197
10/22/80 T.S.

Ai. 1864

HEDL-TME 80-49
UC-79 b,h

MASTER

THE EFFECT OF PRODUCT FORM UPON FATIGUE-CRACK GROWTH BEHAVIOR IN ALLOY 718--ADDITIONAL RESULTS

DO NOT MICROFILM
COVER

Hanford Engineering Development Laboratory

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

DISCLAIMER

NOTICE

Printed in the United States of America
Available from
DOE Technical Information Center
P.O. Box 62
Oak Ridge, TN 37830

NTIS price codes
Printed Copy: A 03
Microfiche copy: A01

HEDL-TME--80-49

DE91 015592

THE EFFECT OF PRODUCT FORM UPON FATIGUE-CRACK GROWTH BEHAVIOR IN ALLOY 718--ADDITIONAL RESULTS

Hanford Engineering Development Laboratory

L.A. James

August, 1980

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

HEDL-TME 80-49
UC-79b,h

THE EFFECT OF PRODUCT FORM UPON FATIGUE-CRACK GROWTH BEHAVIOR IN ALLOY 718 - ADDITIONAL RESULTS

By

Lee A. James

ABSTRACT

A previous study had characterized the fatigue-crack growth behavior of four wrought product forms (sheet, plate, bar and forging) from a single heat of Alloy 718 and concluded that there were no consistent trends in the crack growth rate results that could be attributed to product form variability. The present study adds one additional product form (gas-tungsten-arc weldments) from the same heat, and compares the behavior to that exhibited by the wrought product forms. Two different precipitation heat-treatments were employed at each of five test temperatures.

CONTENTS

FIGURES

TABLES

THE EFFECT OF PRODUCT FORM UPON FATIGUE-CRACK GROWTH BEHAVIOR IN ALLOY 718 - ADDITIONAL RESULTS

(AF-15-10-15)

I. INTRODUCTION

Alloy 718 is a precipitation-hardenable nickel-base superalloy that is employed extensively 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. Such structures are often subjected to cyclic loadings in service, and the possibility therefore exists for subcritical extension of defects, should such defects be present in the appropriate size, shape, and location. The analysis techniques of linear-elastic fracture mechanics (LEFM) are quite useful in estimating the in-service extension of such flaws, but their usage requires knowledge of the fatigue-crack propagation (FCP) behavior of the structural alloy tested under the appropriate conditions.

Considerable work has already been done in characterizing FCP behavior in Alloy 718 at elevated temperatures. Variations in the crack growth behavior have been noted(1-5) between different heats of this alloy. The underlying cause(s) of these differences has been at least partially obscured by the fact that the various material heats represented different product forms and melt practices, as well as having subtle differences in chemical composition which could influence precipitation kinetics. In order to evaluate at least one of these potential influences, a series of experiments(6) was conducted to characterize potential product form variations in the FCP behavior. Reference 6 studied crack growth behavior in four wrought product forms (sheet, plate, bar, and a forging) from the same heat of Alloy 718 at a number of test temperatures, and concluded that there was no apparent influence of product form upon the FCP behavior. Since that time, specimens representing a fifth product form (weldments) from that same heat of

Alloy 718 have been tested. Therefore, the objective of this report is to include these results in the overall assessment of potential product form variations.

II. EXPERIMENTAL PROCEDURE

The heat employed in this study was Cabot-Stellite heat 2180-6-9457. This heat, produced in several different product forms, was procured by the Idaho National Engineering Laboratory (INEL) to serve as a reference heat for Department of Energy programs. The thermomechanical history and properties of this heat are well-documented in Reference 7. The earlier study(6) on potential product form influence upon FCP behavior examined four product forms: 1.57 mm (0.063 inch) sheet, 12.7 mm (0.5 inch) plate, 50.8 mm (2.0 inch) diameter bar, and a forging with a 5:1 upset ratio. The present study examines one additional product form: gas-tungsten-arc (GTA) weldments in 19.1 mm (0.75 inch) plate employing 1.14 mm (0.045 inch) diameter weld filler wire. Both the base metal (plate) and the weld filler metal were from heat 2180-6-9457. Ladle and check analyses for all of the product forms studied are given in Table 1. The minor compositional variations noted are generally within measurement accuracies.

Two different post-weld precipitation heat-treatments were employed in this study: the "conventional" heat-treatment (CHT) as employed in ASTM A637, AMS 5596, etc., and a "modified" heat-treatment (MHT) developed at the INEL to improve the toughness of weldments in Alloy 718.(8) The two heat-treatments are detailed in Table 2, and the resulting tensile properties for the wrought product forms are given in Reference 7.

Standard Compact Type Specimens (see ASTM E647-78T) were employed in the crack growth tests. The specimens had width (W) and thickness (B) dimensions of approximately 29.31 mm (1.154 inch) and 7.62 mm (0.3 inch), respectively. The specimens were oriented with the notch (and hence the nominal direction of crack extension) parallel to the direction of welding and centered within the deposited weld metal. The weldments were of the "vee groove" design.

Fatigue cycling was done on servo-controlled MTS testing machines operating in the load-control mode using a sinusoidal waveform. All testing was done

TABLE 1
CHEMICAL ANALYSES (PERCENT BY WEIGHT)[a]

	Ladle Analysis	Check Analysis					
		Sheet	Plate[b]	Bar	Forging	Weld Wire	Plate[c]
Ni	52.34	52.19	52.17	52.12	52.02	52.28	51.86
Cr	18.21	18.36	18.24	18.36	18.27	18.20	18.20
Fe	19.10	19.27	19.18	19.19	19.14	19.04	19.10
Nb + Ta	5.10	5.16	5.16	5.09	5.10	5.13	5.13
Ti	1.06	1.07	1.06	0.96	1.06	1.05	1.05
Al	0.62	0.59	0.55	0.63	0.55	0.61	0.59
Mo	3.05	3.05	3.05	3.03	3.01	3.05	3.03
Co	0.03	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05
Ta	0.04	<0.10	<0.10	<0.06	<0.10	<0.06	<0.10
Mn	0.30	0.28	0.29	0.31	0.29	0.32	0.32
Si	0.13	0.12	0.15	0.17	0.14	0.13	0.17
C	0.05	0.05	0.05	0.05	0.05	0.05	0.05
Cu	0.02	0.02	0.02	0.02	0.02	0.02	0.03
B	0.003	0.003	0.003	0.003	0.003	0.003	0.002
P	<0.005	<0.005	<0.005	<0.005	<0.005	<0.005	<0.005
S	0.003	<0.002	<0.002	<0.002	<0.002	<0.002	<0.002

---

[a] From Reference 7.

[b] 12.7 mm plate employed in Reference 6.

[c] 19.1 mm plate employed as base metal in present study.

TABLE 2

POST-WELD PRECIPITATION HEAT TREATMENTS FOR ALLOY 718

Conventional Heat Treatment

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.

at a cyclic frequency of 0.667 Hz (40 cpm) except at room temperature where frequency is not expected to be an important variable. The stress ratio ($R = K_{min}/K_{max}$) was 0.05 for all tests.

Tests were conducted at five temperatures: 24°C (75°F), 316°C (600°F), 427°C (800°F), 538°C (1000°F), and 649°C (1200°F). The specimens were tested in an air-circulating furnace where temperatures were controlled to within ±1°C. Crack lengths were determined periodically throughout each test using a travelling microscope. Fatigue-crack growth rates (da/dN) were calculated using the "secant method",(9) and the associated stress intensity factors (K) were calculated using the expression in ASTM E647-78T.

In general, the testing and data analysis methods of ASTM E647-78T were employed in this study. LEFM validity was assured by limiting crack-tip plasticity in the uncracked ligaments by employing a "flow stress criterion".(10) Virtually all of the data reported in this study satisfied the flow stress criterion, and the few exceptions (e.g., see Figures 1b and 3b) are identified by closed data symbols.

III. RESULTS AND DISCUSSION

The results of this study are given in Figures 1-5. The format for each figure is the same: material given the conventional heat-treatment is shown on the left, and that given the modified heat-treatment is shown on the right. In each case, least-squares regression lines are fitted through each set of data (see Table 3 for the regression constants). The regression lines for the wrought product forms (sheet, plate, bar, and forgings) from heat 2180-6-9457 are plotted as dashed lines for comparison purposes. The scatter bands for the wrought product forms are also shown as dotted lines.

Comparing the regression lines for the present study on weldments (the solid lines in Figures 1-5) with the regression lines for the previous study(6) involving wrought product forms from the same heat (the dashed lines) shows that in most cases, the weldments exhibit slightly higher crack growth rate curves. This is in contrast to the findings of Reference 6 which showed no consistent trend in terms of product form for sheet, plate, bar, or forgings over the wide range of conditions covered. It should be noted that the slight tendency for higher crack growth rates in the weldments is not large, and there is generally considerable overlap between the scatter bands of the weldment data and those for the wrought data. Increases in FCP rates in Alloy 718 weldments relative to those in wrought Alloy 718 have been noted previously.(11,12) However, the previous studies compared weldments and wrought materials from different heats, thereby raising the possibility of heat-to-heat variability as well as the differences between weldments and wrought materials.

It will be noted that in some of the curves (e.g., Figures 1a, 1b, 2a, 2b, 3b), the data for the weldment specimens exhibits a change to a steeper slope at the higher values of ΔK. This sort of trend is fairly typical of crack growth rate curves for many types of materials, and is often associated with the approach to instability conditions (either in terms of fracture toughness, plastic limit load, etc.). The curves for the wrought

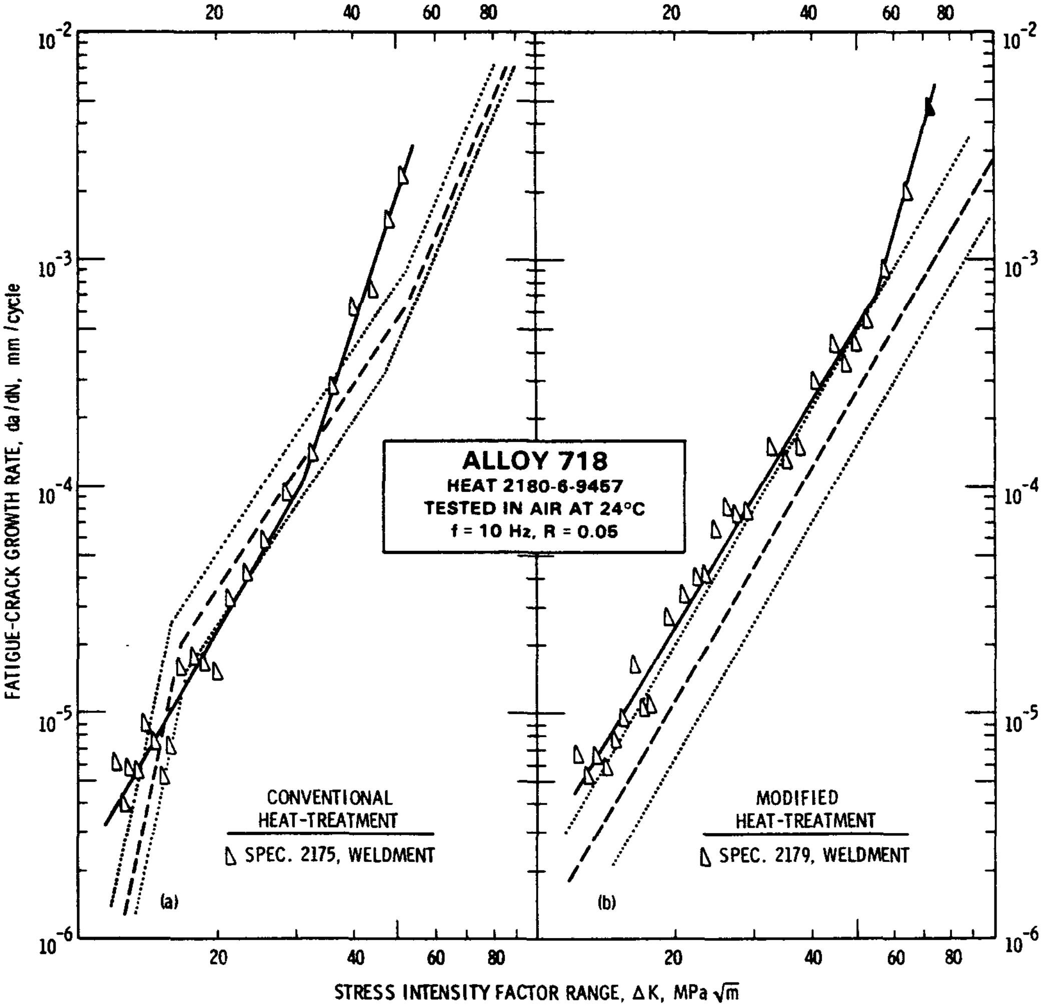

FIGURE 1. Comparison of Crack Growth Behavior in Alloy 718 Weldments and Wrought Product Forms (Sheet, Plate, Bar, and Forgings) at 24°C (75°F). Dashed lines indicate regression lines for wrought material, and dotted lines indicate scatter bands for wrought material (Ref. 6). Neg. 8008383-1.

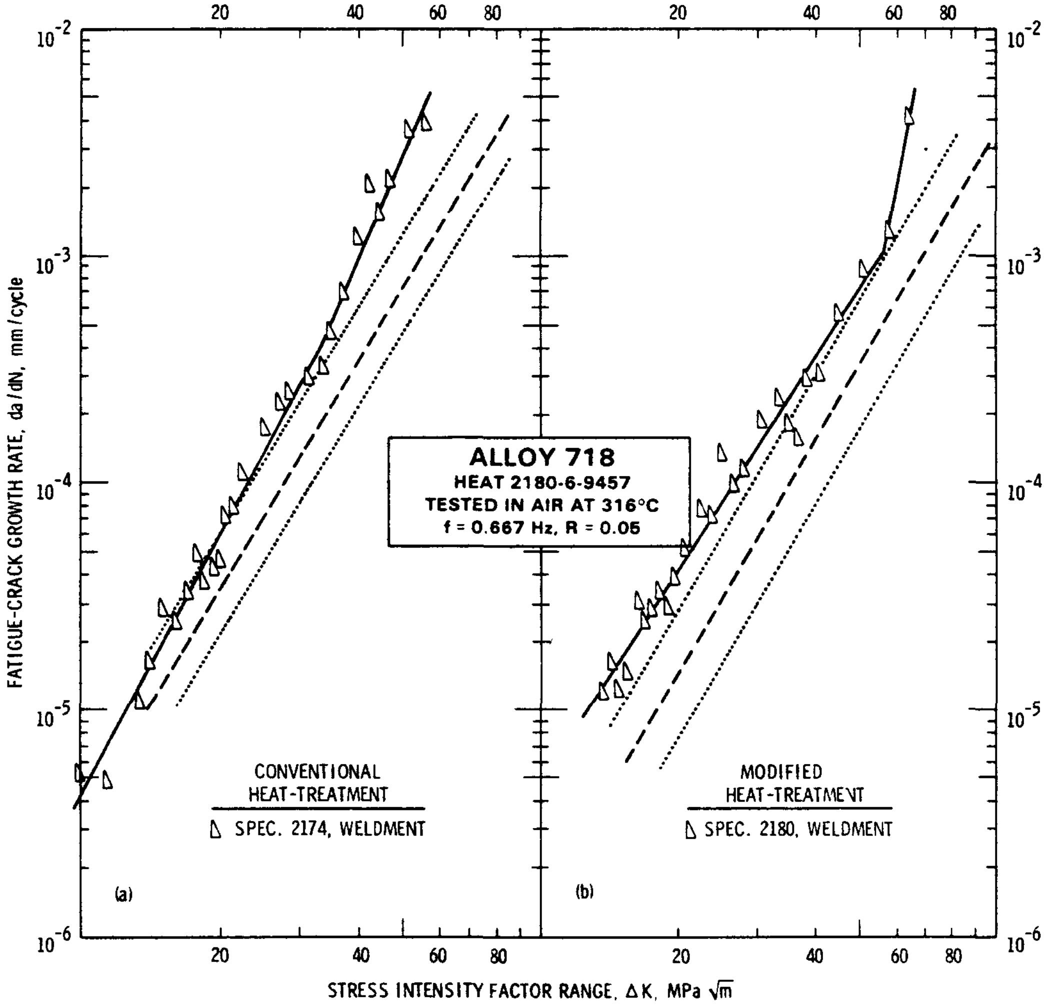

FIGURE 2. Comparison of Crack Growth Behavior in Alloy 718 Weldments and Wrought Product Forms (Sheet, Plate, Bar, and Forgings) at 316°C (600°F). Dashed lines indicate regression lines for wrought material, and dotted lines indicate scatter bands for wrought material (Ref. 6). Neg. 8007779-7.

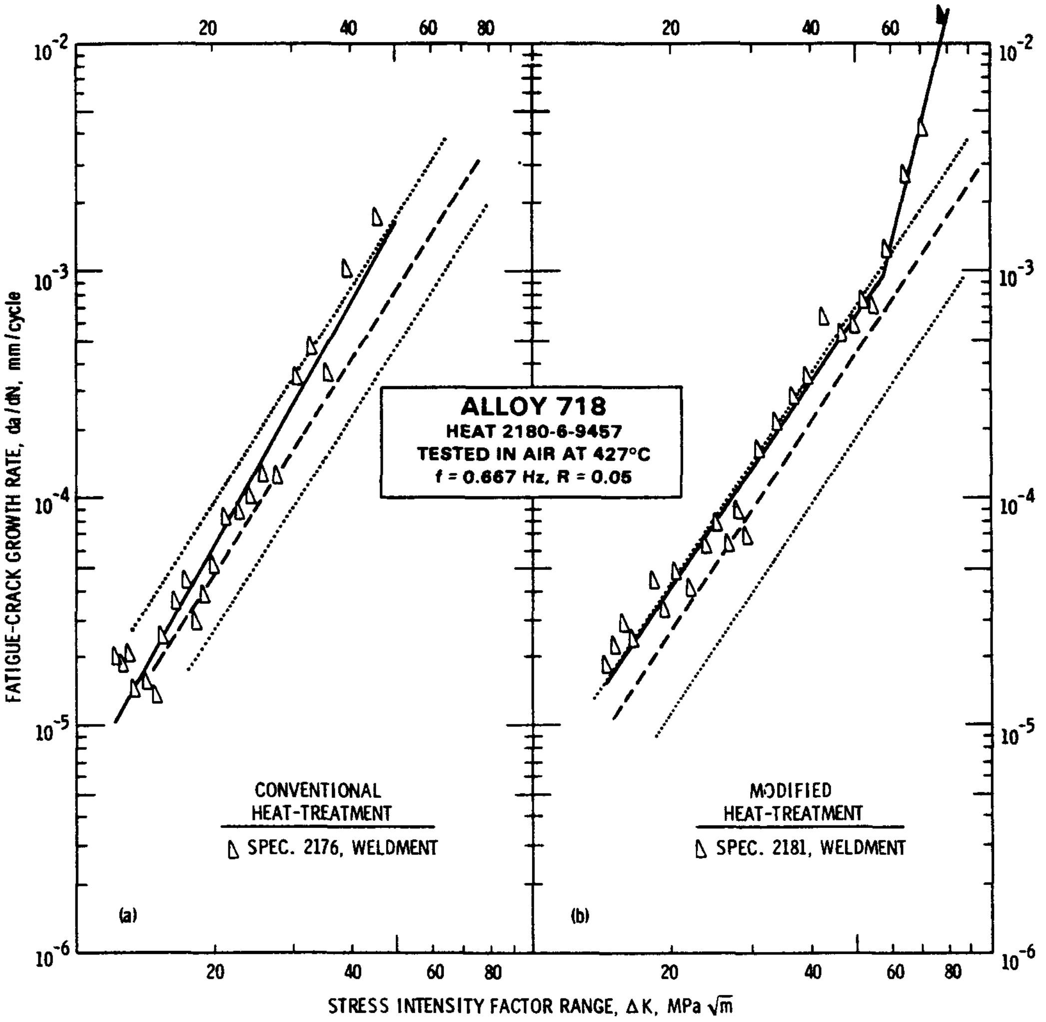

FIGURE 3. Comparison of Crack Growth Behavior in Alloy 718 Weldments and Wrought Product Forms (Sheet, Plate, Bar, and Forgings) at 427°C (800°F). Dashed lines indicate regression lines for wrought material, and dotted lines indicate scatter bands for wrought material (Ref. 6). Neg. 8007779-5.

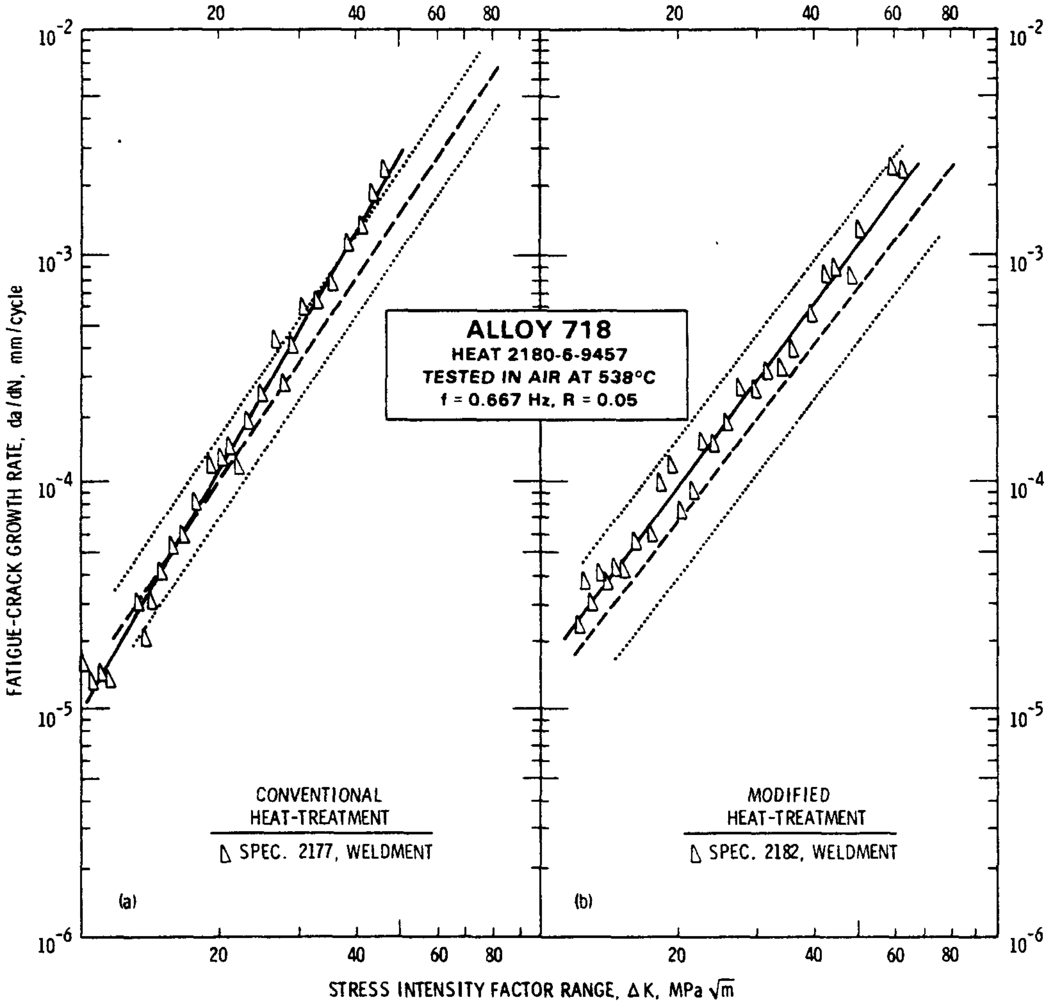

FIGURE 4. Comparison of Crack Growth Behavior in Alloy 718 Weldments and Wrought Product Forms (Sheet, Plate, Bar, and Forgings) at 538°C (1000°F). Dashed lines indicate regression lines for wrought material, and dotted lines indicate scatter bands for wrought material (Ref. 6). Neg. 800779-4.

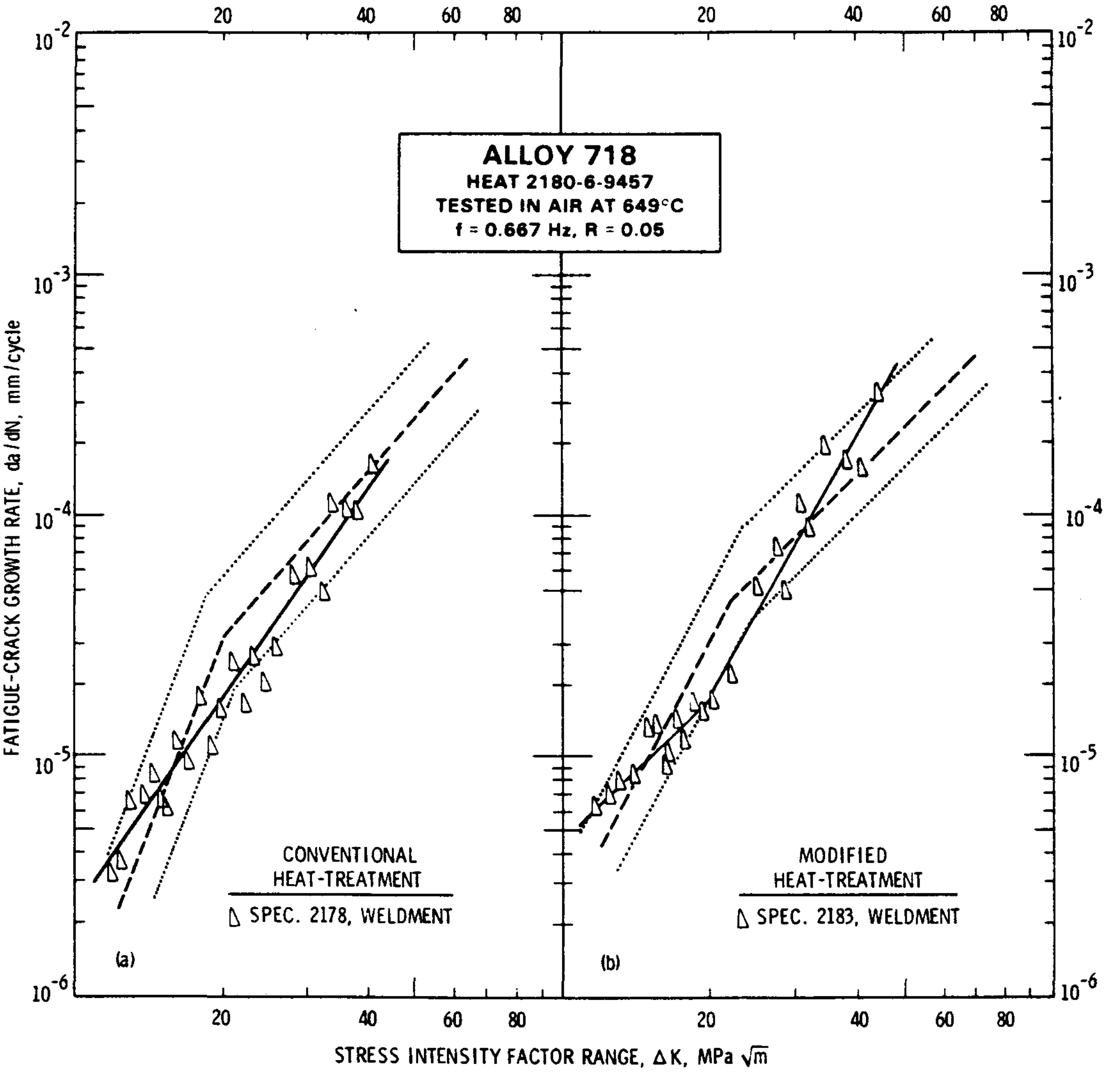

FIGURE 5. Comparison of Crack Growth Behavior in Alloy 718 Weldments and Wrought Product Forms (Plate, Bar, and Forgings) at 649°C (1200°F). Dashed lines indicate regression lines for wrought material, and dotted lines indicate scatter bands for wrought material (Ref. 6). Neg. P08722.

product forms do not exhibit this tendency for a slope transition as strongly, and this is consistent with the observation that wrought forms of Alloy 718 generally have superior fracture toughness relative to weldments in Alloy 718.(13)

Reference 12 suggested that there was somewhat greater data scatter associated with the testing of Alloy 718 weldments than with the testing of Alloy 718 plate. However, the results of the regression analyses shown in Table 3 suggest that this is not always the case. The three measures of data variability (standard error of estimate, correlation coefficient, and scatter factor) do not indicate a consistent trend in the comparison between weldments and wrought product forms. Weldments may exhibit greater data variability for some heat-treatment/test temperature conditions, while the wrought product forms may exhibit greater variability for others. Hence, no general statements may be made concerning the relative variability in data for weldments. Reference 9 suggested that, for a single well-behaved heat of steel tested in air at room temperature, the scatter factor is approximately 2.0 for intralaboratory tests and approximately 3.0 for interlaboratory tests. Reference 14 suggested somewhat higher scatter factors (approximately 2.75 for a single heat of stainless steel) associated with elevated temperature testing. Table 3 shows scatter factors both higher than, and lower than, 2.75 and it is entirely possible that this degree of scatter is normal for regressions involving multiple specimens of Alloy 718. (The average scatter factor for the 29 regressions listed in Table 3 is 2.560.)

TABLE 3

CRACK GROWTH EQUATION CONSTANTS[a]

$$\frac{da}{dN} = C(\Delta K)^n \text{ or } \log (da/dN) = \log C + n \log (\Delta K)$$

Test Temp. (°C)	Product Form[b]	Material Condition	log C	n	No. of Data Pairs	Standard Error[c]	Correlation Coefficient	Scatter Factor[d]	Data Range
24	S, P, B, F	CHT	-48.9769	10.2623	21	0.1361	0.9359	2.932	$11,630 < \Delta K < 15,070$
24	S, P, B, F	CHT	-18.5732	2.9855	110	0.0702	0 9877	2 013	$15,070 < \Delta K < 45,740$
24	S, P, B, F	CHT	-26.8522	4.7620	16	0.0662	0.9788	1.455	$45,740 < \Delta K \;\; 74,140$
24	W	CHT	-21.0384	3.5167	17	0.1164	0.9715	2.579	$10,950 < \Delta K < 27,620$
24	W	CHT	-31.8622	5.9538	6	0.0664	0.9917	1.518	$27,620 < \Delta K < 46,860$
24	S, P, B, F	MHT	-21.0866	3.4584	166	0.0940	0.9910	3.207	$11,230 < \Delta K < 81,930$
24	W	MHT	-20.3153	3.3503	27	0.1100	0.9864	2.442	$11,060 < \Delta K < 50,316$
24	W	MHT	-38.9695	7.3179	3	0.0022	0.9999	1.006	$50,316 < \Delta K < 65,370$
316	S, P, B, F	CHT	-20.2156	3.3657	129	0.1028	0.9855	2.618	$13,630 < \Delta K < 66,680$
316	W	CHT	-21.7515	3.7840	19	0.0921	0.9868	1.806	$8,940 < \Delta K < 29,170$
316	W	CHT	-25.9403	4.7222	9	0.1192	0.9562	2.229	$29,170 < \Delta K < 51,060$
316	S, P, B, F	MHT	-20.7866	3.4156	129	0.1014	0.9882	3.105	$14,010 < \Delta K < 77,120$
316	W	MHT	-19.0553	3.1168	25	0.0989	0.9862	2.793	$12,160 < \Delta K < 51,220$
316	W	MHT	-57.0988	11.1950	2	------	1.0000	-----	$51,220 < \Delta K < 57,910$
427	S, P, B, F	CHT	-19.2573	3.1720	117	0.1414	0.9708	3.916	$13,510 < \Delta K < 62,230$
427	W	CHT	-20.7455	3.5512	22	0.1449	0.9736	3.013	$11,020 < \Delta K < 41,250$
427	S, P, B, F	MHT	-18.8873	3.0275	117	0.1492	0.9732	4.249	$13,010 < \Delta K < 88,050$
427	W	MHT	-18.4070	2.9601	24	0.1098	0.9831	2.8[illegible]3	$13,040 < \Delta K < 52,020$
427	W	MHT	-44.6350	8.5214	4	0.0956	0.9835	1.513	$52,020 < \Delta K < 69,760$
538	S, P, B, F	CHT	-18.0672	2.9753	112	0.0747	0.9899	2.172	$11,820 < \Delta K < 66,000$
538	W	CHT	-20.4684	3.5496	27	0.0796	0.9938	2.136	$9,190 < \Delta K < 41,280$
538	S, P, B, F	MHT	-16.6831	2.6077	102	0.1216	0.9716	4.122	$12,030 < \Delta K < 62,850$
538	W	MHT	-16.9102	2.6938	29	0.0738	0.9929	1.563	$11,050 < \Delta K < 56,840$
649	P, B, F	CHT	-27.1705	5.2290	26	0.1678	0.8339	4.136	$12,580 < \Delta K < 18,090$
649	P, B, F	CHT	-14.6442	2.2868	64	0.1312	0.8990	3.390	$18,090 \;\; \Delta K < 50,200$
649	W	CHT	-17.6862	2.9350	24	0.1060	0.9776	2.086	$10,790 < \Delta K < 37,020$
649	P, B, F	MHT	-21.9306	3.9863	43	0.1072	0.9413	2.761	$11,690 < \Delta K < 20,800$
649	P, B, F	MHT	-13.4852	2.0305	39	0.1085	0.9098	2.693	$20,800 < \Delta K < 54,600$
649	W	MHT	-13.5498	1.9709	14	0.0671	0 9273	1.677	$10,560 < \Delta K < 17,040$
649	W	MHT	-20.0214	3.5003	11	0.1199	0.9570	2.225	$17,040 < \Delta K < 39,400$

---

[a] Units: da/dN = inch/cycle, $\Delta K = \text{psi}\sqrt{\text{in}}$
Conversion to SI Units: (inch/cycle)(25.4) = mm/cycle
$(\text{psi}\sqrt{\text{in}})(1.099 \times 10^{-3}) = \text{MPa}\sqrt{\text{m}}$

[c] Standard error of estimate on log (da/dN)

[d] Total scatter factor on da/dN

[b] S = Sheet
P = Plate
B = Bar
F = Forging
W = Weldment

IV. SUMMARY AND CONCLUSIONS

The present study has shown that there is in most, but not all of the conditions examined, a slight increase in FCP rates in weldments relative to wrought product forms. This is evidenced by the slightly higher regression lines for the weldments. This increase is, however, not large and in several cases there is considerable overlap in the scatter bands for weldments and wrought product forms. Somewhat greater increases in FCP rates of weldments, relative to those in plate, were noted previously,(11,12) but the comparisons were made between weldments from one heat, and plates from another. This introduces the possibility of at least some of the differences might be due to heat-to-heat variations in FCP behavior which have been identified in wrought Alloy 718.(1-5) By employing the same heat of material for all product forms, the present study was able to eliminate any consideration of heat-to-heat variability.

It has been suggested earlier,(12) that there was increased data scatter associated with the testing of weldments, but the present study does not confirm this observation. The present results suggest no consistent trend in comparing data variability between weldments and wrought products tested over a wide range of heat-treatment/test temperature conditions.

V. REFERENCES

1. James, L. A. and Mills, W. J., Effect of Heat-Treatment and Heat-To-Heat Variations in the Fatigue-Crack Growth Response of Alloy 718 - Part 1: Macroscopic Observations, Report HEDL-TME 80-9, Hanford Engineering Development Laboratory, Richland, WA, 1980.

2. Mills, W. J. and James, L. A., Effect of Heat-Treatment and Heat-To-Heat Variations in the Fatigue Crack Growth Response of Alloy 718 - Part 2: Microscopic Observations, Report HEDL-TME 80-10, Hanford Engineering Development Laboratory, Richland, WA, 1980.

3. Mills, W. J. and James, L. A., "Effect of Heat Treatment on Elevated Temperature Fatigue Crack Growth Behavior of Two Heats of Alloy 718," ASME Paper 78-WA/PVP-3, New York, December 1978.

4. Smith, H. H. and Michel, D. J., "Fatigue Crack Propagation and Deformation Mode in Alloy 718 at Elevated Temperatures," in Ductility and Toughness Considerations in Elevated Temperature Service, Series MPC-8, pp. 225-246, ASME, 1978.

5. Sadananda, K. and Shahinian, P., "Effect of Microstructure on Creep-Fatigue Crack Growth in Alloy 718," Res Mechanica, Vol. 1, pp. 109-128, 1980.

6. James, L. A., The Effect of Product Form Upon Fatigue-Crack Growth Behavior in Alloy 718, Report HEDL-TME 80-11, Hanford Engineering Development Laboratory, Richland, WA, 1980.

7. Smolik, G. R. and Korth, G. E., Reference Heat of Alloy 718 for Department of Energy Programs, Report TREE-1253, EG&G Idaho Inc., Idaho Falls, ID, 1978.

8. Smolik, G. R. and Reuter, W. G., Heat Treatment Investigations for Welded Inconel 718 Pressure Vessels for the Power Burst Facility, Report ANCR-1227, Aerojet Nuclear Company, Idaho Falls, ID, 1975.

9. Clark, W. G. and Hudak, S. J., "Variability in Fatigue Crack Growth Rate Testing," Journal of Testing and Evaluation, Vol. 3, No. 6, pp. 454-476, 1975.

10. James, L. A., Specimen Size Considerations in Fatigue-Crack Growth Rate Testing, Report HEDL-TME 78-99, Hanford Engineering Development Laboratory, Richland, WA, 1978.

11. James, L. A., Fatigue-Crack Propagation Behavior of Inconel 718, Report HEDL-TME 75-80, Hanford Engineering Development Laboratory, Richland, WA, 1975.

12. James, L. A., "Fatigue-Crack Growth in Inconel 718 Weldments at Elevated Temperatures," *Welding Journal Research Supplement*, Vol. 57, No. 1, pp. 17s-23s, 1978.

13. Mills, W. J., *Effect of Heat Treatment on the Elevated Temperature Tensile and Fracture Toughness Behavior of Alloy 718 Weldments*, Report HEDL-TME 80-18, Hanford Engineering Development Laboratory, Richland, WA, 1980.

14. James, L. A., "Effect of Heat-to-Heat and Melt Practice Variations Upon Fatigue Crack Growth in Two Austenitic Steels," in *Properties of Austenitic Stainless Steels and Their Weld Metals*, ASTM STP 679, pp. 3-16, 1979.

DISTRIBUTION

UC-79 (130)

UC-79b (37)

UC-79h (28)

DOE/RRT-HQ (2)
Mail Stop B-107
Washington, DC 20545

Program Division Director

DOE/FFTFPO (5)

Director

HEDL (32)

LD Blackburn	W/A-40
KW Carlson	W/A-40
BA Chin	W/A-58
DJ Criswell	W/A-40
AL Dittmer	W/A-40
AM Ermi	W/A-58
DL Greenslade	W/A-40
GW Hollenberg	W/A-59
JJ Holmes	W/A-58
WL Hu	W/A-58
LA James (2)	W/A-40
RL Knecht	W/A-40
DA Mervyn	W/A-58
WJ Mills	W/A-40
WE Roake	W/C-16
CT Schaedel	W/A-46
LK Severud	W/C-98
WF Sheely	W/A-62
JL Straalsund	W/A-57
AL Ward	W/A-40
JA Williams	W/A-40
GL Wire	W/A-58
HH Yoshikawa	W/C-44
Central Files (5)	W/C-110
Publ. Services (2)	W/C-115
S. Berglin, Contract Administration	W/A-21