table 5 in the generally lower correlation coefficients and generally higher standard errors of estimate associated with the modified heat-treatment. Hence, variabilities greater than the factors of 2.0 and 2.75 mentioned previously for room and elevated temperatures are generally seen in the present results. It is assumed that heat-to-heat variations contribute to the source of this variability, but unlike the case for conventionally-treated Heat A, obvious consistent trends from one temperature to another are not observed.

Comparing the chemical composition of Heat A with those for Heats B-G in Table 2 reveals no obvious difference in composition that could help to explain why it consistently exhibits higher FCP rates in the conventional condition. A difference in composition could influence precipitation kinetics resulting in the precipitation of different second phases, or changes in the size, shape or distribution of these precipitates. In addition, although the tensile properties of individual heats are not listed in Table 4, the properties of conventionally-treated Heat A were not significantly different from the others. For example, at room temperature, two specimens of conventionally-treated Heat A averaged yield, ultimate, and elongation values of 1137 MPa, 1435 MPa, and 17.5%, respectively. Hence, it is difficult to explain the observed differences in FCP behavior either on the basis of compositional variation or on tensile properties.

In an earlier paper,⁽⁴⁾ the authors suggested that higher crack growth rates in some heats of conventionally-treated material could be related to the melt practice. Reference 4 compared the FCP behavior of the present Heat A with that of the present Heat E. This comparison suggested that the higher growth rates in conventionally-treated Heat A might be associated with the VIM-VAR melting practice. Supporting this suggestion were the results of Logsdon et al.⁽¹¹⁾ for a conventionally-treated heat of Alloy 718 which had been produced using the VIM-VAR process. Under room temperature conditions, the data of Reference 11 were approximately equal to those of conventionally-treated Heat A (also a VIM-VAR material) as shown in Figure 1a.

Smith and Michel⁽³⁾ have also noted heat-to-heat variations in the FCP behavior of two heats of Alloy 718 tested at 427 and 593°C, with one of their heats consistently exhibiting inferior crack growth properties in both conventionally-treated and modified-treated materials. The inferior heat studied by Smith and Michel was also a VIM-VAR heat. Complicating an easy resolution of the question of possible melt practice effects is the fact that Smith and Michel's superior heat was also a VIM-VAR material, as were Heats B and F in the present study. Hence, the role (if any) of melt practice is not clear. The three "inferior" heats noted to date (the present Heat A, Logsdon's material,⁽¹¹⁾ and one of Smith and Michel's heats⁽³⁾) have all been VIM-VAR heats, and inferior behavior has not been noted to date with other melt practices. On the other hand, not all VIM-VAR heats exhibit higher growth rates, witness Heats B and F of the present study plus Smith and Michel's other heat.

Several product forms are involved in the present study (see Table 1). This is the subject of another investigation in the author's laboratory.⁽¹³⁾ Without going into detail, four product forms (sheet, plate, bar, and forgings) from the same heat of Alloy 718 yielded results that were essentially the same. Hence, it does not appear likely that the differences in product form were a major contributing factor in the variability noted.

Most of the other conventionally-treated specimens (e.g., Heats B, C, E-G) exhibit approximately similar behavior. An exception to this trend is the Heat C material tested at 538°C (Figure 4a). No apparent explanation is available for the significantly reduced rates that were observed, and additional specimens were unavailable to conduct a duplicate test. Note that conventionally-treated Heat C material behaved similarly to the other heats at the other test temperatures.

B. ANNEALED MATERIAL

A limited amount of testing employing Heat B in the mill-annealed (1066°C) condition was done at 24, 316, and 538°C, and these results are shown in Figures 6-8, respectively. It will be noted that a sharp transition to a much steeper slope exists at the lower ΔK levels at 24 and 316°C. At the higher values of ΔK , crack growth rates in the annealed material at all three test temperatures are generally higher than those for conventionally-treated or modified-treated heats tested under similar conditions. The slope transitions at 24 and 316°C do not represent thresholds in the strictest sense. These specimens (as well as all specimens tested in this study) were precracked at the regular test loads, and eventually a crack initiated at the notch and grew. Hence, additional crack growth was probably possible below the minimum K-levels tested here. The slope transitions do, however, represent a significant behavioral difference as compared to the behavior of precipitation heat-treated material.

C. CRACK GROWTH EQUATIONS

The companion paper⁽⁵⁾ will examine some of the postulated reasons for the observed heat treatment and heat-to-heat variations. However, the need also exists to describe the FCP behavior in a manner convenient for design and analysis. The most commonly used form for crack growth description is a "power law"

$$\frac{da}{dN} = C (\Delta K)^n \quad (1)$$

FIGURE 6. Fatigue-Crack Growth Behavior of Annealed Alloy 718 Tested in Air at 24°C . (Neg. 7902646-16)

FIGURE 7. Fatigue-Crack Growth Behavior of Annealed Alloy 718 Tested in Air at 316°C. (Neg. 7902646-15)

FIGURE 8. Fatigue-Crack Growth Behavior of Annealed Alloy 718 Tested in Air at 538°C. (Neg. 7902646-14)

where C and n are functions of the individual material and the test conditions (e.g., temperature, frequency, stress ratio, environment, etc.).

Equation (1) can also be expressed in logarithmic form

$$\log (da/dN) = A + n \log (\Delta K) \quad (2)$$

where $A = \log (C)$.

Linear least-square regression analyses were performed for various groupings of the data shown in Figures 1-8. The results of these analyses are given in Table 5. Also shown are the standard errors of estimate on $\log (da/dN)$, and the correlation coefficient (r).

The values of A and n in Equation (2) given in Table 5 are useful for conducting crack growth analyses on structural components. It is suggested that for conventionally-treated material, where one is uncertain about the individual characteristics of the heat of Alloy 718 to be employed, the use of the equation constants for Heat A are more conservative and would be more appropriate.