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FATIGUE CRACK PROPAGATION IN A514

BASE PLATE AND WELDED JOINTS

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ABSTRACT

Fatigue studies of A514 base type plate material and associated weldments revealed that the fatigue crack growth rate was primarily a function of the applied stress intensity range. However, when the applied net section stress approached or exceeded the yield stress, the growth rates were found to increase rapidly, regardless of the stress intensity range. It was found that in this region of general yielding, the growth rate correlated well with the maximum crack opening displacement. Crack propagation studies in transverse weldments and the associated heat affected zone revealed possible residual stress effects in certain plates. These specimens responded to stress relief heat treatment and mean load variations, consistent with residual stress arguments.

INTRODUCTION

The phenomenon of fatigue crack propagation (FCP) has been widely studied in aluminum, steel and other materials.[1-4] Often such crack propagation information has been related to fracture mechanics parameters such as the stress intensity factor range through equations of the form

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

where $\frac{da}{dN}$ is the growth rate, ΔK is the stress intensity factor range and C and n are constants.

Since many structures are subject to weld related failures, the knowledge of subcritical flaw growth in weld metal and heat affected zones is often very important. Very little data are available on FCP in these regions since most previous studies of weld related fatigue failures have used the S-N approach, which is summarized by Gurney in a recent book.[5] However, two studies of crack propagation in weldments have been performed by Maddox[6] and Dowse and Richards.[7] These investigations have shown that propagation in welds and heat affected zones also obey Equation 1 and that C and n are typical of unwelded steels.

Furthermore, it is not uncommon for such structures to experience loading that approaches or exceeds the yield strength of the material. Thus, knowledge of the parameters that control fatigue crack growth under these conditions is of value. For example, it has been found[8,9,10] that FCP becomes increasingly sensitive to changes in ΔK for large values of the stress intensity factor. This has been attributed to enhanced plasticity effects. Since the above mentioned large ΔK levels were achieved

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by specimen configuration rather than by high applied gross loads, it is of interest to evaluate crack growth under conditions similar to the service environment (i.e., high net section stress situations).

The objectives of this report are two-fold. The first part will deal with the fatigue response of the base plate material. The effect of mean load variations, specimen configuration and thickness on FCP will be examined. With maximum applied loads in the range of approximately 10% to 110% of the yield stress, it will be possible to examine crack propagation under varied conditions including net section yielding. Having established the propagation characteristics of the base metal, FCP in weld metal and heat affected zone (HAZ) will be evaluated with respect to suitable variables in the second part of the investigation. In both Parts I and II an electron fractographic analysis will be employed to determine the role of the test variables on fracture surface morphology and to compare macroscopic and microscopic growth rate data.

Part I

Fatigue Crack Propagation in A514 Base Plate

Procedure

The materials used in this section met ASTM A514F and A514J specifications. Composition and mechanical properties are shown in Table I. Plates, 24" x 25" x 5/8", were cut in half to 12" x 25" x 5/8" dimensions then cut into 12" x 3" x 5/8" strips. Three different specimen geometries were used in this investigation, Table II. Single edge notch (SEN) specimens were made by cutting the 12" x 3" x 5/8" strips along the mid-thickness plane and milling the half-thickness strips to the following final thicknesses: .061", .125" and .265". The center notch (CN) specimens were prepared in a similar manner except that final thicknesses were .050" and .125" and the width varied from 1" to 3". Compact Tensile (CT) specimens were made by cutting the 12" x 3" strips into 3" x 3" squares and then ground to a final thickness of 0.5". Thinner CT specimens (0.125 inches) were prepared by cutting the 3" x 3" squares along the mid-thickness plane and grinding to final dimension. All specimen configurations appear in Fig. 1, (dimensions shown in Table II). All notches were oriented perpendicular to the rolling direction.

Tests were conducted on an MTS electrohydraulic closed loop test machine at 10 cps. Mean loads were varied by changing λ (= Kmax/$\triangle$K) to values of 1.07, 2.14 and 4.3. These correspond to R (=Kmin/Kmax) values of .065, .54 and .77, respectively. Test temperatures ranged from 70 to 80° and the relative humidity from 35 to 80% during the course of the experimental program. A traveling microscope with a vernier scale was used to

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monitor the position of the crack tip. All data were analyzed on a

CDC-6400 computer.

Low gross stress testing was performed on SEN and CT specimens while

high stress experiments were performed on CN specimens. The CN specimen

widths were varied to achieve net section yielding at different values of

the stress intensity range.

A fractographic analysis was performed on some of the low stress speci-

mens. Platinum-carbon two stage replicas were prepared for examination in

an RCA EMU-3G Electron Microscope.

Results and Discussion

Low net section stress testing of the T-1 base plate revealed that

crack propagation in this material was similar to that previously observed

in other steels, (3,4,11)   Fig. 2. The crack growth rate was found to obey

Eqn. 1, with "n" = 2.4, below a growth rate of 5×10^{-5} in/cyc, and equal to

6.5 above that value. Similar increases in the slope have been observed by

others (8,9,10)   and have been attributed to such things as fracture mode

transition or a yielding phenomenon. No fracture mode transition was

observed on surfaces of the specimens except during the final failure;

the effect of yielding will be examined below.

No effect of specimen thickness or geometry was noted. The data in

Fig. 2 were generated from both SEN and CT specimens that varied in thickness

as indicated on the figure.

The effect of the mean load level was investigated by conducting tests

at various values of λ (=Kmax/$\triangle$K). As λ was increased for a given value of

$\triangle$K, the growth rate increased moderately, Fig. 3. It is possible to incorporate

λ into Eqn. 1 and to treat the data presented in Fig. 3 as:

$$\frac{da}{dN} = C\lambda^m \Delta K^n \qquad (2)$$

In the lower portion of the curve, "m" and "n" are approximately 0.4 and 2.4, respectively, while being higher in the upper section of the curve. While a four-fold increase in λ caused a 2-fold increase in FCP, a four-fold increase in ΔK caused a thirty-fold increase in crack growth rates. The much greater importance of ΔK over that of Kmean is consistent with previous observations. (1)

To determine the extent of metallurgical anisotropy upon fatigue crack propagation, panels were prepared such that fatigue cracks were grown both parallel and perpendicular to the sheet rolling direction. No direction- ality effect was observed in A514F material; the fatigue crack propagation rates were identical with the crack traversing both parallel and perpendicular to the rolling direction.

CN specimens were used to obtain high net section stresses at moderate ΔK levels. It was found that when σ_{net} exceeded σ_{ys}, the value of "n" in- creased from 2.4 to as high as 20, Fig. 4. For the five tests conducted, the slope increase occurred at stress intensity range values of 43, 57, 63, 67, and 70 KSI $\sqrt{in}$, respectively. While yielding of the net section occurred in bands that were $\pm$ 45° to the crack plane, crack extension continued along the original crack plane.

The fact that the slope of the growth rate curve increased radically as the net section stress approached the yield strength, independent of the value of the stress intensity range, Fig. 4, indicates that ΔK was no longer the parameter controlling crack extension in this test range. Rather, Irwin (12) has suggested that the crack opening displacement (COD or δ) may be the

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controlling factor. In the elastic region δ is related to the stress

intensity factor by the equation:

$$\delta = K^2/\sigma_{ys}E \qquad\qquad (3)$$

$$(13)$$

where σ_{ys} is the yield stress and E the modulus of elasticity.   The

maximum δ was evaluated in this study and was determined from the known

maximum values of the stress intensity factor by Eqn. (3). The maximum

K values were first corrected to account for the size of the plastic zone

ahead of the crack. Using a plastic zone correction factor of:

$$r_y = \text{Plastic zone size} = (1/2\pi)(Kmax/\sigma_{ys})^2 \qquad (4)$$

values of $\delta_{maximum}$, corresponding to the points in Fig. 4, were obtained

by an iterative process. (The iteration terminated when $(a + r_y)_n$ -

$(a + r_y)_{n-1} \leq .005$ inches. When this did not occur within 20 such iterations,

the data point was not used.) When the growth rate is plotted against the

newly determined values of $\delta_{maximum}$, Fig. 5, the curves from all the yielded

specimens fall within one band of data. It is important to note that a

log-linear relationship between the loading parameter, $\delta_{maximum}$, and the

growth rate has been obtained, which is not sensitive to the onset of net

section yielding. The same analysis was performed on data from a compact

tensile specimen in which the applied stress was well below the yield strength;

these data also fell in the same band. It is apparent that a simple relation-

ship between $\delta_{maximum}$ and the growth rate is obtained irrespective of the

net section stress applied.

Fractographic data from the base metal indicate that the microscopically

determined growth rates do not vary as a simple power of ΔK (i.e., according

to Eq. 1), Fig. 6, as previously observed in other steels.[11] Though the

striations are few in number and ill defined, Fig. 7, they are morphologically

similar to striations found in other steels of this strength level.[14] Each

point in Fig. 7 was the result of averaging at least 10 and sometimes 50

measurements. No effect of mean load on striation spacing was noted; this

may be due to the fact that the striations are ill defined and provided a

poor sampling for analysis. However, since the macroscopic data showed that

mean load variations had only a small effect on FCP, little or no change in

striation spacings was expected. It has been suggested by Broek[15] that

tipping a replica relative to the electron beam may cause striations to

appear in areas where they were previously not observed. One replica, used

in obtaining the presented data, was tipped with the aid of a stereoholder

to determine if striations would appear or disappear, as well as if striation

spacing would be affected. While additional striations were observed (others

disappeared), striation spacing was relatively unaffected.

Part II

Fatigue Crack Propagation in Welded Joints

Procedure

Two 24" x 25" x 5/8" plates of T-1 base metal were cut into 24" x 6" strips. The strips provided with a 60° V-notch were butt welded by a metal inert gas process to a final size of 24" x 12" x 5/8". Of the four final plates, two were welded with AIRCO AX90 and designated Plates 20 and 40, while two were welded with AIRCO AX110 and designated Plates 70 and 80. The composition and static properties of the filler metals appear in Table I. Fatigue specimens were prepared in a manner similar to that described in Part I. Additional compact tensile specimens were made by cutting the 24" x 12" x 5/8" plate into a 24" x 3" x 5/8" strip. The strip was then cut into 3" squares and finished in the above mentioned manner. In all plates, the weld was centered in the specimen and perpendicular to the loading direction. Furthermore, all specimens were loaded parallel to the rolling direction. Testing and analysis procedures were the same as in Part I.

Results and Discussion

The data shown in Fig. 8 reveal that FCP in weld metal is, again, controlled by the stress intensity factor range. In these tests no difference was noted between crack growth "upstream" versus "downstream" relative to the welding direction. This lack of difference may be related to the self-heat treating nature of multipass welding leading to a more homogeneous material. It is readily apparent that the data fall in two distinct bands, indicating a basic difference in FCP response. While Plates 40 and 80 exhibited fatigue behavior similar to that observed for the base plate material (Fig. 2), crack

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growth rates were decidedly lower in specimens taken from plates 20 and 70.

In addition, growth rates were more sensitive to changes in the stress

intensity range (i.e., higher growth rate exponents, "n", were observed).

Since previous investigators [2,11] have found that most steels exhibit

similar fatigue response and good agreement was found between test results

from Plates 40 and 80 and the base metal, it was important to seek an

explanation for the unusual behavior of Plates 20 and 70. Weld metal

compositional differences were eliminated as a cause of the different

response because one plate, number 20, which showed greater FCP resistance

was welded with AX-90 while the other, Plate 70, was welded with AX-110.

The same was true of the plates showing less resistance to crack propagation

(see text above).

It is proposed that the improved fatigue response shown in Plates 20

and 70 was related to the presence of a favorable residual stress pattern.

To test this hypothesis, additional specimens from all four plates were stress

relieved to 1100°F for one hour prior to fatigue testing. This treatment had

no effect on crack growth rates in specimens from Plates 40 and 80, Fig. 9.

On the other hand, growth rates in specimens from Plates 20 and 70 increased

markedly, being comparable to the results from Plates 40 and 80 and base

metal specimens. Thus, the superior resistance to crack propagation, shown

by Plates 20 and 70 test coupons was negated by the stress relief heat treat-

ment. It is interesting to note that none of the tests revealed that stress

relieving improved the fatigue characteristics of a crack propagating along

a weld. Rather, in two sets of data (Plates 20 and 70), stress relieving

heat treatments worsened fatigue performance.

To further examine the hypothesis that a favorable residual stress

pattern beneficially affected FCP in specimens prepared from Plates 20 and

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70, additional tests were performed at various mean load levels.

As previously mentioned in Part I, mean load variations generally do not have a large effect on crack propagation rates. This is true for tension-tension loading conditions. If a portion of the applied load excursion were negative, no crack growth would occur during that portion of the cycle (16) since the crack would be closed. Thus, if a compressive residual stress were present in a specimen, a portion of the applied load cycle would be used to overcome the residual stress and, thereby, open the crack. Consequently, crack extension would only occur during the now reduced tensile portion of the load cycle. By raising the mean level of the applied load, less of the load excursion would be needed to overcome the residual stress. Therefore, a larger mean stress effect would be anticipated in the presence of a residual stress field. Once the residual stress is overcome, further increases in the mean load should cause little or no effect.

As-welded specimens were tested at the following values of λ: 1.07 (initial results, 2.14, and 4.3. The results, presented in Fig. 10, reveal that increasing λ in Plate 80 had approximately the same effect on propagation rates as found in the base metal in Part I. However, increasing λ to 2.14 in Plate 70 caused the specimens to perform as though they had been stress relieved, while raising λ to 4.3 caused no further increase in the propagation rates. Since this behavior is similar to that described above, it tends to reinforce the possibility that a favorable residual stress pattern was present in Plates 20 and 70.

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On the basis of the stress relief and mean stress tests, it is concluded that a favorable residual stress pattern was present in Plates 20 and 70. Initially, one might consider a residual compressive stress perpendicular to the weld line; that is unlikely. Gurney[5] and others have demonstrated that the main residual stresses caused by butt welding are parallel to the weld and are tensile in nature except near the plate edges. These stresses could exert a bending moment which would tend to resist the opening of the crack in the weld plane.[17] Such a moment would have the same effect as a compressive residual stress perpendicular to the crack surfaces. It is possible that this was the case in this investigation. Since applied stress levels rarely exceeded 10,000 psi in this study, the magnitude of the residual stress necessary to cause the observed effect would have been too small to measure without the use of extensive sectioning techniques. This was beyond the scope of the project.

The reason why two of the Plates (20 and 70) apparently contained residual stresses but not the other two (40 and 80) is not readily apparent. Welding processes used to produce the plates were virtually identical, and specimen machining processes sufficiently varied, making it impossible to associate the difference on this basis.

Propagation rates were also measured for a crack growing in the heat affected zone next to the weld. The specimens used in these tests were taken from Plate 20. Similar to weld metal specimens from this plate, the crack growth rate was considerably lower in the HAZ than the growth rate in the base metal. Again, stress relieving caused the growth rate in the HAZ to increase considerably. This suggests that the HAZ was also under the influence of the residual stress pattern described above.

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Microscopic growth rates were generally slower than the associated macroscopic values (Fig. 11). It would appear that fracture mechanisms other than striation formation were also operative during the fatigue process so as to account for the growth rate differences. This is consistent with the observation that striations covered only part of the fracture surface while other mechanisms (e.g., quasi-cleavage and void coallescence) predominated.

Microscopic growth rates from Plates 40 and 80 were the same regardless of the mean load or the heat treatment as were the microscopic growth rates from Plates 20 and 70 in the stress relieved condition or at $\lambda = 2.14$ in the as-welded condition. Only the as-received Plate 20 and 70 specimens at $\lambda = 1.07$ showed a lower microscopic rate of growth, consistent with the macroscopic response.

SUMMARY

The following conclusions summarize the findings of this investigation:

1) Crack growth rates in both A514 base metal, heat affected zone and weld metals (AX-90, AX-110) could be described in terms of a Paris type power relation: $\frac{da}{dN} = C\triangle K^n$

2) The application of net section stresses near or at the yield point cause fatigue crack growth rates to increase rapidly regardless of the value of the stress intensity range. Good correspondence was obtained between the crack opening displacement and the crack growth rate in this region.

3) Crack propagation rates in weld metal or HAZ may be slowed by residual welding stresses. Stress relief heat treatments of such specimens resulted in a considerable increase in the crack growth rates. Reduced crack growth in as-welded plates was not observed in every plate tested, and in those where it was not observed, stress relieving had no effect on FCP.

4) Fractographic examination revealed that the striation spacings were not a good indication of the macroscopic growth rate. The microscopic growth rates, however, did respond to test variables in the same manner as the macroscopic behavior.

ACKNOWLEDGEMENTS

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TABLE I

Composition

	C	Mn	P	S	Si	Ti	Ni	Cr	Mo	V	Cu	B	Al
A514F	.10/.20	.60/1.00	.035max	.040max	.15/.35	-	.70/1.00	.40/.65	.40/.60	.03/.08	.15/.50	.002/.006	-
A514J	.12/.21	.45/.70	.035max	.040max	.20/.35	-	-	-	.50/.65	-	-	.001/.005	-
AX-90	.07	1.35	.008	.008	.45	.10	2.00	.04/.07	.45	.01/.02	-	-	.01/.015
AX-110	.09	1.67	.010	.010	.46	.12	2.50	.13	.57	.011	-	-	.005

Mechanical Properties

	YS	TS	Elong.2"	RA
A514F	108	118	17%	~50%
AX-90	99	108	24%	70%
AX-110	119	128	20%	60%

TABLE II

Specimen Dimensions

Specimen	A*	B	C	D	E	F
SEN	12"	3.000"$\pm$.005	6"	1/2"	1.500"$\pm$.002	4.500"$\pm$.005
CT	3.000"$\pm$.005	3"	1.500"$\pm$.002	.750"$\pm$.002	2.500"$\pm$.002	.700"$\pm$.003
CN	12"	3.000"$\pm$.005	6"	1/4"	1.500"$\pm$.002	4.500"$\pm$.005

*Letters refer to dimensions indicated in Fig. 1
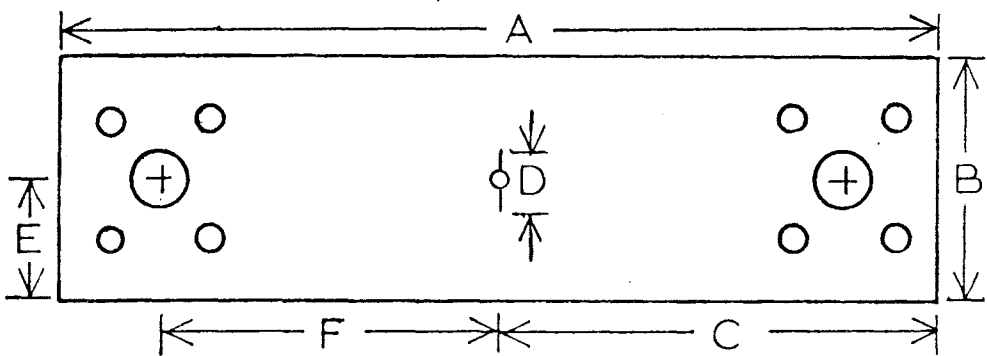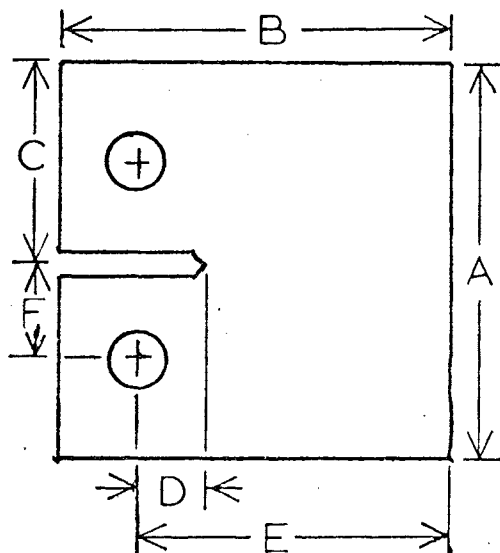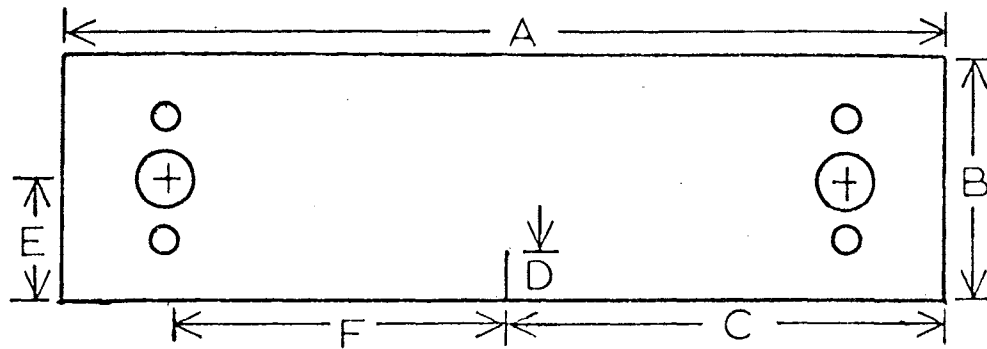
Fig. 1 - Configuration of Single Edge Notch, Compact Tensile, and Center Notched Fatigue Specimens.
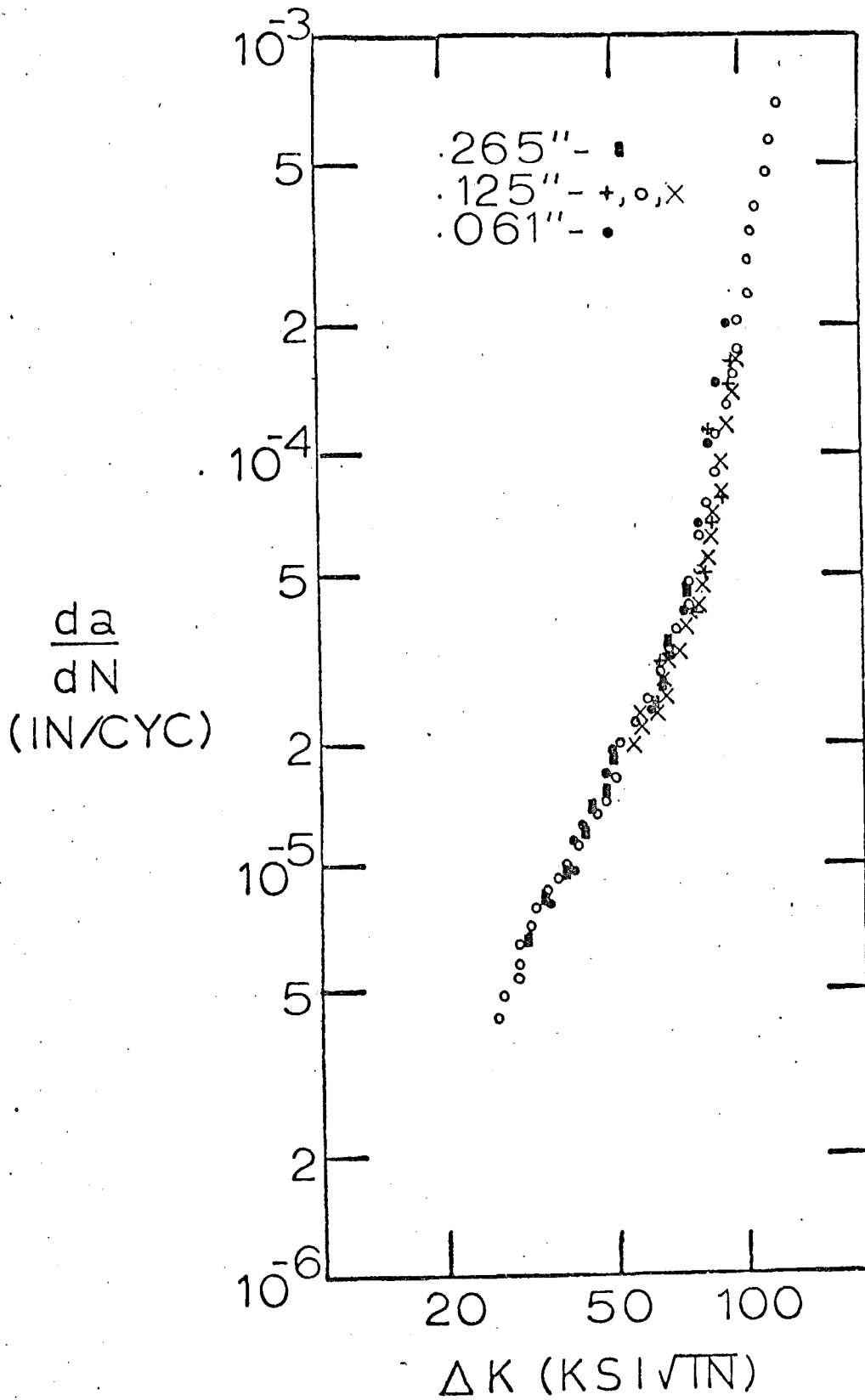
Fig. 2 - Fatigue Crack Growth Rates in Type A514 Steel for Specimens of Varying Thickness.
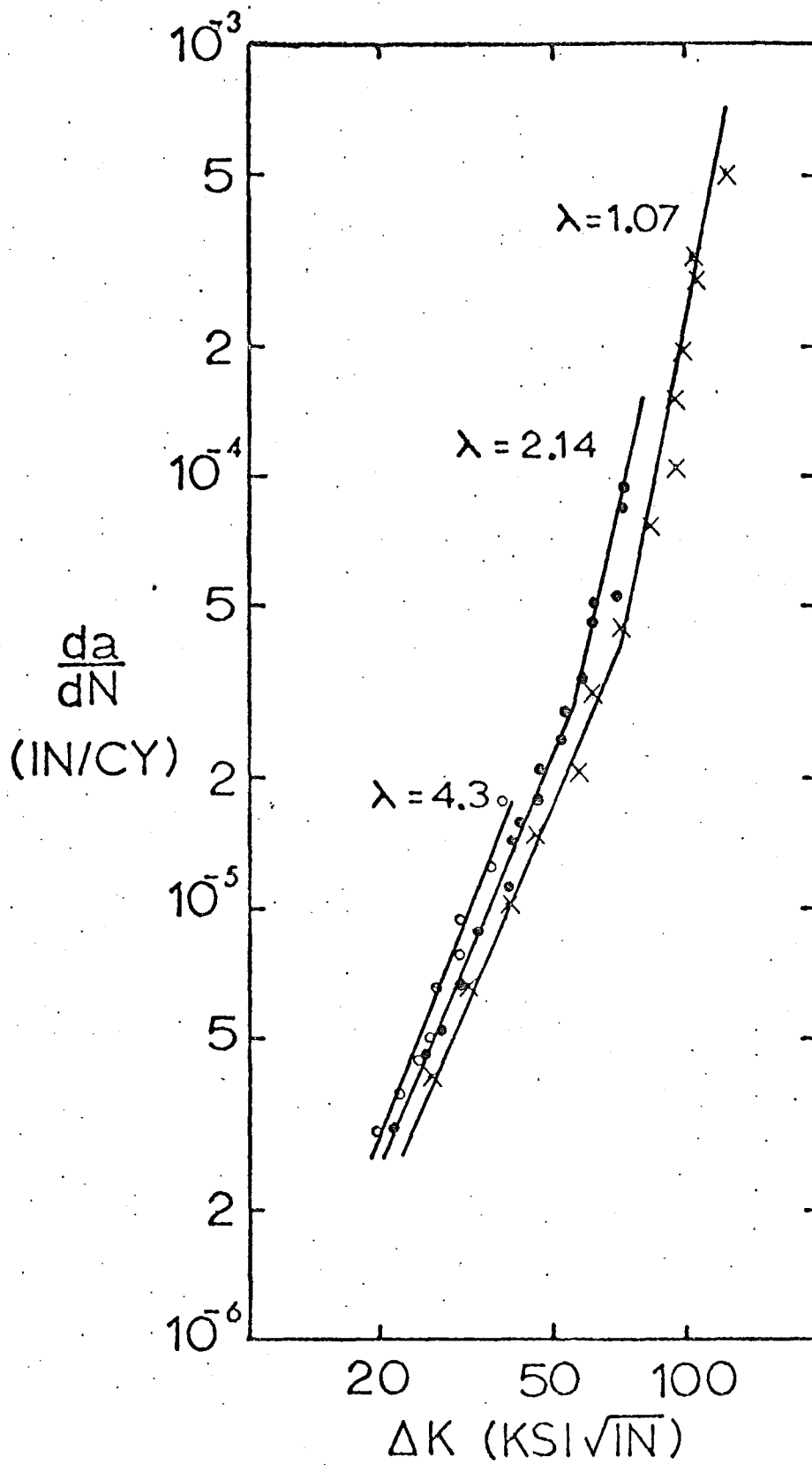
Figure 3: Effect of λ ($K_{max}/\Delta K$) Upon Fatigue Crack Propagation on A514J Steel
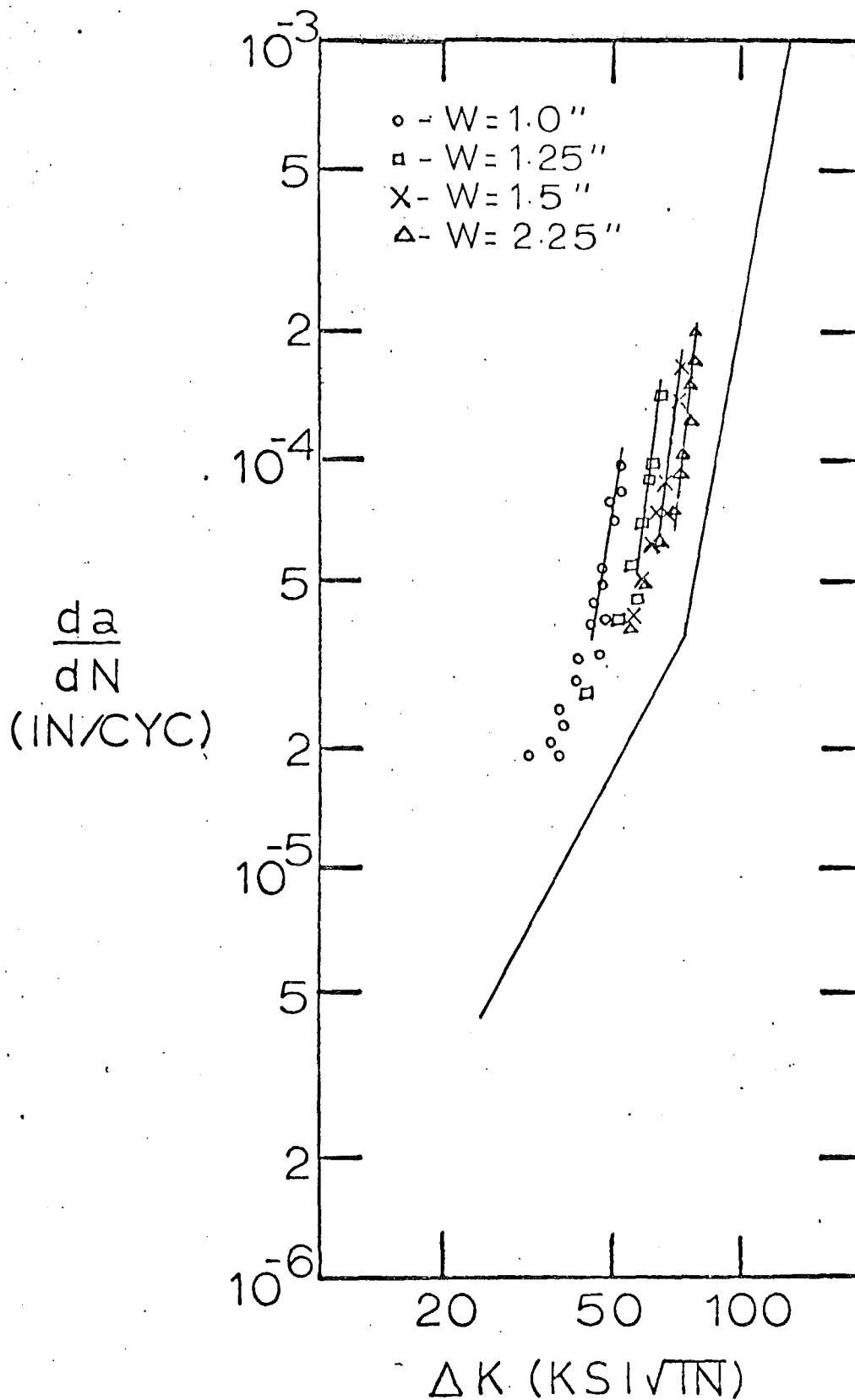
Fig. 4 - Fatigue Crack Propagation Rates in A514F Steel Under High Net Section Stress Conditions. Data Obtained from Specimens with Different Widths. Solid Line Represents Data from Fig. 3 ($\lambda = 1.07$).
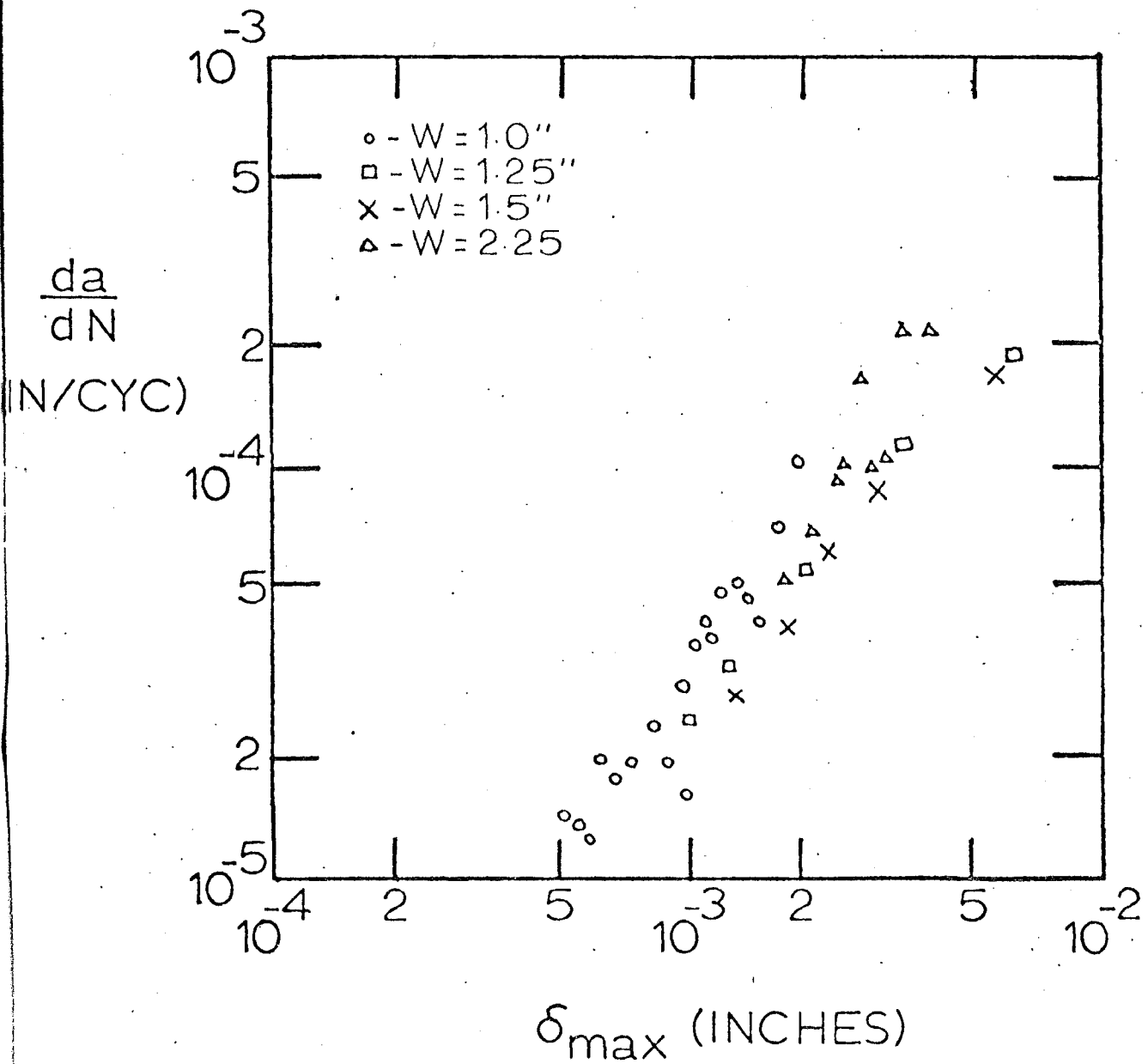
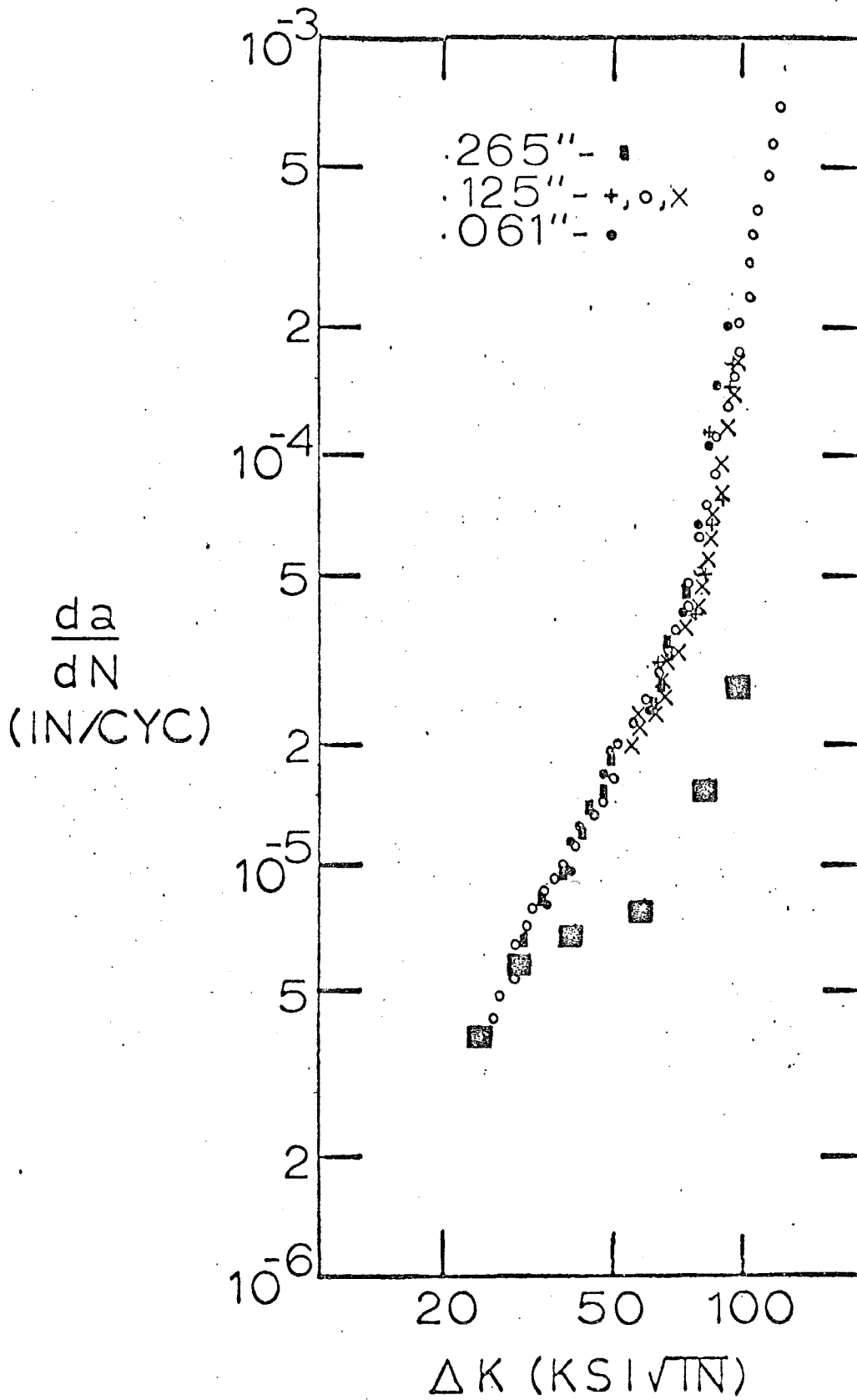Fig. 5 - Growth Rate VS. Maximum Crack Opening Displacement under High Net Section Stress Conditions.

$$\frac{da}{dN}$$

(IN/CYC)

.265"- ■
.125"- +,o,×
.061"- ●

10^{-3}

5

2

10^{-4}

5

2

10^{-5}

5

2

10^{-6}

20   50   100

ΔK (KSI$\sqrt{IN}$)

Fig. 6 - Effect of ΔK on Microscopic Growth Rate in Base Plate
(Including Macroscopic Data from Fig. 2).

Fig. 7 - Typical Appearance Of A Fatigue Surface
Of A514 Steel Associated With A Macro-
scopic Growth Rate Of 7 x 10^{-6} in/cycle.
MAG: 11,700X.
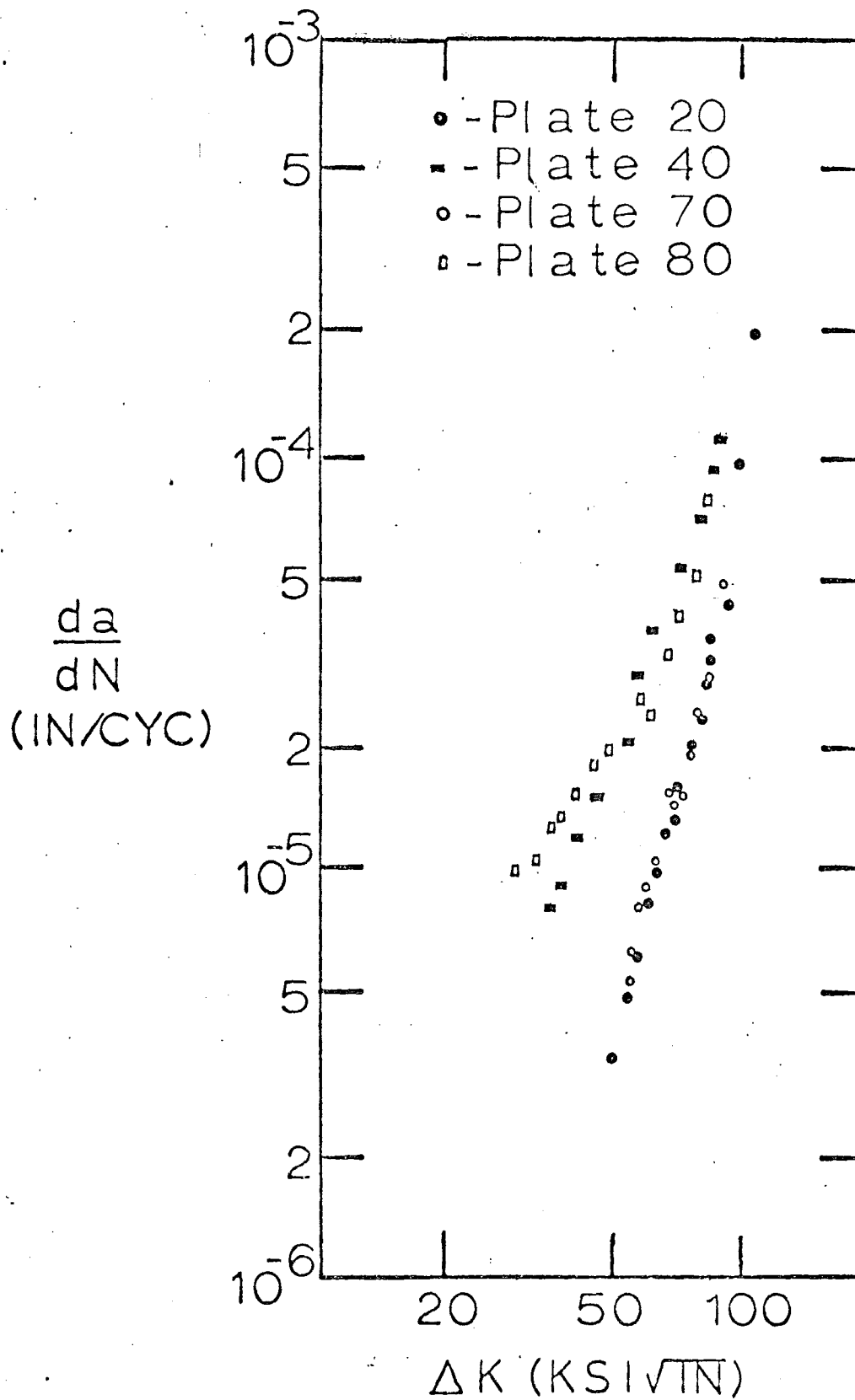
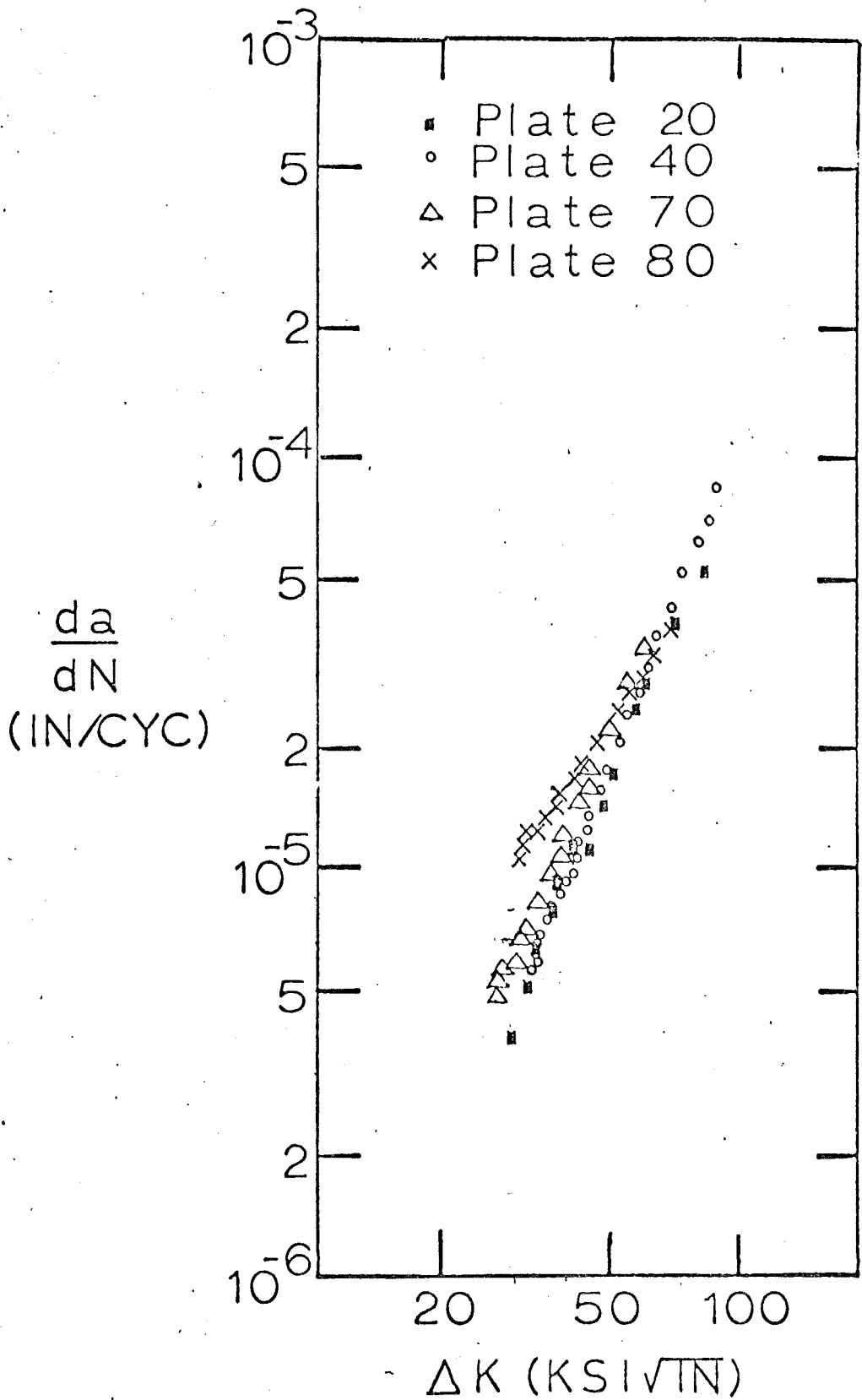Fig. 8 - Fatigue Crack Growth Rates in As-Received Welded Plates 20, 40, 70, 80.

Fig. 9 - Effect of Stress Relief Heat Treatment on Fatigue Crack
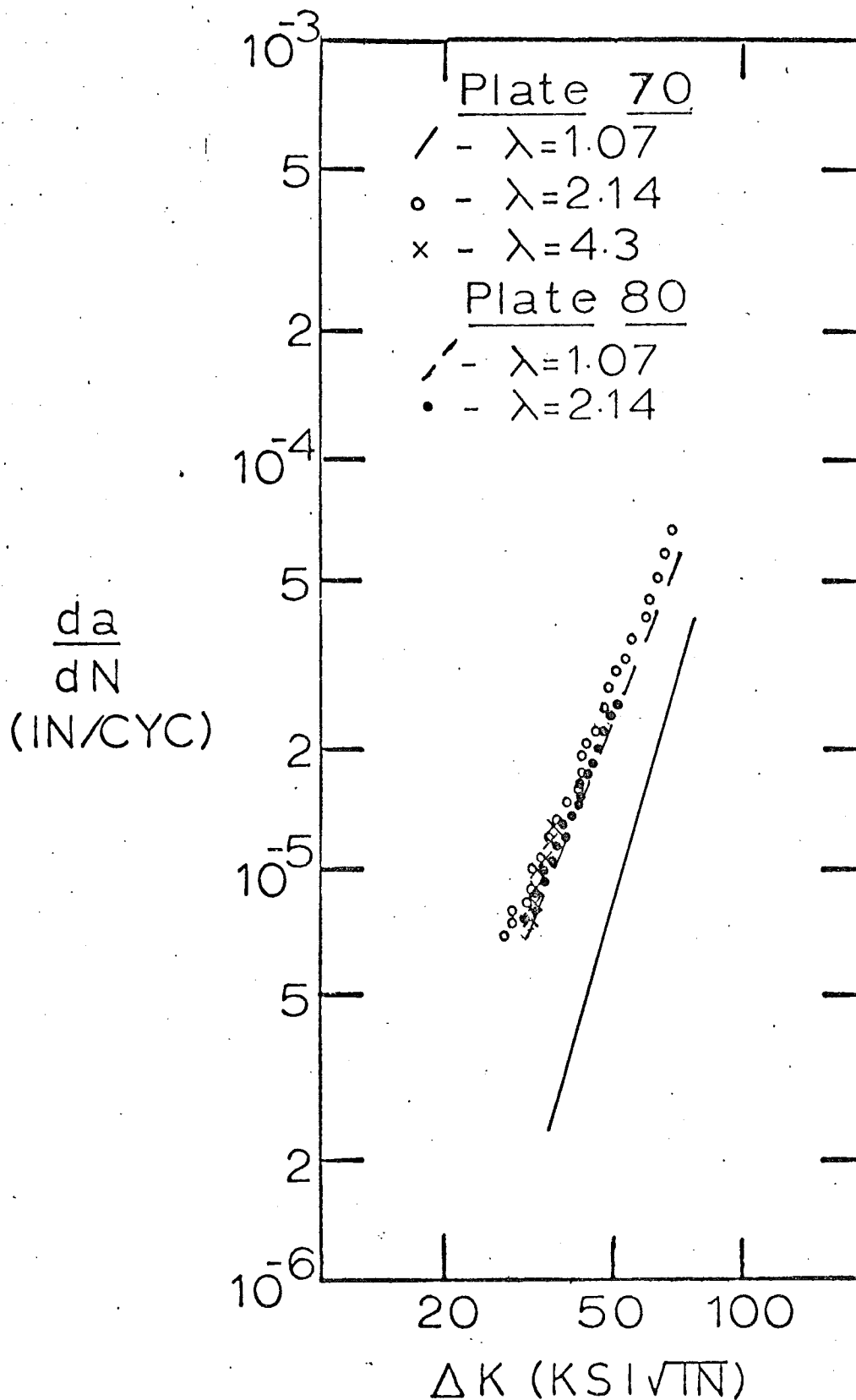Growth Rates in Plates 20, 40, 70, 80.

Fig. 10 – Effect of Increasing λ (=Kmax/△K) on Fatigue Crack
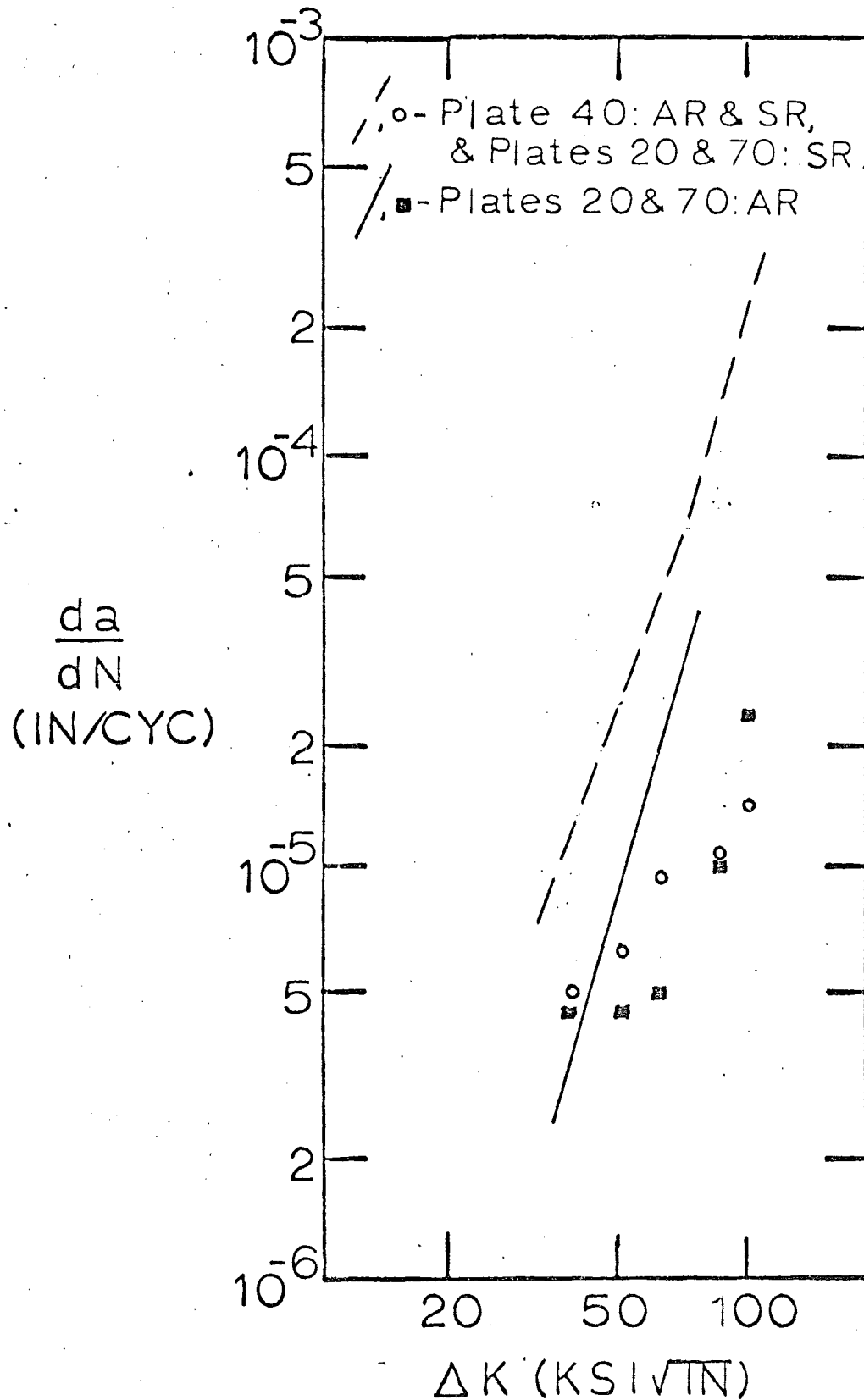Propagation in Plates 70 and 80.

Fig. 11 – Effect of ΔK on Microscopic Growth Rate in Weld Metal
(Including Macroscopic Data from Figs. 8 and 9).