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ABSTRACT

This report presents a summary of investigations into the fatigue response of butt welded plates. It was found that crack growth rates in as-welded material may be lower than in as-received specimens. The retardation in crack growth rate is attributed to a reduction in the effective stress intensity range caused by a residual stress field introduced by the welding procedure. Stress relieving, which removed the residual stress pattern, caused the growth rate to increase. Not all plates tested showed a difference in the fatigue response between the as-welded and stress relieved specimens, indicating that the residual stresses do not always occur. The crack growth rate was not reduced by stress relieving in any of the plates tested.

The microscopic growth rates as determined by striation spacings, were not found to be a simple function of the stress intensity range. They did, however, reflect the above mentioned trends that were observed macroscopically.

An investigation into the rate of crack propagation in material that had been stressed beyond the point of general yielding was also conducted. It was observed that the crack growth rate accelerated greatly, with respect to low stress tests, as the net section stress exceeded 95 percent of the yield strength. Good correspondence between crack growth rates and the maximum crack opening displacement was obtained under these conditions.

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WELDED STRUCTURAL STEEL

by

Michael Owen Parry

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in
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Certificate of Approval

This thesis is accepted and approved in partial fulfillment of the requirements for the degree of Master of Science.

May 17, 1971
(date)

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I. INTRODUCTION

Until recently, the main approach in evaluating the fatigue of welded structures has been the S-N approach, where the applied stress range, S, is compared with the number of cycles to failure, N. A comprehensive review of the research performed using this approach has recently been published by Gurney.(1) Results have shown that the fatigue life of a structure is inversely proportional to the applied stress range. The fatigue strength which is used as a parameter for comparing weldments, is defined to be that stress range necessary to cause failure in $2X10^6$ cycles. Application of a smaller range will generally not cause failure.

The fatigue strength of a weld is found to be relatively unaffected by the static strength or the general metallurgical condition of the material under consideration. The surface condition of the specimen used, however, was found to be an important variable. Improper surface finishing tended to create sites for the initiation of cracks. The metallurgical preparation of the surface (i.e., carburized, nitrided, etc.) also affected fatigue strength for the same reason.

Though widely used, the S-N approach does not separate the phenomenon of crack initiation from crack propagation. Signes, et.al.(2) have shown that a typical weld defect may have a root radius of .0001" or less. Under such conditions, initiation of a crack in fatigue would represent only a very short portion of a structure's fatigue life; consequently the rate of crack propagation would control the number of cycles to failure.

Fatigue crack propagation has been investigated in unwelded specimens of aluminum, steel, and other materials. These investigations, using a fracture mechanics approach,(3) have indicated that the rate of crack growth is directly related to the applied stress intensity range raised to a power:(3-9)

$$da/dN = C(\Delta K)^n \qquad (1)$$

where da/dN equals the crack growth rate, ΔK is the stress intensity factor range and C and n are material constants. The value of n, though it may vary from material to material, is relatively unaffected by an alteration in the metallurgy of a given material,(9-12) and only slightly affected by an alteration of the material's yield strength.(13,14)

Recently the fracture mechanics approach has been applied to the fatigue of transverse butt weldments by several investigators. Maddox(15) demonstrated that cracks in low strength steel welds obeyed the above mentioned power law relation and the values found for C and n were typical for steels previously tested.(10-12) Dowse and Richards(16) showed that a crack initiating in a weld, or the immediate neighborhood of it, would tend to grow into the region, be it weld metal, heat affected zone, or base metal, that had the lowest yield strength. The crack also tended to grow at a slightly faster rate in this region.

Hertzberg and Nordberg,(17) working with higher strength steel weldments than either Maddox or Dowse and Richards, also found agreement with the power law relation. However, they observed that the weld metal in the as-welded condition showed considerably greater resistance to fatigue crack propagation than did the base metal material. Upon stress relieving, they found the weld lost this apparent ability to perform in a superior manner, and the growth rates became approximately the same as the growth rates in the base metal. Since previously mentioned authors (9-13) have found that steels, in general, perform the same in fatigue, and since the difference Hertzberg and Nordberg found between the weld and base metal was removed by stress relieving, the latter investigators were led to conclude that a favorable residual stress pattern had been created during the welding process. Gurney (1) noted, however, that in general the residual stress patterns in the neighborhood of a transverse butt weld had only a slight but negative effect on the fatigue strength. Consequently, fatigue performance was improved by stress relieving. Furthermore, Maddox (15) did not observe any such difference between crack growth rates in the weld and base metals that he investigated.

Hertzberg and Nordberg also showed that as the crack growth rate increased above 10^{-4} in./cycle, the value of "n" in Eqn. (1) increased from 2.4 to 6.5. This has been observed several times by others (12,18,19). The specimens used in these tests were such that, due to their configuration, the value of ΔK was elevated by a geometrical correction factor rather than by a large applied uniaxial stress. The net section stress, therefore, was well below the yield strength of the material.

Lui (18) attributed the increase in the value of "n" to an increase in the size of the plastically yielded zone ahead of the crack tip and thus associated the acceleration of the crack growth to a yielding phenomenon. This observation, however, was made in a specimen where the net section stress was again less than the yield stress. The plastic zone, which in static fracture, elevates the applied stress intensity level, is usually ignored in low net section stress fatigue tests because it's effect is usually minimal.

Studies involving completely yielded specimens have been performed (20-23) but the authors have chosen to compare crack growth rates with the plastic strain range applied rather than the fracture mechanics parameter, K. Thus, little or no use of the stress intensity range as a variable has been made in high stress fatigue.

While Hertzberg and Nordberg's results were based mainly on macroscopically determined growth rates, some fractographic information concerning microscopic rates at various stress intensity levels was reported. It was found that the exponent "n" in Eqn. (1) was lower for striation spacing growth rate measurements which is in agreement with previous results by Pelloux (24) and Heiser and Hertzberg (25) in unwelded steel. Clark and Bates, (26) however, have recently shown that an excellent correspondence between microscopic and macroscopic growth rates did exist in a wide range of steels.

The objective of this investigation will be to extend the Hertzberg-Nordberg findings with respect to fatigue crack propagation in welds, crack propagation in yielded material, and an extensive study of the microscopic growth rates. First, since Hertzberg and Nordberg studied the fatigue of only one welded plate, it is possible that their results were caused by some unique combination of welding and machining procedures resulting in abnormal behavior. To determine if this is the case, specimens prepared in a similar manner but from different welded plates will be examined and compared with the previous findings. In this manner the reproducibility and cause of the results described by Hertzberg and Nordberg may be determined. Furthermore, other specimen designs will be considered in the investigation along with an evaluation of strain aging effects as suggested by Coffin.(27)

Secondly, in their high growth rate experiments, Hertzberg and Nordberg used specimens in which the applied stress was not a large fraction of the yield stress. Thus, they did not evaluate the effect of net section yielding on the rate of crack propagation. In this project, experiments will be conducted in such a manner that high net section stresses are obtained while the applied stress intensity range will take on approximately the same values used in the previous investigation. An attempt will be made to correlate the rate of crack propagation under these conditions with fracture mechanics parameters and a comparison will be made with the previous findings for low stress tests.

Finally an extensive investigation of the fracture surface morphology will be performed. A comparison of macroscopic growth rates, determined from visual examination of the crack tip position during testing, and microscopic growth rates, based on striation spacing, will be made. Since Hertzberg and Nordberg found relatively few areas with well defined striations, an attempt will be made to determine if the angle the replica makes with the microscope beam is important. (Broek (28) has shown that by tipping a replica, striations can become visible in areas where none were observed when the replica was flat.)

2. PROCEDURE

2.1 Materials

Base plate material used in this investigation was U.S. Steel's T-1 steel which meets ASTM A514F and A517F specifications. Weld metal used as AIRCO AX-90 and AX-110. Composition and mechanical properties of all three are presented in Table I.

2.2 Specimen Preparation

Specimens were made from plates welded in the following manner: Strips of base metal 24" x 6" were cut from a plate 24" x 25" x 5/8". The strips were butt welded with a 60°-V-notch in the longitudinal direction to a final size of 24" x 12" x 5/8" using a Metal - Inert-Gas process. The weld was laid perpendicular to the rolling direction of the plate with only enough hold down pressure to prevent lateral movement of the plates but not enough to prevent bending in the amount of 5 to 10 degrees during solidification.

Three types of specimens were used for the investigation: Single Edge Notch (SEN), Compact Tensile (CT), and Center Notched (CN) (Fig. 1). The dimensions and initial crack sizes for all specimens appear in Table II.

Two methods were used for preparing the specimens. The first consisted of cutting the 24" x 12" x 5/8" welded plate, perpendicular to the weld, into 3" x 12" x 5/8" strips. For CT specimen, the strips were cut into 3" x 3" x 5/8" squares with the weld in the middle. For 1/8" or thinner specimens, the strips or squares were sliced along their mid-thickness plane. Specimens were then cut and ground to final thickness and dimensions, and holes and initial cracks were introduced.

The second method used for making CT only consisted of cutting the 24" x 12" x 5/8" plate into a 24" x 3" x 5/8" strip with the weld centered in it and running the length of the strip. This was cut into 3" x 3" x 5/8" squares and specimens were made from the squares the same as in Method I.

In all specimens the weld was perpendicular to both the rolling direction of the base plate and the loading direction of the specimen and it was centered with respect to the leading pins. An initial crack was introduced into the weld prior to testing.

2.3 Testing Procedure

Testing was performed on an MTS closed-loop, electro-hydraulic, high speed fatigue testing machine. All tests were run at 10 cycles per second. No special atmosphere was provided; test temperatures and relative humidity ranged from 72° to 80°F and from 40% to 80%, respectively. A traveling microscope with a vernier scale was used to measure crack tip position during each test. All data were analyzed with the aid of a CDC-6400 computer.

Low stress, high cycle fatigue testing was performed on three plates, one welded with AX-90, and two welded with AX-110, designated plates 40, 70, and 80, respectively. A plate of AX-90 originally tested for the Hertzberg-Nordberg report and designated Plate 20, was used for comparison. Specimens of all three geometries previously described and of varying thicknesses were fatigued in both the as-received and stress-relieved conditions. The stress relief used was one hour at 1100°F, followed by an air cool. Mean load effects were evaluated by varying $\lambda(=K_{max}/\Delta K)$ to three different levels: $\lambda = 1.07$, $\lambda = 2.14$, and $\lambda = 4.3$. (These correspond to values of $R(=K_{min}/K_{max})$ of .065, .53, and .77, respectively.)

High stress or low cycle fatigue testing was performed using specimens of unwelded base plate. Due to specimen geometry, compact tensile specimens were used to obtain stress intensity range levels as high as 130 KSI $\sqrt{IN}$. while maintaining a low applied stress. Reduced width center notched specimens (CN) were used for high applied stress, high stress intensity level tests. The initial ΔK levels in the CN specimens ranged from 50 to 90 KSI $\sqrt{IN}$. Variations in the width were used to cause yielding to occur in the net section at different values of ΔK.

Strain aging effects were investigated by first stress relieving an unnotched SEN specimen of AX-90, straining it 6% and aging at 600°F for one hour (air cool). The sample was then notched and tested.

2.4 Fractography

Fractographic analysis was performed on an RCA-EMU-3G electron microscope. Standard two stage replication techniques were employed with a Platinum-Carbon mixture used as a shadowing agent.

3. RESULTS

3.1 High Cycle Fatigue

Test results from plates, welded and prepared for the purpose of extending the Hertzberg-Nordberg study, are presented in Figs. 2-5. The data shown are uncorrected for plastic zone size. Fig. 2 displays the results of testing specimens in the as-welded condition. Plate 70 specimens, welded with AX-110, demonstrated a higher slope, 4.0 vs. 2.4, and lower intercept, $1.0X10^{-24}$ vs. $1.0X10^{-20}$, than Plates 40 (AX-90) and 80 (AX-110). Thus below $da/dN = 10^{-4}$ where the curves converge, Plate 70 demonstrated more resistance to crack propagation and as such, was in agreement with Plate 20 performance.(17)

When the mean load was increased in Plate 80 specimens, the da/dN vs. ΔK curve shifted slightly, Fig. 3, in a manner observed previously in the base metal.(17) This is consistent with the generally accepted fact that mean stress effects normally play a secondary role in fatigue crack propagation. However, increasing the mean load applied to Plate 70 specimens from $\lambda = 1.07$ to $\lambda = 2.14$ caused a surprisingly large shift in the growth rate curve (Fig. 4) so that the data from Plate 70 and Plate 80 (both at $\lambda = 2.14$) are virtually indistinguishable. The apparent strong mean stress sensitivity of Plate 70 was examined by conducting further tests at $\lambda = 4.3$. In this case a much smaller effect (similar to that observed in reference 17) was noted.

Stress relieving specimens from Plates 40 or 80 produced no significant effect in the fatigue crack propagation rates over the range investigated. However, stress relieving specimens from Plate 70 caused the growth rate curve to shift upwards so that the curve was now identical to the Plate 40 and 80 curves, Fig. 5. Hertzberg and Nordberg observed similar behavior in Plate 20.(17)

No effect of specimen geometry or thickness was noted during these tests. For example the data for Plate 80 was obtained from 1/8" thick center notched specimens, while the data for Plates 40 and 70 were obtained from 1/8" and 1/2" thick compact tensile specimens.

3.2 Low Cycle Fatigue

The da/dN vs. ΔK data for base metal specimens which had a high applied ΔK but low applied stress appear in Fig. 6. Below $da/dN = 10^{-4}$ in./cycle, the slope is 2.4, the same as in Plates 40 and 80, and above it the slope increases to 6.5. The specimens used to obtain these data were compact tensile specimens, both 1/8" and 1/2" thick. These results are confirmed by Hertzberg and Nordberg for base metal using 1/8" thick single edge notch specimens and again demonstrate a lack of thickness or specimen configuration effects on fatigue crack propagation.

Using .050" thick center notched specimens, it was possible to obtain high stress intensity levels along with net section stresses near or at the yield point of the material. Furthermore by varying the specimen width it was possible to produce net section yielding at different values of the applied stress intensity factor. In such tests the slope of the growth rate curve increased dramatically to a value as high as 20 when the net section stress exceeded approximately 95% of the yield strength, Fig. 7. These transition points were associated with stress intensity levels of 43, 57, 63, 67, and 70 KSI $\sqrt{IN}$. in the tests performed. It was noted that yielding occurred by the formation of plastic bands that emanated from the crack tip at approximately ±45° to the plane of the crack. The crack, however, did not follow these yielded paths but continued in a straight line. After the specimens were fractured it was noted that shear-lips formed near the point where yielding occurred. Previous to that the fracture surfaces were flat.

3.3 Strain Aging

Strain aging procedures produced no deviation from normally stress relieved material in the one specimen examined for this study, Fig. 8. A recent study of aging in 18% Ni Maraging steel (31) has shown that aging in that material also had no effect on crack propagation rates.

3.4 Fractographic Analysis

In general, striations on the weld metal and base metal fatigue surfaces were few in number and poorly defined. A typical area of the surfaces appears in Fig. 9. As ΔK increased, the clarity of the striations improved but their number decreased, while the amount of cleavage and quasi-cleavage increased. Most visible striations appeared on surfaces that were inclined to the plane of the crack. This was determined by examination of shadowing differences on the replica. Furthermore, tipping a replica caused additional striations to be observed, as previously shown by Broek.(28) Thus, more striations are actually formed than is apparent from viewing the replica in only one orientation.

Growth rates, determined from striation spacings, increased with the stress intensity range but at a lower rate than the macroscopic data. Microscopic growth rates determined from specimens from Plates 40 and 80 were the same in both the as-received and stress-relieved condition, and were identical to the stress-relieved Plate 70, Fig. 10. Furthermore, no effect of mean load was noted in these specimens. Growth rates based on striation spacings from Plates 20 and 70 as-received specimens ($\lambda = 1.07$) however, were lower than the growth rates determined from stress-relieved Plate 20 and 70 specimens and from all Plate 40 and 80 specimens. This observation is consistent with variations in the associated macroscopic data.

4. DISCUSSION

4.1 High Cycle Fatigue

The results of testing three additional plates, Figs. 2-5, which were similar to the plates tested by Hertzberg and Nordberg indicated that their observation that the weld metal was more resistant to crack propagation in the as-welded condition than in the stress-relieved condition was reproducible but not in a consistent manner. Specimens from Plate 40, welded with the same material, AX-90, as Plate 20, did not show any difference between the as-welded and stress-relieved conditions. Similarly, Plate 80 which was welded with AX-110, revealed no effect of stress relief treatment on subsequent fatigue crack propagation. However, the as-welded specimens from Plate 70, using AX-110 weld metal, were more resistant to crack growth than stress relieved specimens from the same plate.

The fact that Plates 40 and 80 performed as one would expect on the basis of past experience with unwelded specimens(3,4,6,7,9-13,15,29) indicates that the greater resistance to fatigue crack propagation observed in Plates 70 and 20 may have represented unusual behavior. Compositional differences as a cause of the different response of the two sets of plates were dismissed because one plate in each set (20 and 40 series) was welded with AX-90, while the other plate in each set (70 and 80 series) was welded with AX-110. Strain aging effects were considered unlikely because of the lack of effect on the propagation rates found in the specimen examined, Fig. 8.

However, the fact that stress relieving specimens from Plates 70 and 20 caused them to perform the same as specimens from Plates 40 and 80 and the base metal, indicates that a favorable residual stress pattern as previously suggested (17) may have been present in the as-received Plates 20 and 70. A residual stress is further indicated by the manner in which specimens from the as-welded Plate 70 responded to changes in the mean load, Fig. 5. Doubling λ from 1.07 to 2.14 produced the same effect as stress relieving while doubling λ again, 2.14 to 4.3, produced only slight increases in the growth rate for a given value of the stress intensity range. The increase in growth rate from $\lambda = 2.14$ to 4.3 in Plate 70 was similar to the increase in growth rate experienced by the base metal under the same increases in λ.

Earlier investigation into the effect of mean load on fatigue strength (1) or on the rate of crack propagation (29) in steel have shown that alterations of the value of a tensile mean load have little or no effect. However, these authors and others (30) have indicated that if a portion of the applied loading cycle is compressive, only the tensile portion of the cycle causes crack growth and that raising the mean load to eliminate the compressive portion can cause significant increases in the growth rate. This is due to the fact that the stress range experienced by the crack tip is now the entire range applied rather than only some fraction of it. Thus, if a completely tensile load excursion is applied to a specimen containing a pre-existent compressive residual stress field, a portion of the cycle would be used to overcome the residual stress. Consequently, the effective stress range experienced by the crack would be reduced. If the applied mean load was then increased, less and less of the load excursion would be needed to overcome the residual stress so that the load and stress intensity ranges would be increased. Once the applied mean load reaches a value such that the entire load range applied is experienced by the crack tip, further increases in mean load should not have any significant effect on the growth rate.

Applying these arguments to the results obtained by Hertzberg and Nordberg, and the results from Plate 70, it would appear that both plates contained residual compressive stresses which reduced the effective stress intensity range when $\lambda = 1.07$. The substantially higher growth rates associated with a higher mean stress, $\lambda = 2.14$, would be consistent with the above comments. Also, since there was no effect of increasing λ from 2.14 to 4.3, it appears that $\lambda = 2.14$ was sufficient to overcome the residual stress.

The occurrence of a compressive residual stress normal to the weld line is rather unlikely. Gurney(1) and others have demonstrated that the residual stresses caused by butt welding are tensile in nature. Fig. 11 displays the residual stress patterns expected in the neighborhood of the weld. Clearly the stress perpendicular to the weld cannot act in a compressive nature. However, the stresses parallel to the weld are of such a configuration that they could apply a moment, which, would act in the direction indicated by the arrows in Fig. 11. This moment would tend to resist the opening of the crack, thus having the same effect as a compressive residual stress acting perpendicular to the crack surfaces.(32) Since the residual stresses parallel to the weld are generally greater in magnitude than those perpendicular to it, it is quite possible that these stresses could have been the cause of the fatigue behavior observed.

Because the loads applied during testing rarely exceeded 10,000 psi., 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 this project.

No explanation is apparent for the reason why two of the plates (20 and 70) should contain residual stresses and not the other two (40 and 80). Welding processes used to produce the plates were virtually identical, and the machining processes sufficiently varied (see PROCEDURE) so that it is impossible to make a determination on this basis. It is interesting to note, however, that none of the tests revealed that stress relieving improved the fatigue characteristics of a crack propagating along a weld. In fact, in two sets of data (Plates 20 and 70), stress relieving heat treatments worsened fatigue performance.

4.2 Low Cycle Fatigue

The fact that the slope of the growth rate curve increases radically as the net section stress approaches yielding, regardless of the value of the stress intensity range, Fig. 7, indicates that ΔK is no longer the parameter that controls the crack propagation rate in this range. Another parameter was, therefore, sought. Irwin (33) has suggested that the crack opening displacement, or δ, may be the controlling factor. The crack opening displacement is a measure of how far the crack actually opens during each load excursion. In the elastic region it may be related to the stress intensity factor by the equation:

$$\delta = K^2/\sigma_{ys}E \tag{2}$$

where σ_{ys} is the yield stress and E the modulus of elasticity.(34) As the net section yields, the permanent displacement, due to the superposition of a plastic strain, causes increases in both the maximum and minimum values of δ (hence K) but their difference, $\hat{\delta}$ (ΔK) should be relatively unaffected. Since the growth rate is accelerated by yielding, it was thought that comparing the former with a loading parameter that was also increased by yielding (e.g., the maximum or minimum value of δ) would lead to an improved correlation. The maximum δ was chosen and was determined from the known maximum values of the stress intensity factor by Eqn. (2). 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:

$$r_y = \text{Plastic zone size} = (1/2\pi)(K/\sigma_{ys})^2 \tag{3}$$

values of δ, corresponding to the points in Fig. 7, 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 δ_{maximum}, Fig. 12, the curves from all the yield specimens fall within one band of data. The fact that the specimen goes through yielding is now of little consequence since a linear relationship between a loading parameter, δ, and the growth rate has been obtained in that region. The same analysis was performed on data from a compact tensile specimen in which the applied stress was well below the yield strength, this data fell in the same band. It is apparent that a simple relationship between δ and the growth rate is obtained irrespective of the gross stress applied.

Correspondence should now be sought by actually measuring δ instead of computing it from the stress intensity factor and comparing it to the crack growth rate.

4.3 Fractography

In general the appearance of the striations observed in both the base metal and the weld metal were similar to those found in other steels,(35) though they were somewhat less well defined and fewer in number. Tipping the replica in the proper direction was found to improve the clarity and definition of the striations but it is doubtful that by tipping each replica the average value of the growth rate would be altered in a significant manner. This is because the values presented in Fig. 10 are the result of averaging at least 10 separate measurements, and in some cases as many as 50 readings.

The fact that the microscopic growth rate was less sensitive than the macroscopic growth rate to changes in ΔK, and did not obey a simple power law function of ΔK indicates that striation spacings in T-1 steel may not be as good an indicator of loading conditions as they are in other steels.(26) Therefore, care should be exercised when using striation spacings in post fracture analyses in this material.

No effect of mean load on striation spacing was noted. That is, at a given ΔK level the striations were the same regardless of λ. The one exception to this was that microscopically determined growth rates from as-welded Plate 70 specimens at $\lambda = 1.07$ were noticeably lower for a given ΔK than striation spacings from stress relieved Plate 70 specimens at $\lambda = 1.07$, or from as-welded specimens at $\lambda = 2.14$. That is, the as-welded specimens which showed more resistance to crack propagation macroscopically showed the same tendencies microscopically. This also indicates that the effective stress intensity range may have been less than the applied range, further reinforcing the argument for a residual stress effect.

5. CONCLUSIONS

The results of testing three welded plates indicate that the Hertzberg-Nordberg observation that a fatigue crack propagates at a slower rate in as-welded weld metal than in stress-relieved weld metal does not always occur. One of the welded plates tested did resist crack growth more in the as-welded condition while the other two plates showed no difference between the as-received and stress-relieved conditions. The greater resistance to propagation observed by Hertzberg and Nordberg and seen again in Plate 70 in this investigation was attributed to a reduction on the applied stress intensity range caused by some favorable residual stress effect. Stress relieving such a weld served to increase fatigue crack propagation rates.

The testing of unwelded specimens in low cycle fatigue revealed that yielding in the net section of the specimen accelerated the crack growth. It was also found that ΔK was no longer the controlling load parameter. Good correlation was obtained, however, by comparing the growth rate with the maximum crack opening displacement.

Fractographic studies demonstrated that the microscopic growth rate was not a simple power function of ΔK as has been observed in other steels. In specimens where the macroscopic growth rate was observed to be slower in the as-welded condition, the microscopic growth rates showed the same tendencies.

Strain aging was found to have no effect on the rate of crack propagation in the one specimen tested.

6. NOMENCLATURE

C	Material Constant
da/dN	Crack Growth Rate
K	Stress Intensity Factor
K_{max}	Maximum Stress Intensity Factor
ΔK	Stress Intensity Range
N	Number of Cycles to Failure
n	Material Constant
r_y	Plastic Zone Size
S	Stress Range
W	Specimen Width
δ	Crack Opening Displacement
$\hat{\delta}$	Crack Opening Displacement Range
λ	Ratio of $K_{max}/\Delta K$

7. TABLES AND FIGURES

TABLE I

Composition

Material	C	Mn	P	S	Si	Ti	Ni	Cr	Mo	V
Ti[36]	.10/.20	.6/1.00	.035 max.	.040 max.	.015/.35	-	.70/1.00	.040/.65	.040/.60	.03/.08
AX-90[37]	.07	1.35	.008	.008	.45	.10	2.00	.04/.07	.45	.01/.02
AX-110[37]	.09	1.67	.010	.010	.46	.12	2.50	.13	.57	.011

Material	Cu	B	Al
Ti[36]	.15/.50	.002/.006	-
AX-90[37]	-	-	.01/.015
AX-110[37]	-	-	.005

Mechanical Properties

	YS	TS	Elong.2"	RA
T-1[38]	108	118	17%	~50%
AX-90[39]	99	108	24%	70%
AX-110[39]	119	128	20%	60%

TABLE II

Specimen	Length	Width	Thickness	a
SEN	12"	3"	.125"	~.50
CT	3"	3"	.125" to .50"	
CN	12"	1"→ 3"	.050" to .125"	.25" to .50"

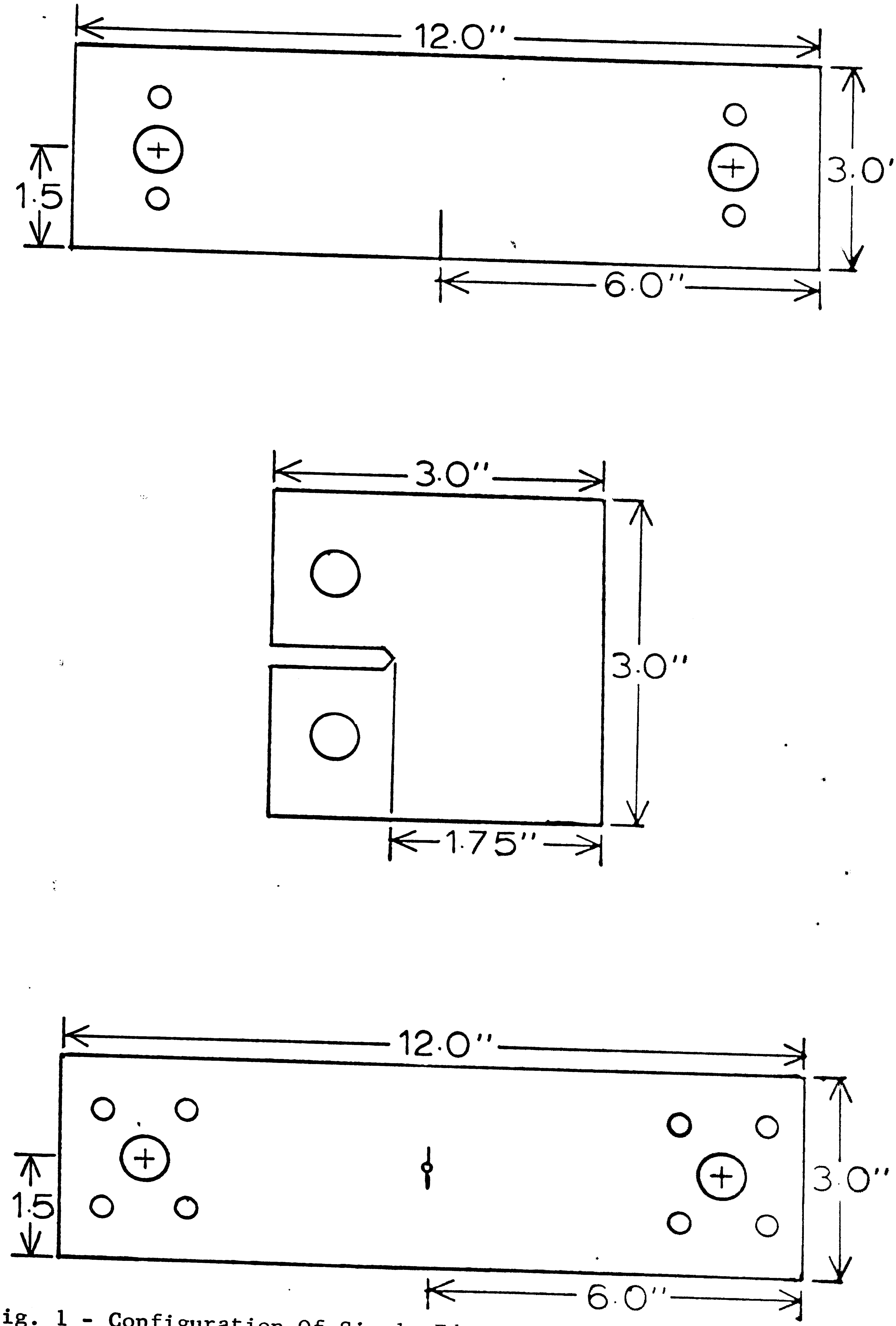

Fig. 1 - Configuration Of Single Edge Notch, Compact Tensile And Center Notched Fatigue Specimens.

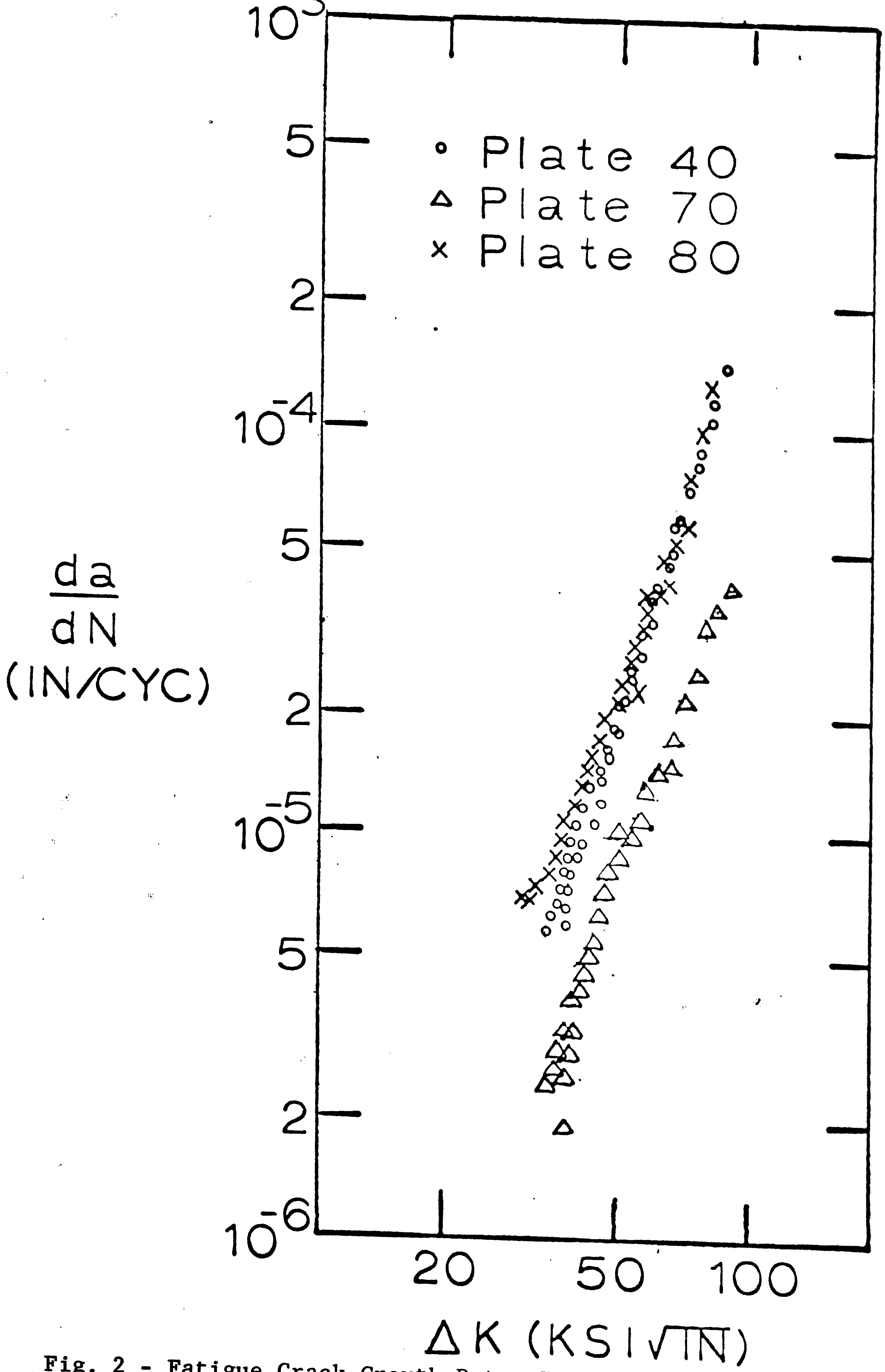

Fig. 2 - Fatigue Crack Growth Rates In As Received Welded Plates 40, 70 and 80.

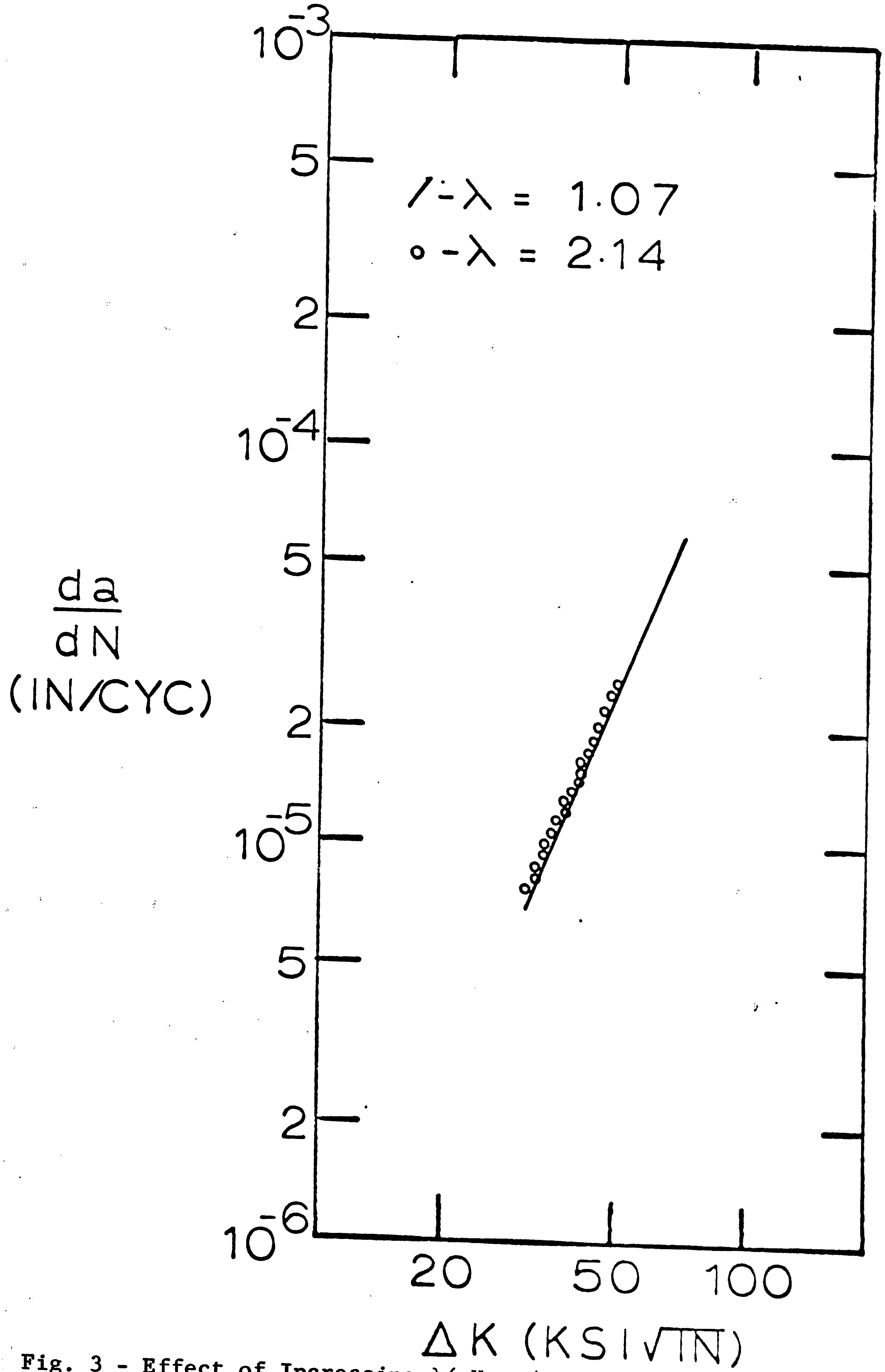

Fig. 3 - **Effect of Increasing** $\lambda(=K_{max}/\Delta K)$ on Crack Growth **in Plate 80.**

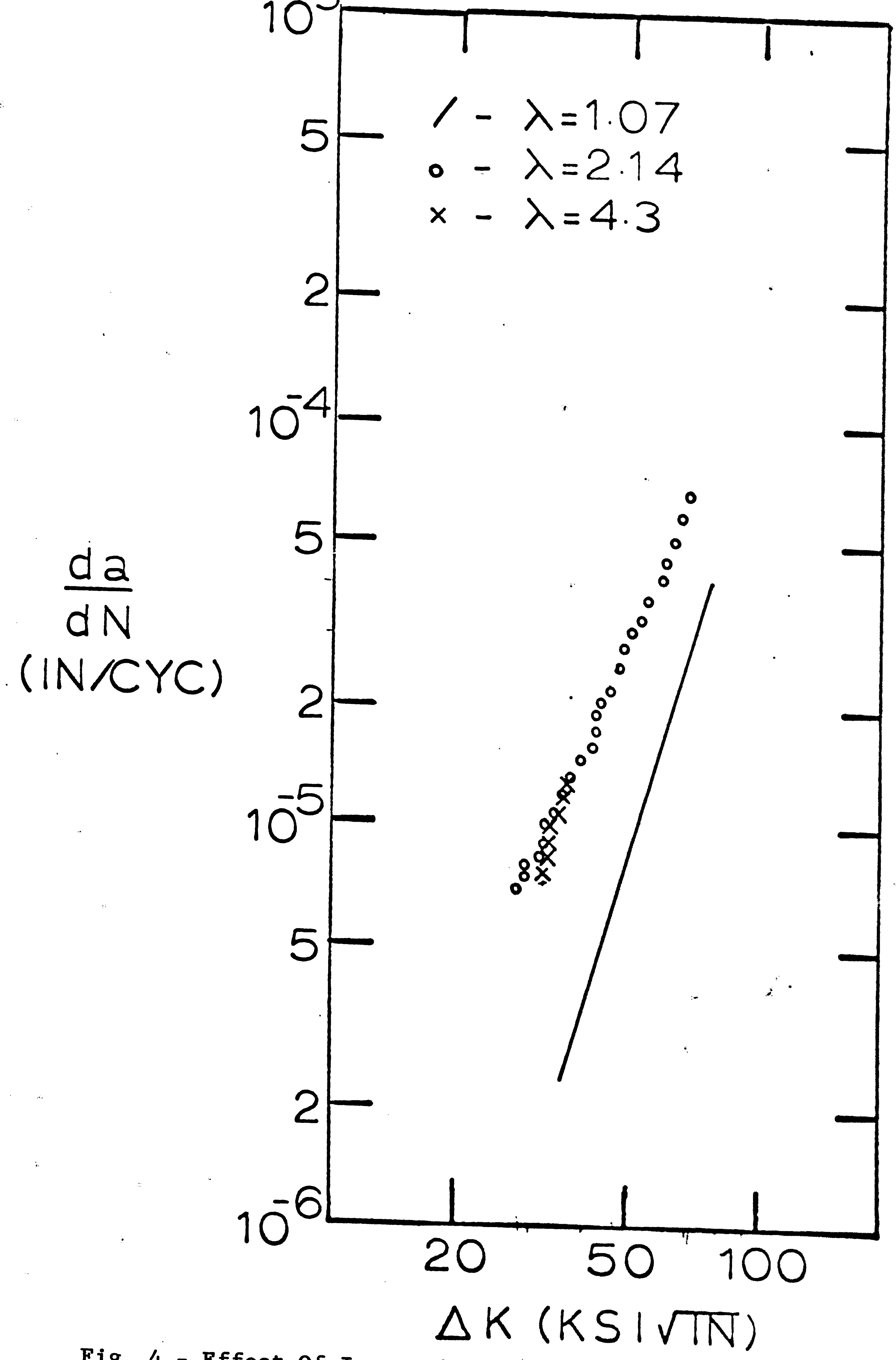

Fig. 4 - Effect Of Increasing $\lambda(=K_{max})\Delta K$ On Crack Growth In Plate 70.

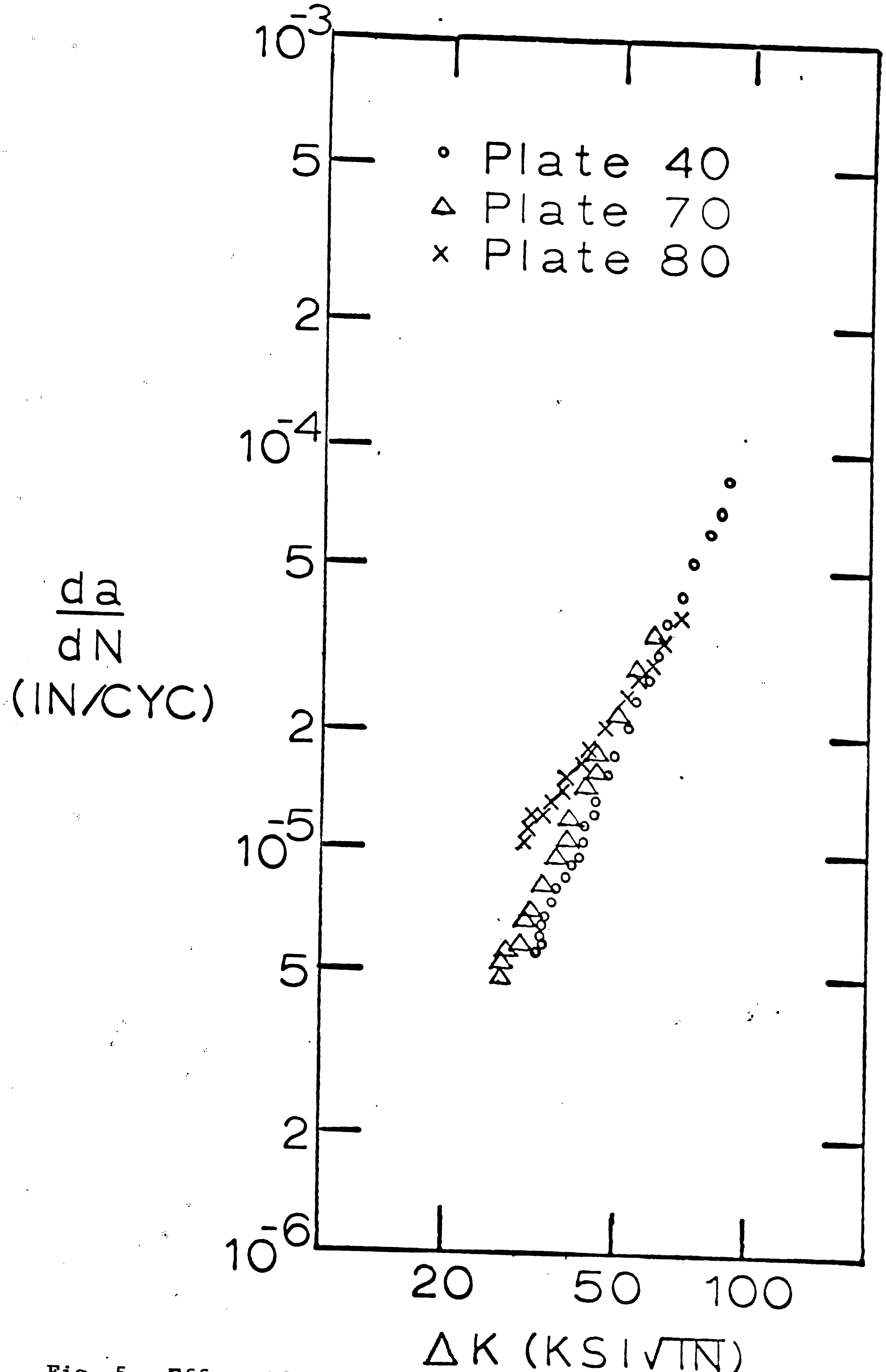

Fig. 5 - **Effect Of Stress-Relieving On Fatigue Crack Growth Rates In Plates 40, 70 and 80.**

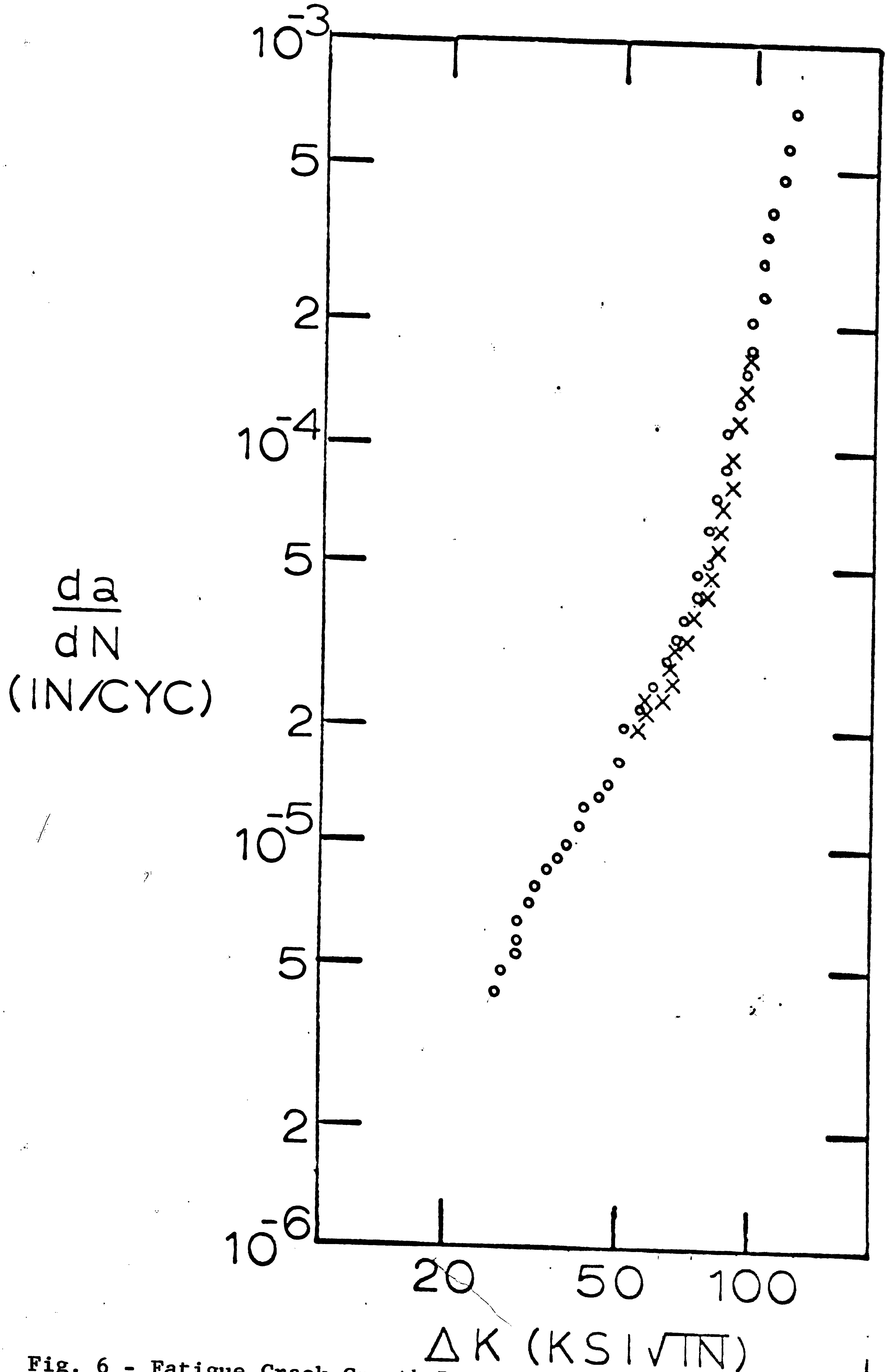

Fig. 6 - Fatigue Crack Growth Rates In T-1 Steel Under High Stress Intensity, Low Net Section Stress Conditions.

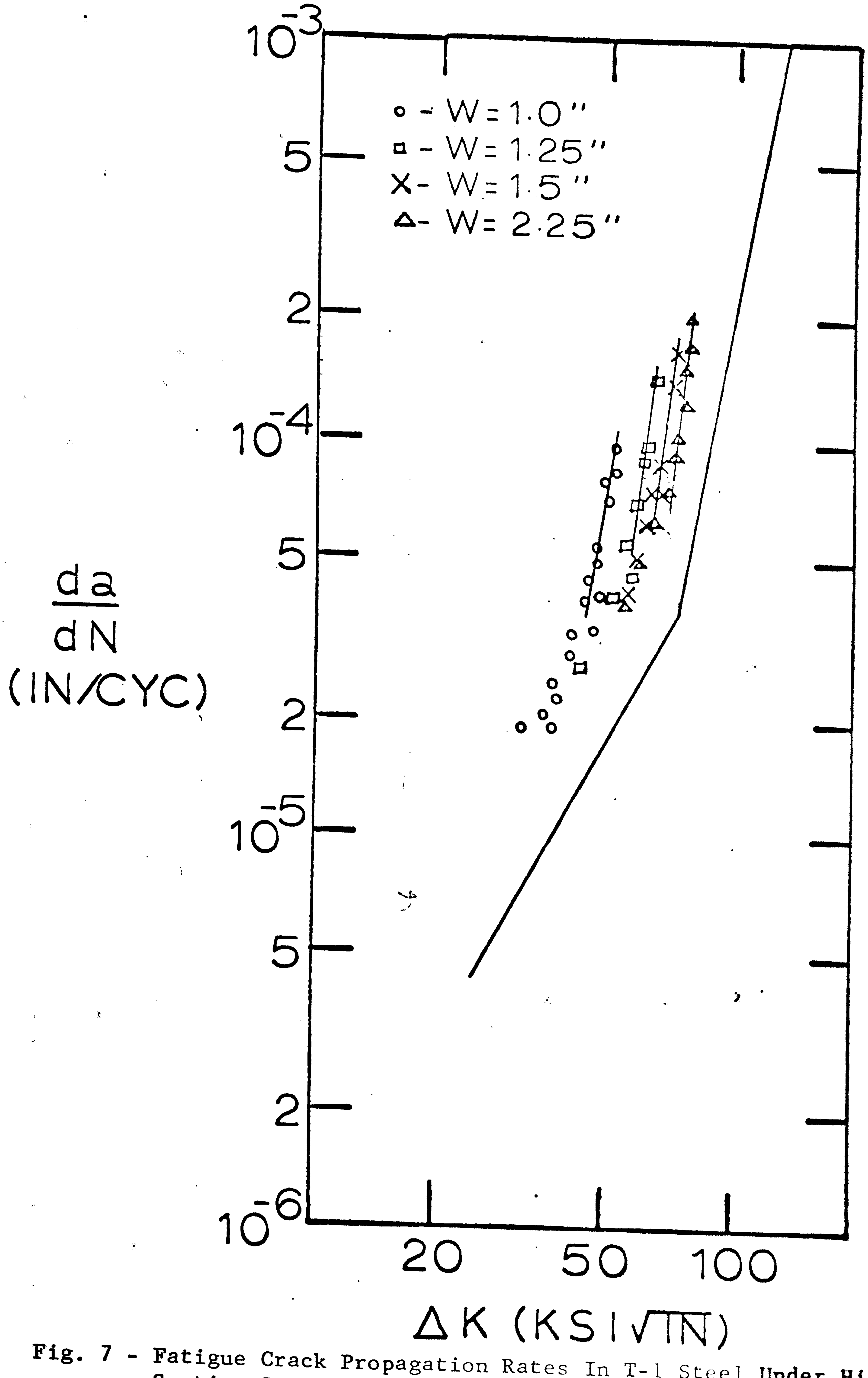

Fig. 7 - **Fatigue Crack Propagation** Rates In T-1 Steel **Under High Net Section Stress Conditions.** Data Obtained From **Specimens With Different Widths.**

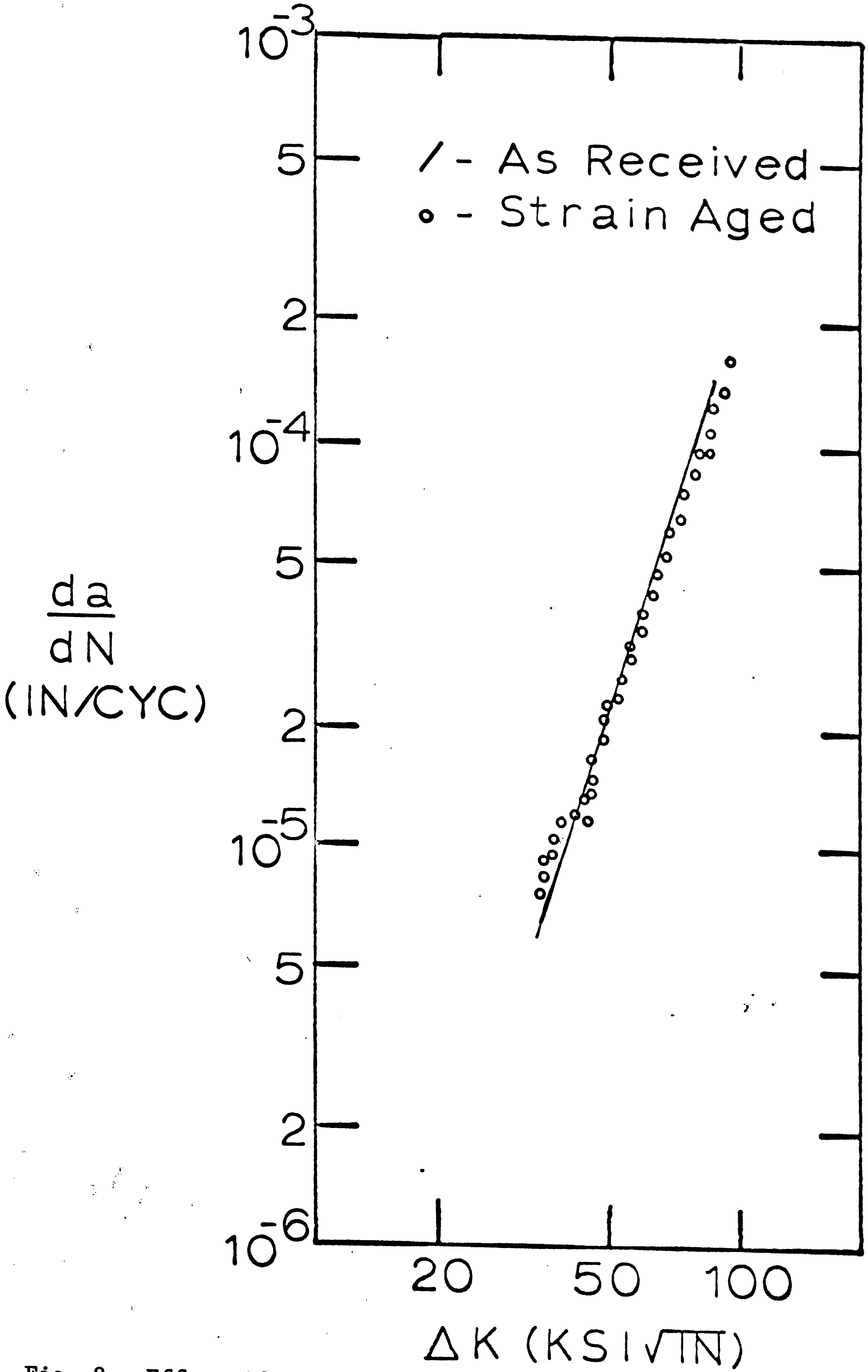

Fig. 8 - **Effect Of Strain** Aging On Fatigue Crack Growth **Rates In AX-90** Weld Metal.

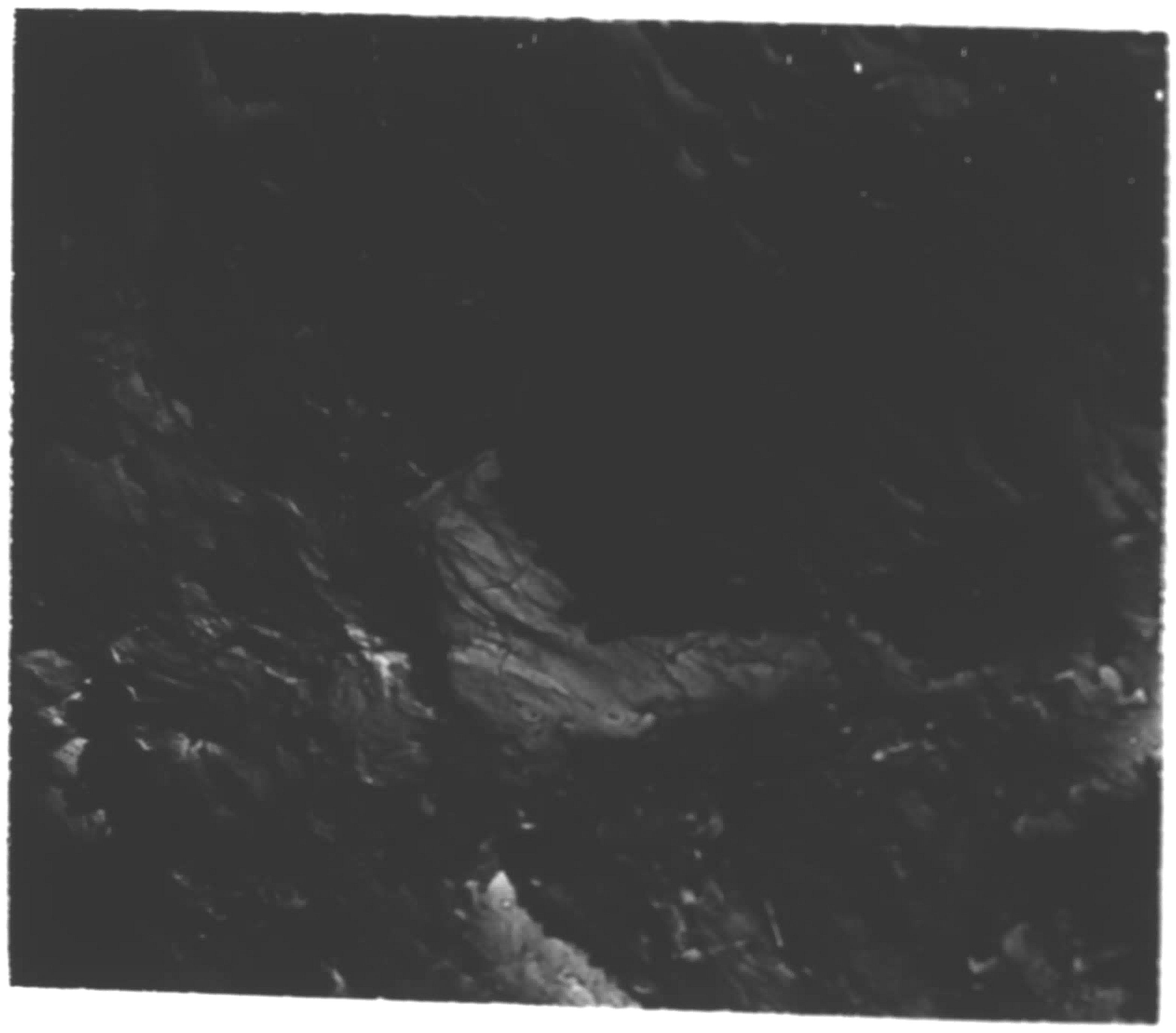

Fig. 9 - Typical Appearance Of A Fatigue Surface Of T-1 Steel Associated With A Macroscopic Growth Rate Of 7 x 10^{-6} in/cycle. MAG: 11,700X.

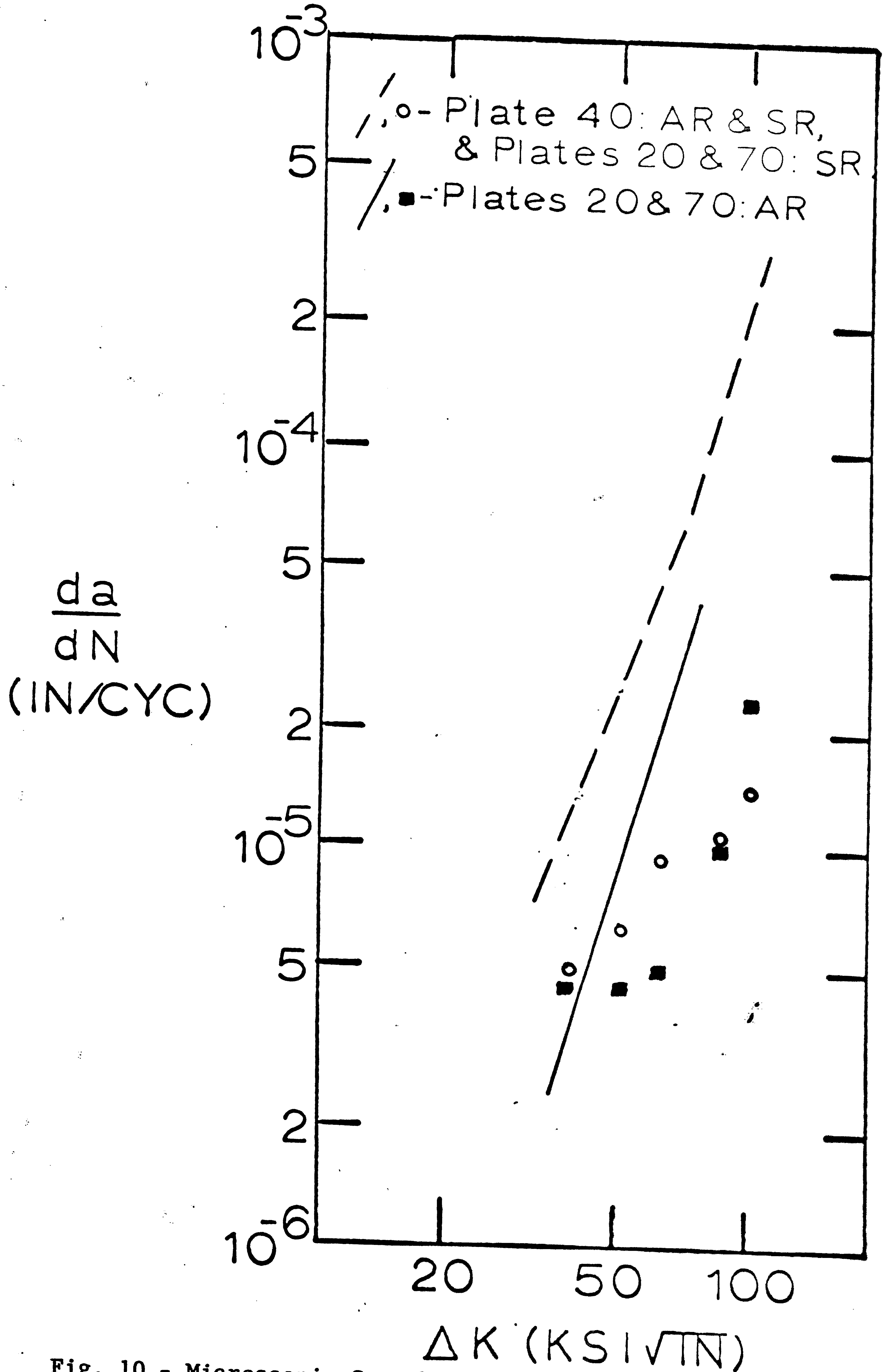

Fig. 10 - Microscopic Growth Rates At Various Levels Of Applied Stress Intensity Range.

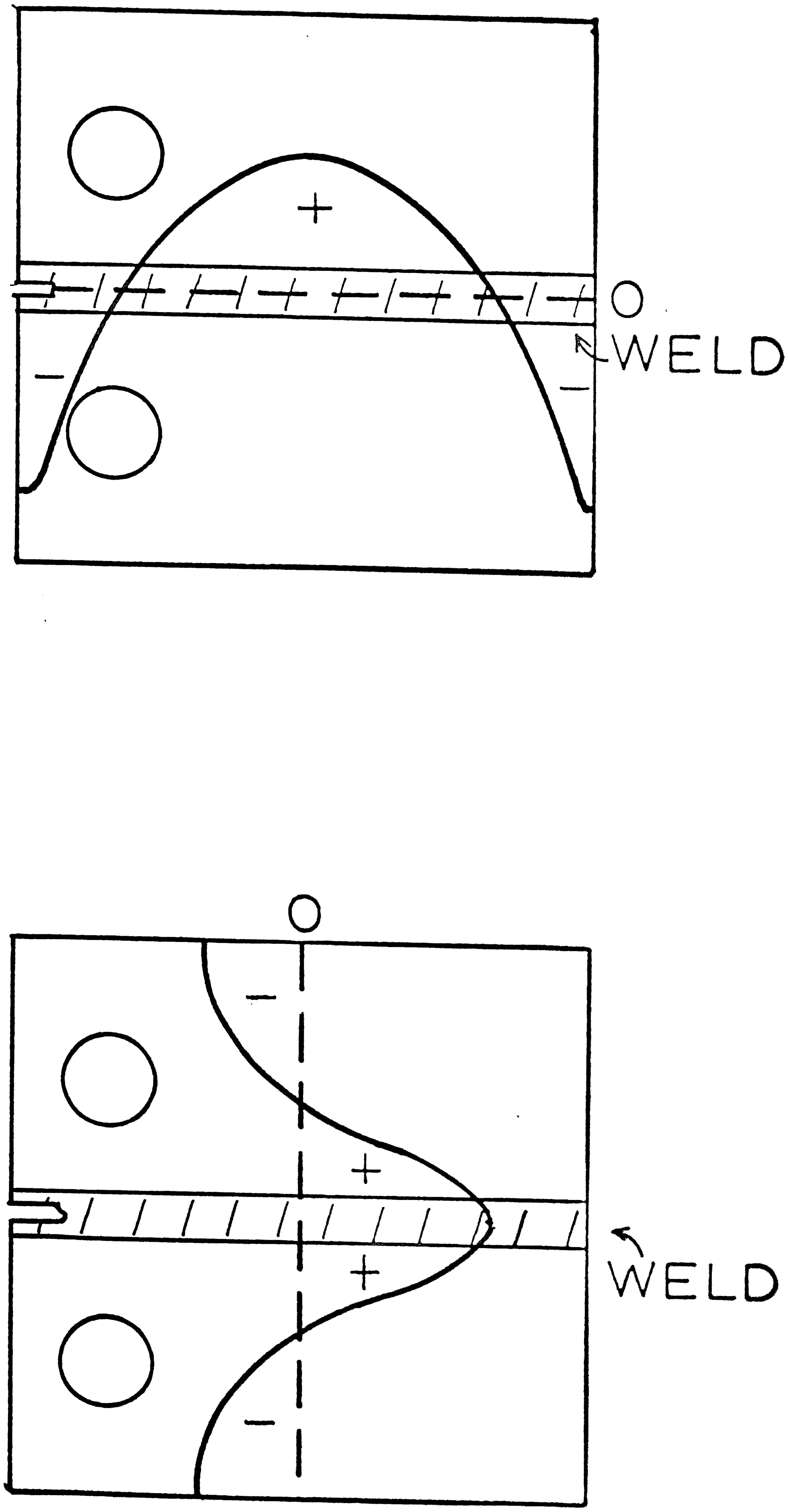

Fig. 11 - Residual Stress Patterns In The Neighborhood Of A Typical Butt Weld.

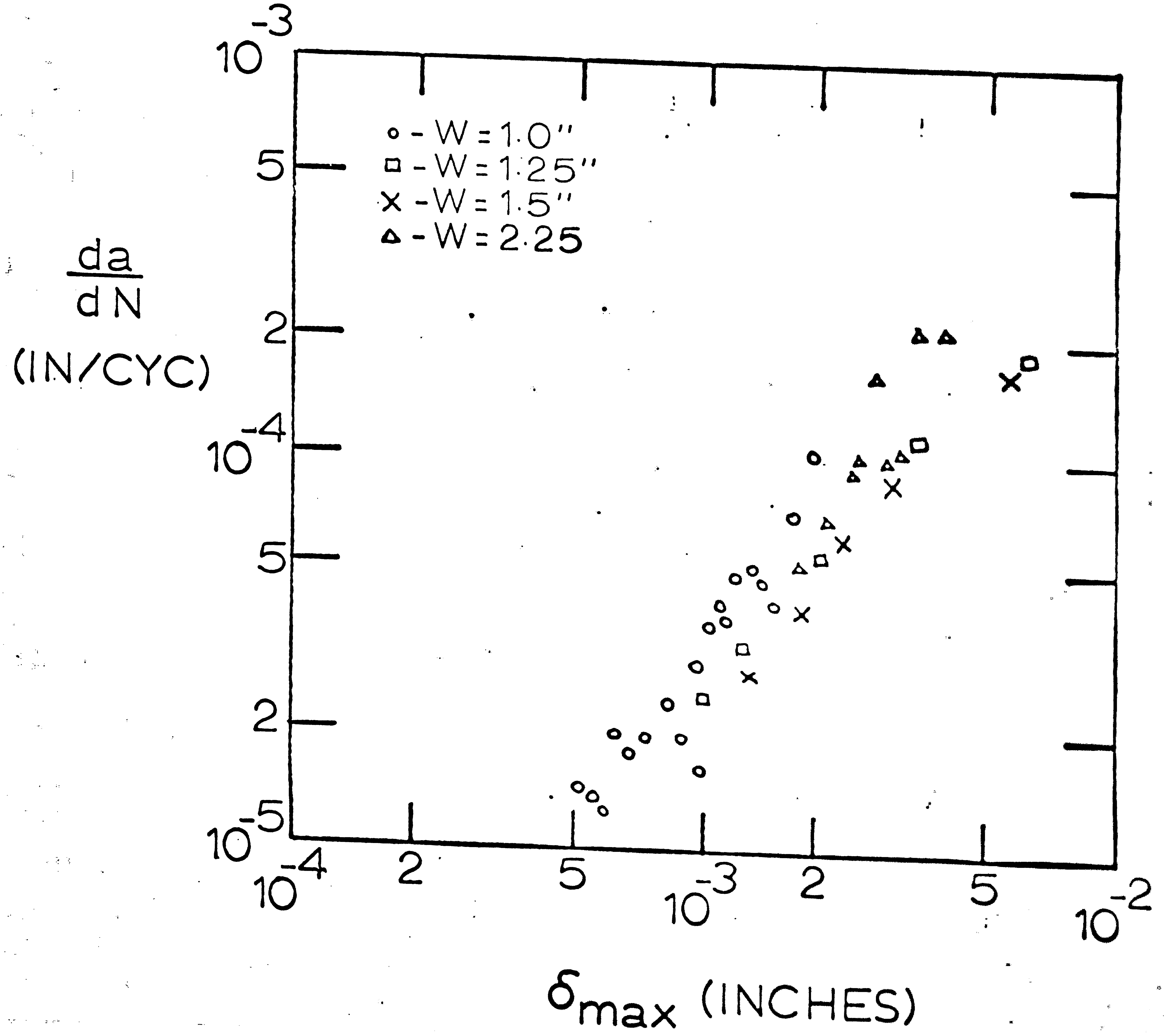

Fig. 12 - Growth Rate vs. Maximum Crack Opening Displacement Under High Stress Conditions.

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