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THE EFFECT OF TEMPERATURE UPON THE FATIGUE-CRACK PROPAGATION BEHAVIOR OF INCONEL X-750

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ABSTRACT

The techniques of linear-elastic fracture mechanics were employed to characterize the effect of temperature upon the fatigue-crack propagation behavior of precipitation heat-treated Inconel X-750 in an air environment over the range 75°-1200°F (24°-649°C). In general, fatigue-crack growth rates increased with increasing test temperature.

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THE EFFECT OF TEMPERATURE UPON THE FATIGUE-CRACK PROPAGATION BEHAVIOR OF INCONEL X-750

INTRODUCTION

Inconel X-750* is a precipitation-hardenable nickel-base alloy which has been considered for reactor applications. Since most reactor components are subjected to in-service loading fluctuations during their lifetimes, the potential exists for subcritical extension of cracks or crack-like flaws. The analytical techniques of linear-elastic fracture mechanics (LEFM) allow accurate estimation of such in-service crack extension(1), and are being increasingly used in the analysis of reactor structural components. The purpose of this study, therefore, was to characterize the effect of temperature upon the fatigue-crack propagation behavior of Inconel X-750 using LEFM methods.

EXPERIMENTAL PROCEDURE

The Inconel X-750 used in this study was purchased in the form of 1-inch (25.4 mm) plate. The heat of material (Huntington heat HT6716X) had been air-melted. The plate had been annealed for two hours at 2100°F (1149°C) and air cooled. After machining, the specimens were given a duplex precipitation heat-treatment as follows: age 24 hours at 1550°F (843°C) and air cool, then age 20 hours at 1300°F (704°C) and air cool. The chemical composition and mechanical properties of this material are given in Tables I and II, respectively, and the detailed thermal-mechanical processing history of the plate is given in Reference 2.

The tensile specimens employed in this study had a nominal diameter of 0.125 inch (3.175 mm) and a gage length of 1.125 inch (28.575 mm). The fatigue-crack growth specimens were of the ASTM "Compact Specimen" design(3), and had nominal dimensions of "W" = 2.00 inch (50.8 mm) and "B" = 0.42 inch (10.67 mm). The specimen dimensions and test parameters are given in Table III.

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*Inconel is a registered trademark of the International Nickel Company. The general specifications for this alloy in plate form may be found in AMS Specifications 5542 and 5598.

TABLE I

CHEMICAL COMPOSITION (percent by weight)

Producer/Heat No.	C	Mn	Fe	S	Si	Cu	Ni	Cr	Al	Ti	Co
Huntington/HT6716X	0.03	0.56	6.66	0.007	0.40	0.09	72.84	15.27	0.67	2.60	0.07

Melt process: air-melt

Heat treatment: Solution anneal 2100°F (1149°C) for two hours and air cool. Age 24 hours at 1550°F (843°C) and air cool. Age 20 hours at 1300°F (704°C) and air cool.

TABLE II

TENSILE PROPERTIES**

Specimen Number	Test Temp.	0.2% Yield Strength	Ultimate Strength	Uniform Elongation	Total Elongation	Red. in Area	Hardness	Site Sequence Number***
T106	75°F 24°C	93,090 psi 648.1 MPa	149,190 psi 1028 MPa	14.18%	14.33%	15.45%	R_c=32.98	H05986
T107	600°F 316°C	85.660 psi 590.6 MPa	140,000 psi 965.3 MPa	13.91%	14.32%	26.33%	*	H05983
T108	800°F 427°C	82,100 psi 566.1 MPa	148,390 psi 1023 MPa	18.79%	19.62%	25.81%	*	H05984
T109	1000°F 538°C	81.560 psi 562.3 MPa	134,840 psi 929.7 MPa	15.87%	16.89%	21.31%	*	H05982
T110	1200°F 649°C	79.670 psi 549.3 MPa	108.030 psi 744.8 MPa	5.30%	5.82%	11.48%	*	H05987
T111	1300°F 704°C	78,460 psi 541.0 MPa	91.710 psi 632.3 MPa	3.54%	4.25%	11.38%	*	H05981

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* Not reported.

** Strain rate = 1.78×10^{-3} min^{-1}

*** HEDL LMFBR Fuel Cladding Information Center

TABLE III

SPECIMEN DIMENSIONS AND TEST PARAMETERS

Specimen Number	Test Temp. (°F)	Cyclic Freq. (cpm)	Stress Ratio	Specimen Width "W" (in.)	Specimen Thickness "B" (in.)	Maximum Load (lb.)
478	75	300	0.05	2.0035	0.4205	1500
485	800	40	0.05	2.0053	0.4225	1450
480	1000	40	0.05*	2.0072	0.4205	Variable**
482	1000	40	0.05	1.9921	0.4203	1450
481	1200	40	0.05	2.0037	0.4184	1600

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* R = 0.05 during load control cycling. During stroke control cycling, R started at 0.05 and decreased during this phase to R = 0.004.

** Max. load = 1600 lb. during initial load-control cycling. During stroke control cycling the max. load initially started at 2200 lb. and decreased during this phase to 1650 lb. At this point, testing was resumed in the load control mode at a max. load of 1400 lb. The crack was extended approximately 0.095 inch at this new load before data taking was resumed.

The fatigue-crack growth specimens were tested on a feedback-controlled MTS testing machine, using load as the control parameter (except for one specimen where stroke was the control parameter). Either "sawtooth" or sinusoidal waveforms were employed, and all specimens were tested in an air environment. The elevated temperature tests were conducted in an air-circulating furnace. Crack lengths (a) were measured periodically throughout each test using a traveling microscope. Crack growth rates (da/dN) were based on dividing each increment of crack extension (Δa) by the number of loading cycles producing that extension (ΔN). The stress intensity factor (K) corresponding to each increment was based on the average crack length for that increment, using the formula of Reference 3 for $0.30 < a/W < 0.70$, and that of Reference 4 for $a/W > 0.70$. The results were plotted as log (da/dN) versus log (ΔK).

One specimen (Specimen No. 480) was tested in an air environment at 1000°F (538°C) using displacement control during a portion of the test, rather than the more usual load control. This specimen was precracked in load control at a maximum load of 1600 lb. (7117 N) and one increment of crack extension was recorded at this load. At that time, the mode of control was switched to displacement control using the LVDT built into the hydraulic actuator as the displacement transducer. The specimen was then cycled at a constant LVDT displacement of 0.0188 inch (0.478 mm). At the start of this phase of testing this corresponded to a maximum cyclic load of 2200 lb. (9786 N) and a minimum cyclic load of 110 lb. (489 N). This produced an initial stress ratio (R) of 0.05. One feature of testing this type of specimen under conditions of constant deflection is that the load decreases as the crack length increases, and the decrease in load occurs more rapidly than the increase in f(a/W) given in Reference 3. This produces a decrease in K with increasing crack length, and therefore also a decrease in crack growth rates with increasing crack length. This, of course, is just the opposite from the case where specimens are cycled at a constant maximum load.

This behavior is illustrated in Figure 1 with Specimen 480 (deflection control) exhibiting decreasing crack growth rates with increasing crack lengths, and Specimen 482 (load control) exhibiting increasing crack growth rates with increasing crack lengths. During this phase of testing, the

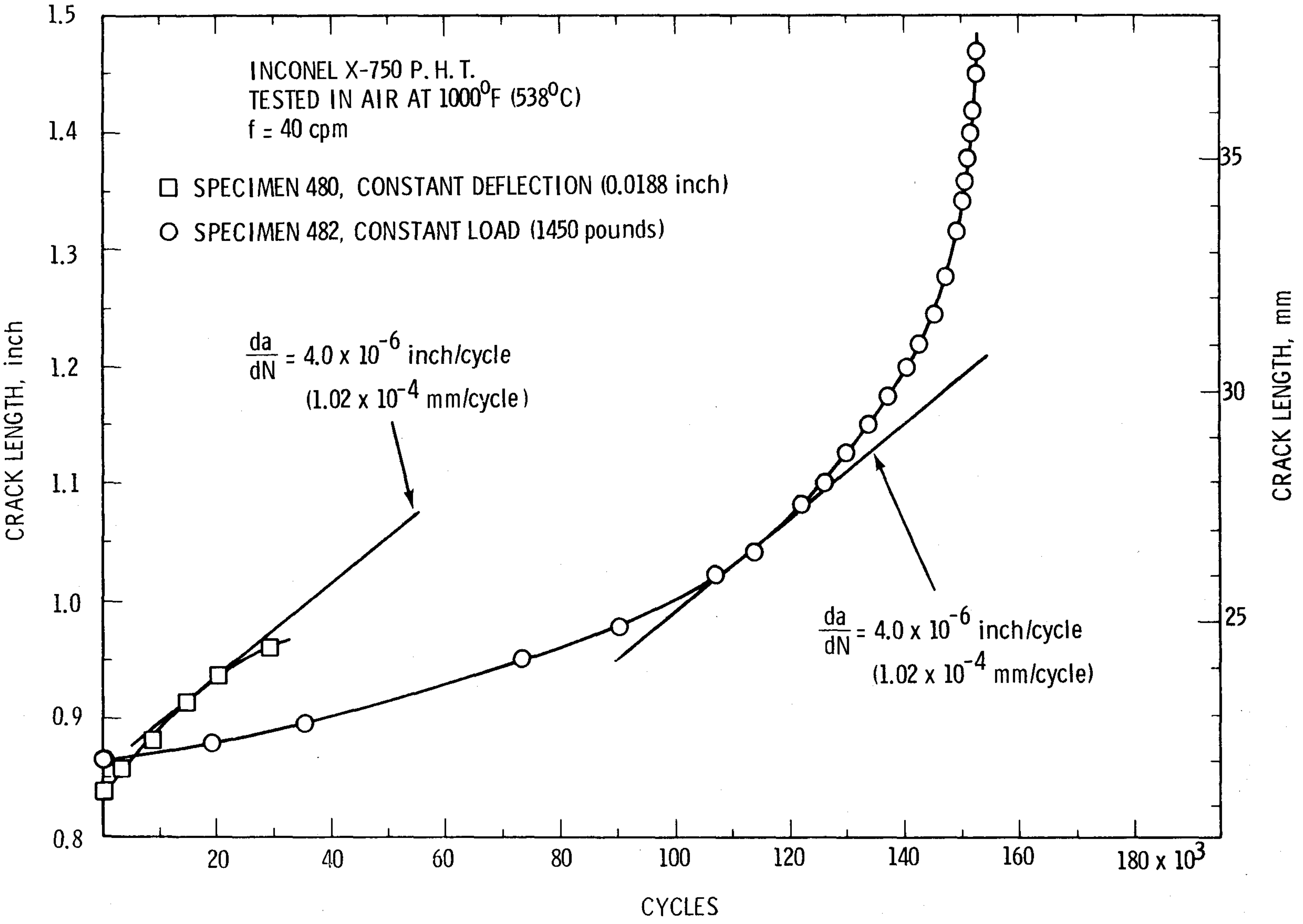

Figure 1. Comparison of fatigue-crack growth behavior of Inconel X-750 tested in air at 1000°F (538°C) under conditions of constant load amplitude, and under constant cyclic deflection. (Neg. L-399-8)

maximum load on Specimen 480 decreased from 2200 lb. (9786 N) to 1650 lb. (7340 N), while the minimum loads had decreased from 110 lb. (489 N) to 6 lb. (27 N). At this point the minimum loads started becoming compressive, and since this is not a desirable situation for this type of specimen in displacement control, the testing in displacement control was stopped. Testing was resumed in load control with a maximum load of 1400 lb. (6228 N) and the specimen was precracked approximately 0.095 inch (2.41 mm) at this new load before data taking was resumed.

RESULTS AND DISCUSSION

Fatigue-crack growth tests were conducted at temperatures of 75°F (24°C), 800°F (427°C), 1000°F (538°C), and 1200°F (649°C), and the results are shown in Figures 2-5, respectively. The results for all four temperatures are also summarized in Figure 6. The linear portions of the crack growth curves were fitted with a simple "power law" using least-squares regression techniques, and the results are summarized in Table IV. From Figure 6, the observation may be made that, in general, at a given value of ΔK fatigue-crack growth rates increase with increasing temperature. This has been previously observed in several nickel-base alloys tested in an air environment, including Inconel 600(5), Inconel 718(5,6), cast Inconel 738 LC(7), Hastelloy X(8), and Hastelloy X-280(9). Although the general trend is for increasing growth rates with increasing temperature, it will be noted that the behavior at 800°F (427°C) and 1000°F (538°C) is essentially the same. This has also been noted for Inconel 718(6) and Hastelloy X-280(9) at the same two test temperatures and frequencies.

It has been suggested(10) that much of the increase in crack growth rates noted as the temperature is increased in an air environment is due to the aggressive corrosive nature of the air itself, rather than being due to an interaction between creep and fatigue.

The trend of sharply decreasing crack growth rates at the lower values of ΔK (probably approaching a crack growth "threshold") has also been noted in the other nickel-base alloys(5-9). It should be noted, however, that the prerequisite for a true threshold was not met in the present study: the complete cessation of all crack extension. Although it is probable that

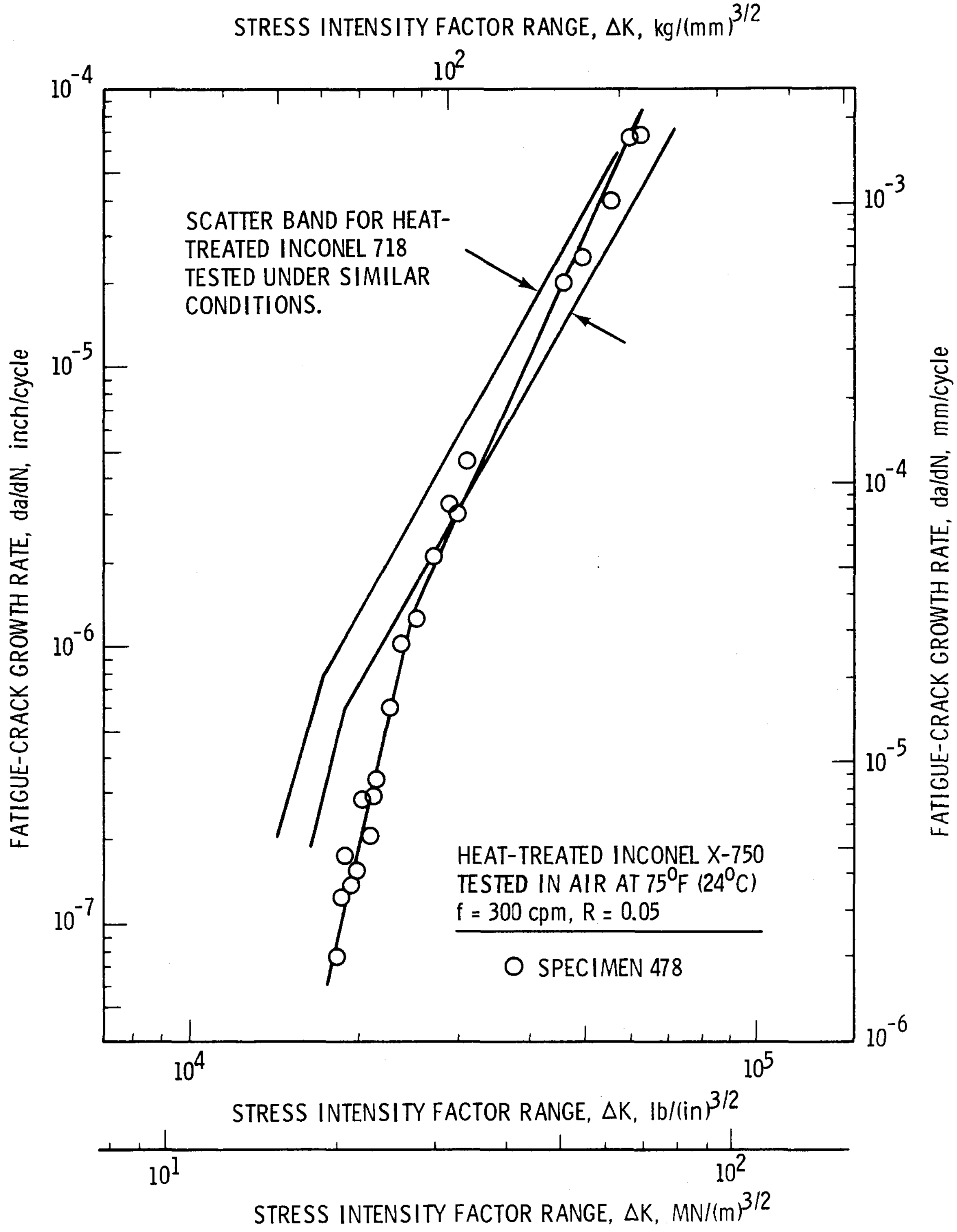

Figure 2. Fatigue-crack propagation behavior of Inconel X-750 tested in air at room temperature. (Neg. L-400-6)

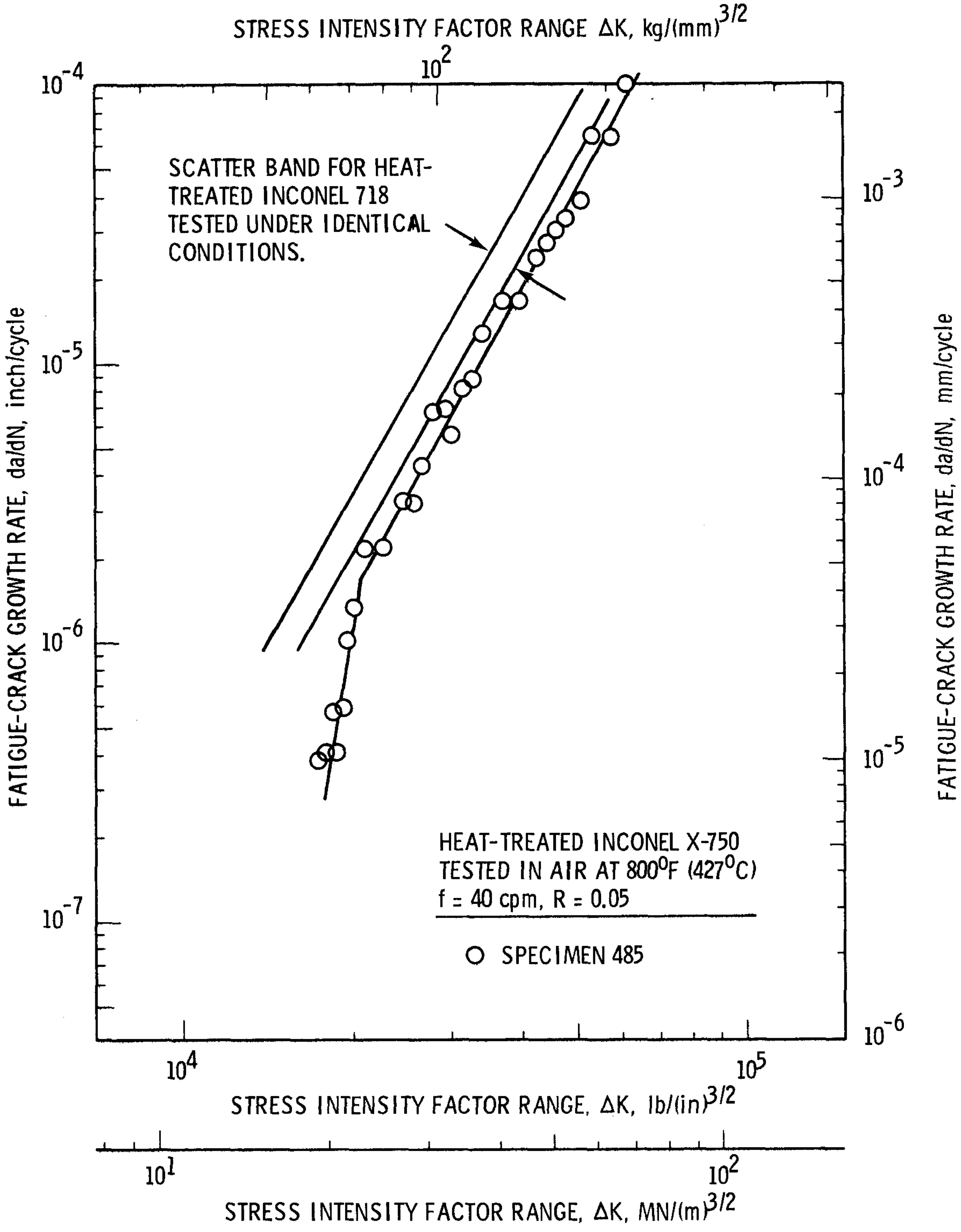

Figure 3. Fatigue-crack propagation behavior of Inconel X-750 tested in air at 800°F (427°C). (Neg. L-400-1)

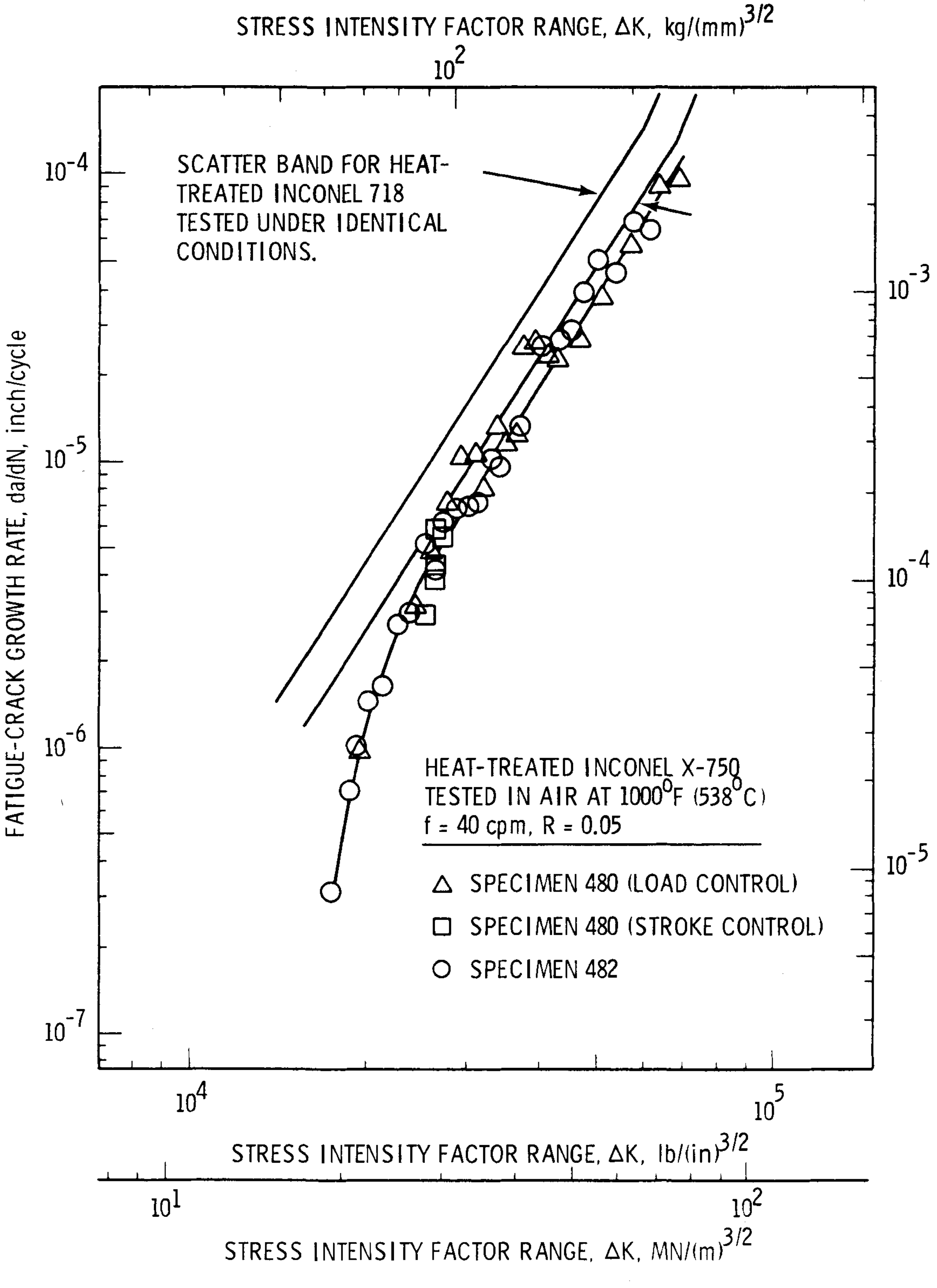

Figure 4. Fatigue-crack propagation behavior of Inconel X-750 tested in an air environment at 1000°F (538°C). (Neg. L-400-3)

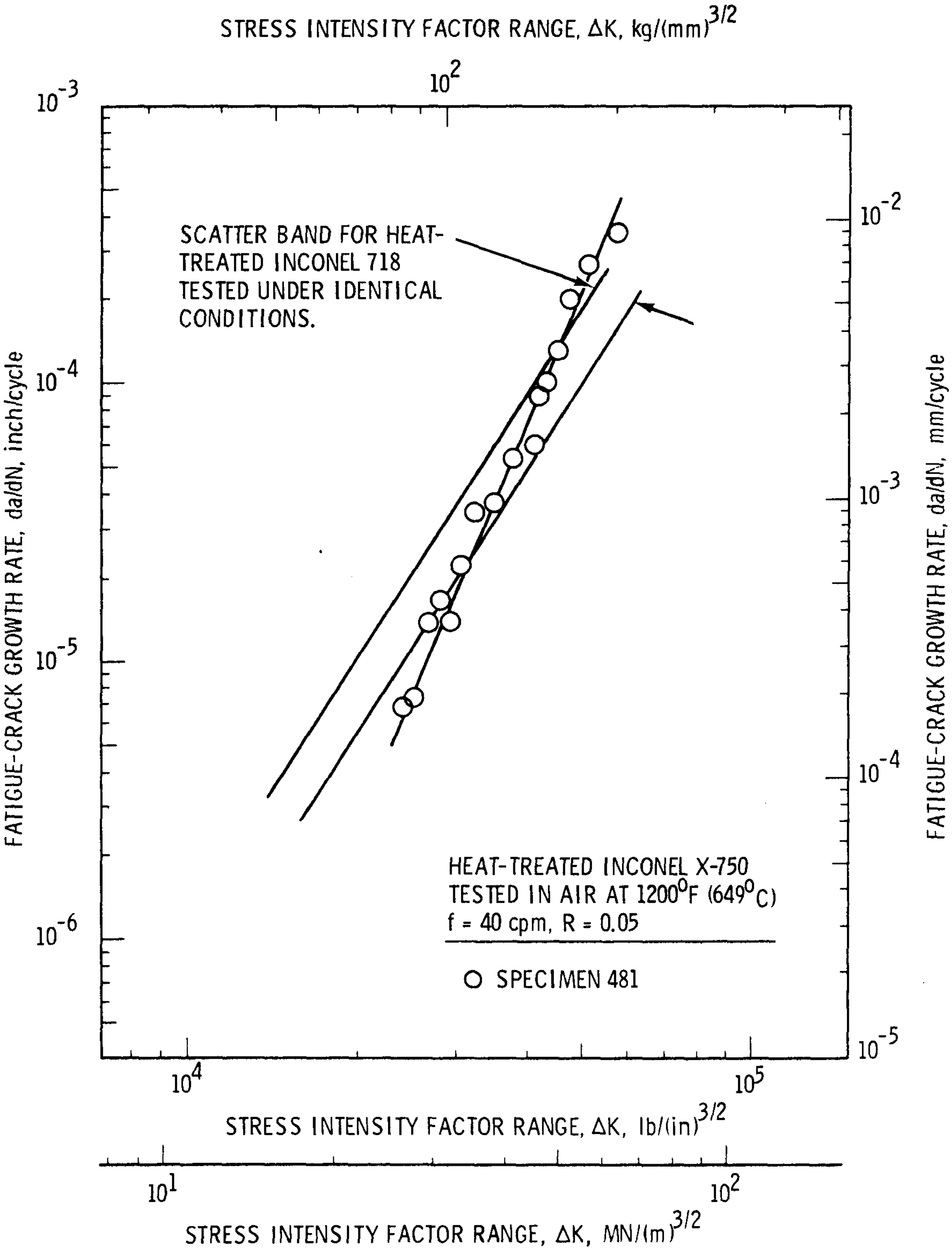

Figure 5. Fatigue-crack propagation behavior of Inconel X-750 tested in an air environment at 1200°F (649°C). (Neg. L-400-5)

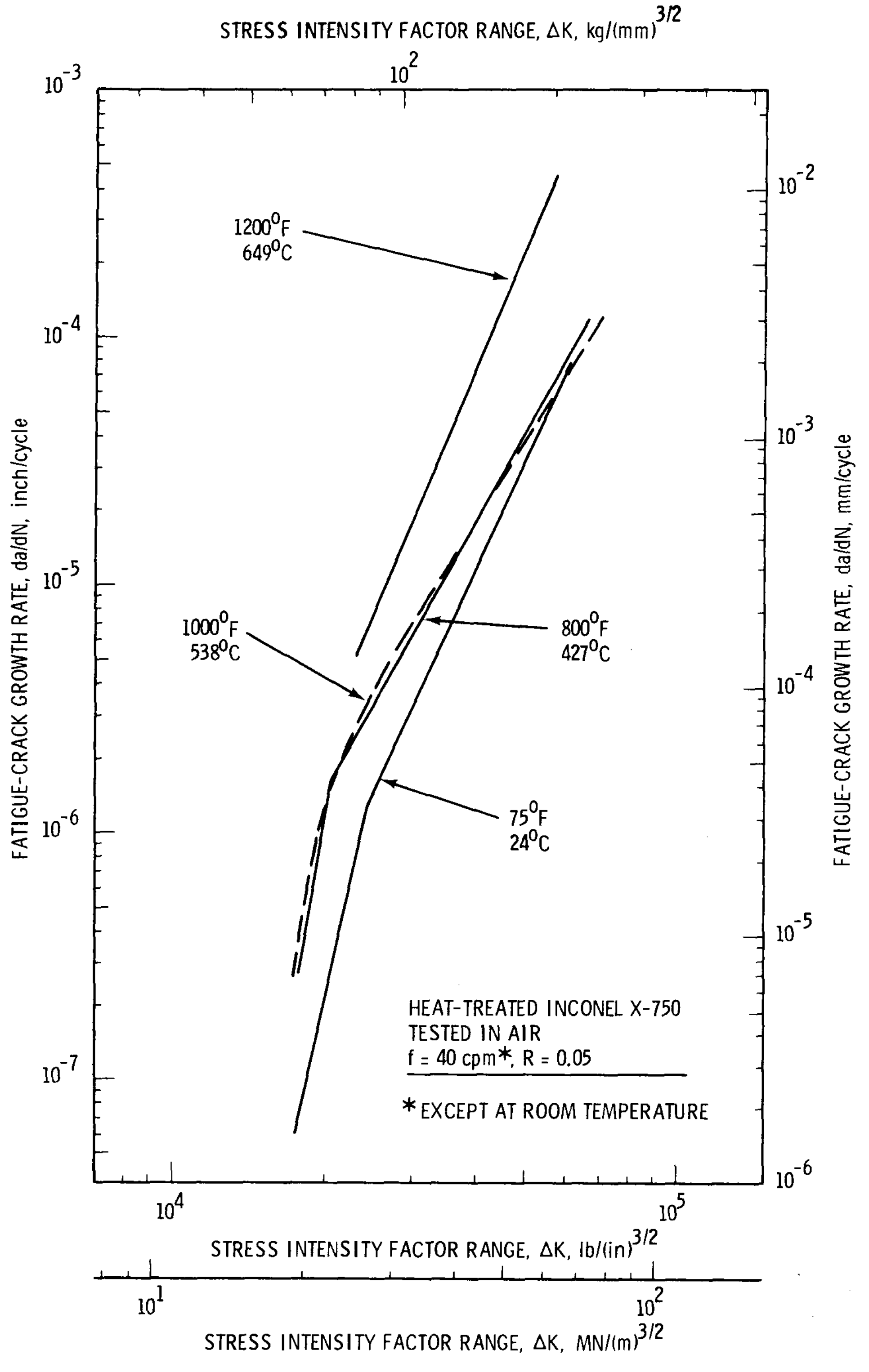

Figure 6. The effect of temperature upon the fatigue-crack propagation behavior of Inconel X-750 tested in an air environment. (Neg. L-400-4)

TABLE IV
CRACK GROWTH LAW CONSTANTS* FOR INCONEL X-750

Temperature	Range of Validity	$\frac{da}{dN} = C(\Delta K)^n$ "C"	"n"	Coefficient of Determination
75°F (24°C)	$da/dN < 1.62 \times 10^{-6}$	7.63133×10^{-44}	8.47023	0.86452
75°F (24°C)	$da/dN > 1.62 \times 10^{-6}$	2.98195×10^{-26}	4.47848	0.98999
800°F (427°C)	$da/dN < 2.04 \times 10^{-6}$	1.31674×10^{-42}	8.34650	0.75733
800°F (427°C)	$da/dN > 2.04 \times 10^{-6}$	1.37025×10^{-22}	3.72988	0.97989
1000°F (538°C)	$da/dN > 4 \times 10^{-6}$	5.45507×10^{-20}	3.16889	0.96198
1200°F (649°C)	$da/dN > 6 \times 10^{-6}$	2.32595×10^{-26}	4.68130	0.98459

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*Units for $\frac{da}{dN}$ are inch/cyle, and for ΔK are $lb/(in.)^{1.5}$

f = 40 cpm (except at room temperature)

R = 0.05

testing at K-levels slightly lower than the minimum K-levels employed in this study would have resulted in no crack extension (even after many millions of cycles), determination of thresholds was not an objective of this study and was therefore not done.

Comparing the results for the test conducted in displacement control with those conducted in load control (see Figure 4), it will be seen that the results are not dependent upon the method of testing. This type of comparison (comparing specimens where K increases with increasing a, against specimens where K decreases with increasing a) is not new, having been done at room temperature as long as fifteen years ago(11). However, since some of the loadings at elevated temperatures on reactor structures are load-controlled (e.g. pressure, deadweight, seismic) and some are deflection-controlled (e.g. thermal expansion), it is worthwhile to demonstrate that at elevated temperatures the results are still not dependent upon the method of testing.

Tests were conducted on precipitation heat-treated Inconel 718 (see Ref. 6) at temperatures, frequencies, and stress ratios similar to those employed in the present study, thereby allowing a direct comparison with the present results. The scatter bands for the Inconel 718 data are shown in Figures 2-5, and in general the two alloys exhibit similar crack propagation behavior. In some cases, there appears to be a tendency for Inconel X-750 to exhibit slightly lower growth rates, but the differences are not large.

It is also possible to compare the present results at room temperature on Inconel X-750 with those of Logdson(12). Logsdon studied the effect of various manufacturing process/heat-treatment combinations on the fracture toughness and fatigue-crack propagation behavior of Inconel X-750. The room temperature crack growth results from the two studies are compared in Figure 7, and it appears that, at least at room temperature, the melt practice can influence the fatigue-crack propagation behavior. What influence (if any) melt practice might have on the crack growth behavior at elevated temperatures is, at this time, unknown.

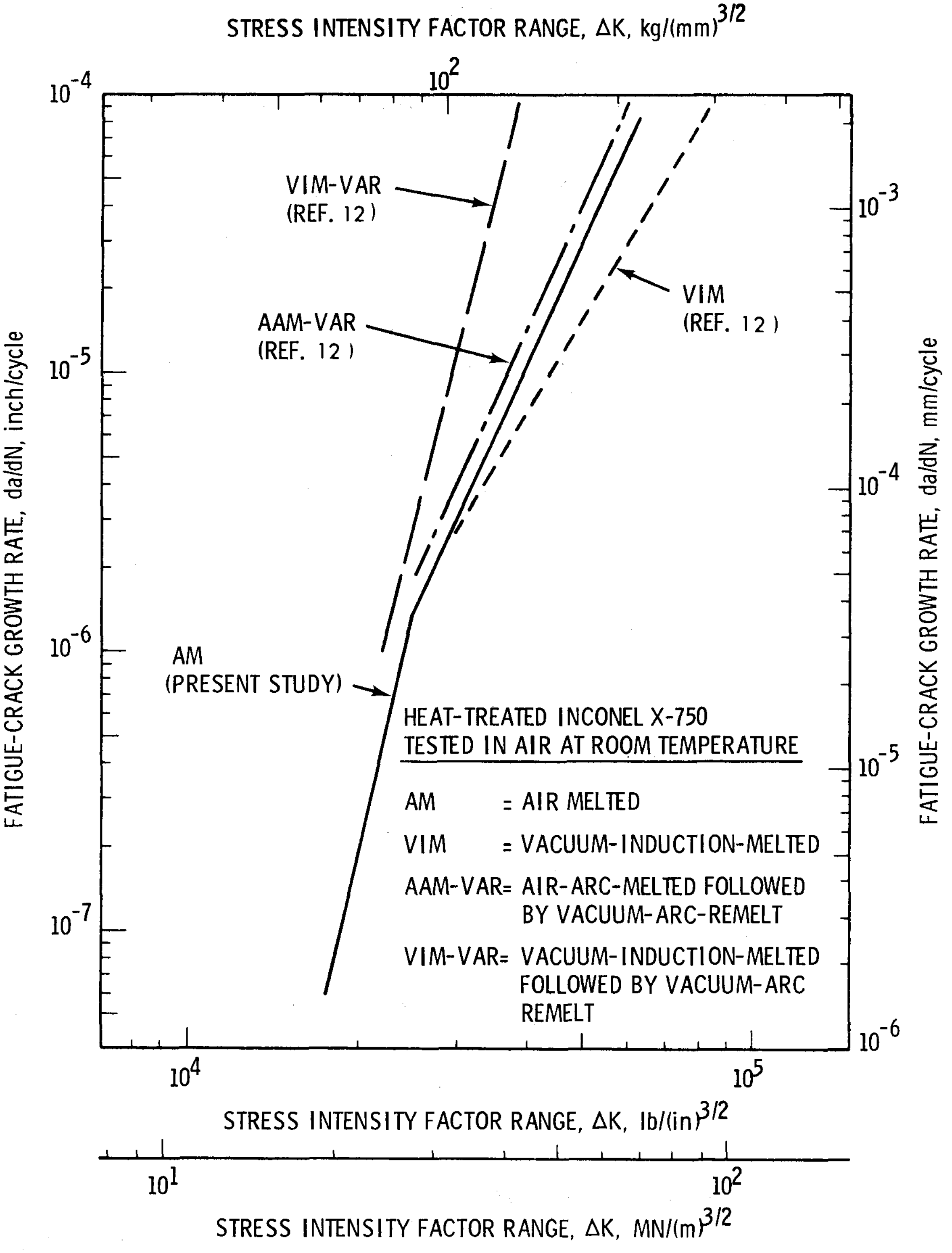

Figure 7. Comparison of the fatigue-crack propagation behavior of Inconel X-750 at room temperature for material produced using different melt practices. (Neg. L-400-2)

SUMMARY AND CONCLUSIONS

LEFM methods were employed to characterize the effect of temperature upon the crack growth behavior of Inconel X-750 tested in an air environment over the range 75°-1200°F (24°-649°C). The results may be summarized as follows:

- In general, fatigue-crack growth rates increased with increasing temperature, and this is in agreement with similar observations on other nickel-base alloys.

- Over the range of temperatures studied, the fatigue-crack growth behavior of Inconel X-750 appears to be similar to that observed in Inconel 718 tested under similar conditions.

- Limited testing at 1000°F (538°C) indicates that the fatigue-crack propagation behavior of Inconel X-750 is the same, when expressed in terms of ΔK, whether the tests are conducted in load control or deflection control.

- Comparison with the results of another study suggests that, at room temperature, melt practice appears to have an effect upon the fatigue-crack growth behavior of Inconel X-750. Whether or not there is also an influence at elevated temperatures is not known at this time.

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