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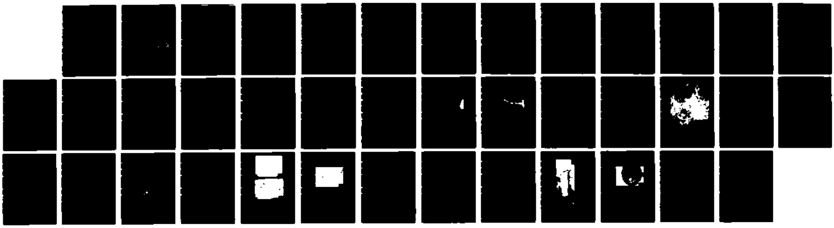

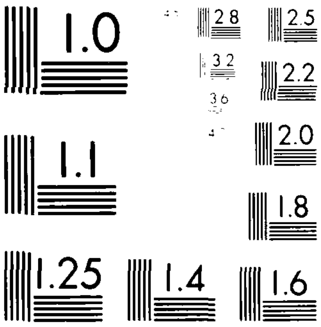

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REPORT DOCUMENTATION PAGE

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1. REPORT NUMBER **AFOSR-TR- 86-0224**	2. GOVT ACCESSION NO. ADA170199	3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle) A Study of the Fatigue Behavior Short Cracks in Nickel-Base Superalloys		5. TYPE OF REPORT & PERIOD COVERED Progress Report 1/1/84-11/30/85
		6. PERFORMING ORG. REPORT NUMBER
7. AUTHOR(s) R.M. Pelloux G.R. Romanoski J. Feng		8. CONTRACT OR GRANT NUMBER(s) AFOSR 84-0075
9. PERFORMING ORGANIZATION NAME AND ADDRESS Massachusetts Institute of Technology Cambridge, MA 02139		10. PROGRAM ELEMENT PROJECT, TASK AREA & WORK UNIT NUMBERS 2306/A1 PE 61102F
11. CONTROLLING OFFICE NAME AND ADDRESS Air Force Office of Scientific Research /NE Bolling Air Force Base, DC 20332		12. REPORT DATE November 1985
		13. NUMBER OF PAGES 33
14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office) Same as #11		15. SECURITY CLASS. (of this report) unclassified
		15a. DECLASSIFICATION DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

approved for public release - distribution unlimited

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20,

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18. SUPPLEMENTARY NOTES

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

superalloys, high temperature, fatigue, short cracks, thresholds

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

The fatigue of behavior of short cracks has been studied in Inconel X-750, Inconel 718, Waspaloy and PM-Rene' 95. Crack growth rates have been measured for crack lengths from ~50μm to ~2mm. Three regimes of behavior are observed: 1)an initiation regime in which crack propagation rate is nearly zero, 2) a short crack regime in which crack propagation rate increases slowly and variably with crack length but with a propagation rate higher than would be predicted by LEFM in the near-threshold regime and 3) a long crack regime in which conventional fracture mechanics is applicable.

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The threshold criterion and crack propagation rates were shown to be strongly dependent on the stress ratio. The work includes extensive fractographic analysis.

AFOSR-TR- 86-0224

PROGRESS REPORT

A STUDY OF THE FATIGUE BEHAVIOR OF SHORT CRACKS IN NICKEL-BASE SUPERALLOYS

Submitted to

AFOSR - 76 - 2928 + AFOSR 84-0075

Work performed from January 1, 1984-November 30, 1985

by

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ABSTRACT

The fatigue behavior of short cracks, ~~has~~ been studied in Inconel X-750, Inconel 718, Waspaloy and PM-Rene' 95. Crack growth rates have been measured for crack lengths from 50µm to 2mm. Three regimes of behavior are generally observed: 1) an initiation regime in which crack propagation rates are nearly zero; 2) a short crack regime in which crack propagation rates increase slowly and variably with crack length but with propagation rates higher than would be predicted by LEFM in the near-threshold regime, and 3) a long crack regime in which conventional fracture mechanics is applicable.

The threshold criterion and crack propagation rates for short cracks are shown to be strongly dependent on the stress ratio. Negative stress ratios promotes rapid crack initiation. This behavior is confirmed theoretically by a Dugdale model which establishes a criterion for crack extension based on the accumulation of plastic work in the crack tip plastic zone.

Extensive fractographic investigations shows that short cracks propagate in a transgranular-crystallographic mode following a zig-zag path which is macroscopically perpendicular to the applied stress.

An experimental technique was developed to generate small elliptical crack initiation sites using a pulsed Nd-YAG laser. An A.C. potential drop system for continuous and automated measurements of crack length at elevated temperature has been assembled. The system is being developed in parallel with the ongoing study which uses the plastic replica technique for the measurement of crack length.

I. Introduction

Gas turbine disks are regarded as the most critical flight safety components of high performance jet engines. Presently, turbine disks are designed on the basis of a low-cycle fatigue (LCF) life limitation criterion. This LCF criterion tends to be conservative since it "builds in" a futher life margin associated with crack propagation. Hence, there is considerable economic incentive to extend engine service lives by combining crack initiation and crack propagation criteria in life prediction methodologies of turbine disks.

Some materials are subject to premature crack initiation due to handling damage, fretting and intrinsic defects such as porosity and inclusions found in powder metallurgy (PM) alloys. Given initial or premature cracking, it is necessary to employ a defect-tolerant design approach to assure adequate crack propagation lives from small initial defects and/or cracks.

To achieve either of the two goals described above, extending lives of LCF damaged disks or assuring safe lives for defect-containing disks, requires the application of a fracture mechanics type approach to very short cracks. This entails the determination of threshold criteria and fatigue crack growth rates for short cracks. It has been shown that the fatigue behavior of short cracks cannot be described accurately by conventional linear elastic fracture mechanics (LEFM). More specifically it was found that short cracks propagate below the threshold values predicted by LEFM and that their growth rates are faster than that of long cracks. Furthermore, the threshold values of the stress intensity range (ΔK_{th}) for short cracks was shown to be a strong function of the crack length, the applied stress range, the load ratio (R) and the microstructure of the material considered.

Due to the very high operating stresses in gas turbine disks, critical crack sizes are on the order of 1-2mm. Initial crack sizes associated with defects are on the order of 25 to 50μm. Consequently, crack propagation lives for disks involve the crack length regime from about 25μm to 2mm.

The materials presently being studied in this investigation include: Inconel X-750, Inconel 718, Waspaloy, PM-Rene' 95 and PM-IN100. All, with the exception of Inconel X-750 are currently being used as materials for fast turbine disks. Inconel 718 is a γ-γ' nickel-base superalloy. The other materials are γ-γ nickel-base superalloys which rely on the precipitation of the ordered γ phase for strengthening at elevated temperatures. At disk-relevant temperatures these precipitates promote planar slip which strongly influences the physical nature of crack initiation and crack propagation. Values of ΔK_{th} for long cracks are characteristically 7-8 MPa$\sqrt{m}$ for these materials. They also have a tendency to be creep brittle under sustained load crack extension.

The goal of this research is to acquire crack propagation data for disk materials over the relevant crack length regime and loading conditions, and to attempt to quantify the observed behavior through mechanistically based modelling.

More specifically the objectives include:

1.) The measurement of fatigue crack growth rates of short cracks in the low crack growth rate regime.

2.) The determination of the threshold stress range and/or threshold stress intensity range ΔK for nonpropagating fatigue cracks.

3.) The study of the effect of temperature and environment on short cracks in the near threshold regime.

4.) The study of the effect of R-ratio on crack growth rates.

5.) A determination of the conditions under which a short fatigue crack will be different from a long fatigue crack.

II. Summary of Work

A. Fatigue propagation of short cracks at room temperature.

The room temperature fatigue behavior of short cracks has been investigated for Inconel X-750, Inconel 718, Waspaloy and PM-Rene' 95 doped with ceramic inclusions. The test variables considered were primarily stress range and stress ratio. The data are summarized in Table I.

Inconel X-750

Cracks were initated at small hemispherical pits produced by electro-discharge machining (EDM). Crack lengths were measured by the plastic replica technique. This study examined the effect of R-ratio on short crack growth behavior. In particular, the effects of compressive stresses was studied thoroughly. The threshold stress ranges for crack growth ($da/dN = 10^{-11}$ m/cycle) at a given R-ratio and crack length were determined. ΔK_{th} for short cracks was found to depend on the R-ratio as shown in Figure I. This behavior has been modelled and will be discussed in a later section. Faster crack growth rates were observed for short cracks than would be predicted by application of LEFM using available long crack data.

Fractographic examinations revealed that short cracks propagate in a transgranular crystallographic mode following a zig-zag path which is macroscopically perpendicular to the applied stress. Microscopically, cracks extended by a shear mechanism along favorably oriented crystallographic planes and twin boundaries as shown in Figure 2.

Waspaloy

Cracks were initiated at small hemispherical pits produced by EDM. Crack lengths were measured by the plastic replica technique. The experimental variables were stress range and R-ratio. Short cracks propagated along a transgranular crystallographic path by a shear decohesion mechanism. The microstructure was of the duplex type as can be seen in Figure 3. Crack growth rates were observed to be faster in the large grains compared to smaller grains. The resulting variablilty can be seen in Figure 4 where crack growth rate is plotted against crack depth for a stress range of $\approx$70Ksi. The corresponding plots of crack growth rate versus ΔK can be seen in Figure 5.

Experiments are also being performed in which laser induced defects are employed as crack initiation sites (see Figure 6). This permits lower values of ΔK for a given stress range.

PM-Rene' 95

Cracks were initiated at Al_2O_3 particles of approximately 20μm in diameter which were intentionally added to the metal powder before consolidation. Crack lengths were measured by the plastic replica technique. The experimental variables were stress range and R-ratio. Three regimes of crack growth behavior were observed: 1.) an initiation regime in which crack propagation rate is nearly zero, 2.) a small crack regime in which crack propagation rate increases slowly and variably with crack length, but with a propagation rate higher than would be predicted by LEFM in the threshold regime and 3.) a long crack regime in which conventional fracture mechanics is applicable.

The initiation regime is strongly influenced by the stress ratio as can be seen in Figure 7. R=-1 loading conditions resulted in the shortest initiation life and total fatigue life, whereas R=0.5 loading conditions resulted in the longest initiation life and total fatigue life for similar initial defect sizes. Higher values of maximum stress also promote early initiation.

Figures 8 and 9 show the variation in crack propagation rate with crack depth and ΔK, respectively. The propagation rate of small cracks, especially for the stress range ±110Ksi, drops to a minimum as crack depth approaches 80μm. This is probably due to a crack closure effect. Note the grain size is 3μm for this alloy.

Figure 10 compares long crack data for R=0.1 with our small crack data for R=0. The long crack curve for R=0 would be expected to be in a position slightly displaced to the right of that for R=0.1. As shown in Figure 10, the small crack data are distributed along the threshold area of the long crack curve but have a faster more variable propagation rate.

In Figure 11 the results of test 1 with R=-1 and $\Delta\sigma = \pm 70$Ksi are compared to that of test 2 with R=-1 and $\Delta\sigma = \pm 110$Ksi. It can be seen that ΔK correlates crack growth rates to account for differences in stress range.

In Figure 12 data from tests with different R-ratios are superimposed. Crack growth rates for a given value of ΔK rank according to R-ratio. R=-1 yields the highest crack growth rates and R=0.5 the lowest for the test conditions considered.

A fractographic investigation revealed the fracture path to be transgranular and crystallographic as shown in Figure 13. Cracks were observed to be open at the intersection with the specimen surface at zero load as seen in Figure 14. This suggests that crack closure is occuring at asperities on the fracture surfaces. A more detailed study is being made of this phenomenon.

Inconel 718

Experiments were performed on bending fatigue specimens made from Inconel 718 sheet. Micro-cracks initiated at persistent slip bands and propagated by an incremental shearing mechanism which also involved linkage of micro-cracks. Crack lengths were measured by the plastic replica technique. An S-N curve was also determined. An attempt is being made to relate the micro-crack growth rate to the S-N curve. Tests will also be performed on longitudinal specimens with artificial defects.

B. Modelling of short crack behavior by the Dugdale Model

A model for the propagation of small surface fatigue cracks has been developed. The criterion for crack extension is based on the accumulation of plastic strains within the plastic zone. The Dugdale analysis is applied to calculate the crack tip opening displacement and plastic zone size at the crack tip. The theoretical curves predict the general trends in crack propagation rate for PM-Rene' 95.

The final expression for crack propagation rate is given by

$$\frac{da}{dN} = \frac{4f\sigma_0^2}{\pi E U_c} \ln\left[\sec\left(\frac{\pi\sigma_\infty}{2\sigma_0}\right)\right](a + R_P)R_P$$

where:

σ_∞ = applied external stress

σ_0 = flow stress in the plastic zone

a = crack depth

R_P = plastic zone size

Uc = critical energy to produce one unit area of crack

f = plastic zone shape factor

= free volume undergoing plastic work

assumes triangular volume undergoing plastic work

A comparison between predicted behavior and experimental data is shown in Figure 15.

The above model was further developed to describe the R-ratio effect on the threshold stress for non-propagation (da/dN = 10^{11} m/cycle) of short cracks in Inconel X-750. The mode II component of CTOD was considered in addition to the plastic work done in the crack tip plastic zone. The threshold stress range calculated by this model is shown as a function of R-ratio in Figure 16. The agreement with experimentally determined values is quite good.

C. Fatigue propagation of short cracks at elevated temperature

Our initial thrust in the elevated temperature program has been to develop an AC potential drop system capable of continuous and automated measurement of crack length. The complete system has been purchased and assembled. In developing a calibration curve for the system a problem has been encountered in the long term stability of the potential measurements. In view of the complexity of this problem, elevated temperature tests were begun using the plastic relica technique to measure crack length. Further development of the AC potential drop system will be carried out in parallel with elevated temperature testing.

Waspaloy

Short crack growth rates are currently being measured in Waspaloy at 800°F. The material was taken from the same lot as that used in the room temperature study. Micro-cracks are being initiated at laser induced defects. This technique will permit near threshold values of ΔK even for high values of the stress range. Test conditions are being chosen to match those used for the room temperature study.

Short crack growth rates have been measured for a stress range of ±70Ksi and an R-ratio of -1. The results are shown in Figure 17 where crack growth rates are plotted against ΔK. This data is nearly coincident with the upper bound of the data obtained at room temperature.

Fractographic evidence suggests that the same mechanism of crack extension that was observed at room temperature is also operative at 800°F.

IN 100(PM)

A powder metallurgy IN100 gas tubine disk has been obtained form Pratt and Whitney. Specimens are being fabricated.

D. Test Procedures

Due to the experimental difficulties inherent in the study of the fatigue behavior of short cracks, considerable effort has been invested in devleloping experimental techniques.

Initiation of Short Cracks

Two considerations dictate the solution of a technique for initiating micro-cracks. (1.) Due to the statistical nature of short cracks, the probability of having a characteristically maximum size defect intersecting the surface of the gauge section of a laboratory test specimen is small. (2.) Measuring short crack lengths is experimentally difficult. However, this task can be greatly facilitated by knowing their locations.

The desired defect geometry is that which is conducive to crack initiation at the smallest possible defect size. Such a pseudo-crack should have a sharp crack tip radius and be oriented normal to the principal applied stress. The process employed to produce defects must not induce significant residual stresses or other microstructural damage.

The above objectives were accomplished by using a focused laser pulse from a Nd-YAG laser. Defects were generated by vaporization of the material from a pit. This laser technique has demonstrated many advantages over alternative techniques.

Many alternative approaches for generating short cracks are simply time consuming and expensive. For example, one technique involves propagating a long crack in a specimen and subsequently machining away the crack flanks to leave a remnant short crack.

The use of micro-hardness indentations or small drilled hold yield concerns about residual stresses.

An alternative which has similar characteristics to the laser induced defect is the use of electro-discharge machined (EDM) pits.

This technique also leaves the surrounding matrix free of residual stress but has greater limitations on minimum defect size and defect tip radius.

Figure 18 shows a typical defect produced by the laser technique in a Waspaloy fatigue specimen. This defect geometry is more conducive to crack initiation due to the sharper defect tip radius as compared to an EDM defect of similar pseudo-crack size as shown in Figure 19.

The smaller defect size possible with this technique permits lower calculated values of the stress intensity parameter for any given value of the stress range.

Crack length measurement by plastic replica

The plastic replica technique has been used in the measurement of crack lengths at room temperature and at elevated temperature. This technique has a resolution of about lμm in crack length. In addition, it serves as a valuable record which can be used to correlate crack growth rates with crack tip-microstructural interactions and crack tip orientations. The principal shortcoming of this technique is that it is rather labor intensive and requires interrupting tests to make measurements. At elevated temperature, making a single measurement reguires cooling and reheating of the specimen. This provided the impetus for developing a continuous and automated system for the measurment of short cracks at elevated temperature.

Crack length measurement by A.C. potential drop.

The complete AC potential drop system has been purchased and assembled. The various components and their functions have been described in a previous proposal. Essentially, the system is built around a lock-in frequency amplifier which measures the potential drop across the crack by closely positioned probes. There are two reasons for the high sensitivity made possible by this system; 1.) The skin effect associated with AC conduction. 2.) The lock-in amplifier generates a reference frequency (50 KHz) which oscillates a current driver at the same frequency (50KHz and l amp r.m.s.). The amplifier then accepts for measurment only the potential signal at the reference frequency. This is shown schematically in Figure 20.

We are presently facing a problem with the long term stability of the potential signals. The source of the instability appears to be related to variations in power line conditions and noise in ground loops. Efforts are currently underway to understand and resolve these problems

It was decided that high temperature testing should begin using the plastic replica technique to measure crack length. Further development of the AC potential drop system will be carried out concurrently.

III. Achievements

1.) Developed an experimentally expedient means of initiating short cracks by the laser technique. Through our interaction with Pratt and Whitney, they have adopted this technique to initiate short cracks in disk alloys.

2.) Measurement of short crack growth behavior for more than one hundred cracks in superalloys.

3.) Made initial attempts at modelling short crack behavior.

4.) Have maintained fruitful interactions with General Electric and Pratt and Whitney.

IV. Publications

A Model for Life Prediciton of Nickel-Base Superalloys in High Temperature-Low Cycle Fatigue, G.R. Romanoski, S.D. Antolovich and R.M. Pelloux, Presented at the Sagamore Conference on Low Cycle Fatigue, October 1985.

The Effect of Load-Ratio on the Short Crack Behavior in Inconel X-750, J. Feng, G.R. Romanoski and R.M. Pelloux. To be published.

V. Thesis

J. Feng, Short Cracks in Nickel-Base Superalloys at Room Temperature, Sc.D. thesis, completion June 1986.

G. Romanoski, Short Cracks in Nickel-Base Superalloys at High Temperature, Sc.D. thesis, completion December 1986.

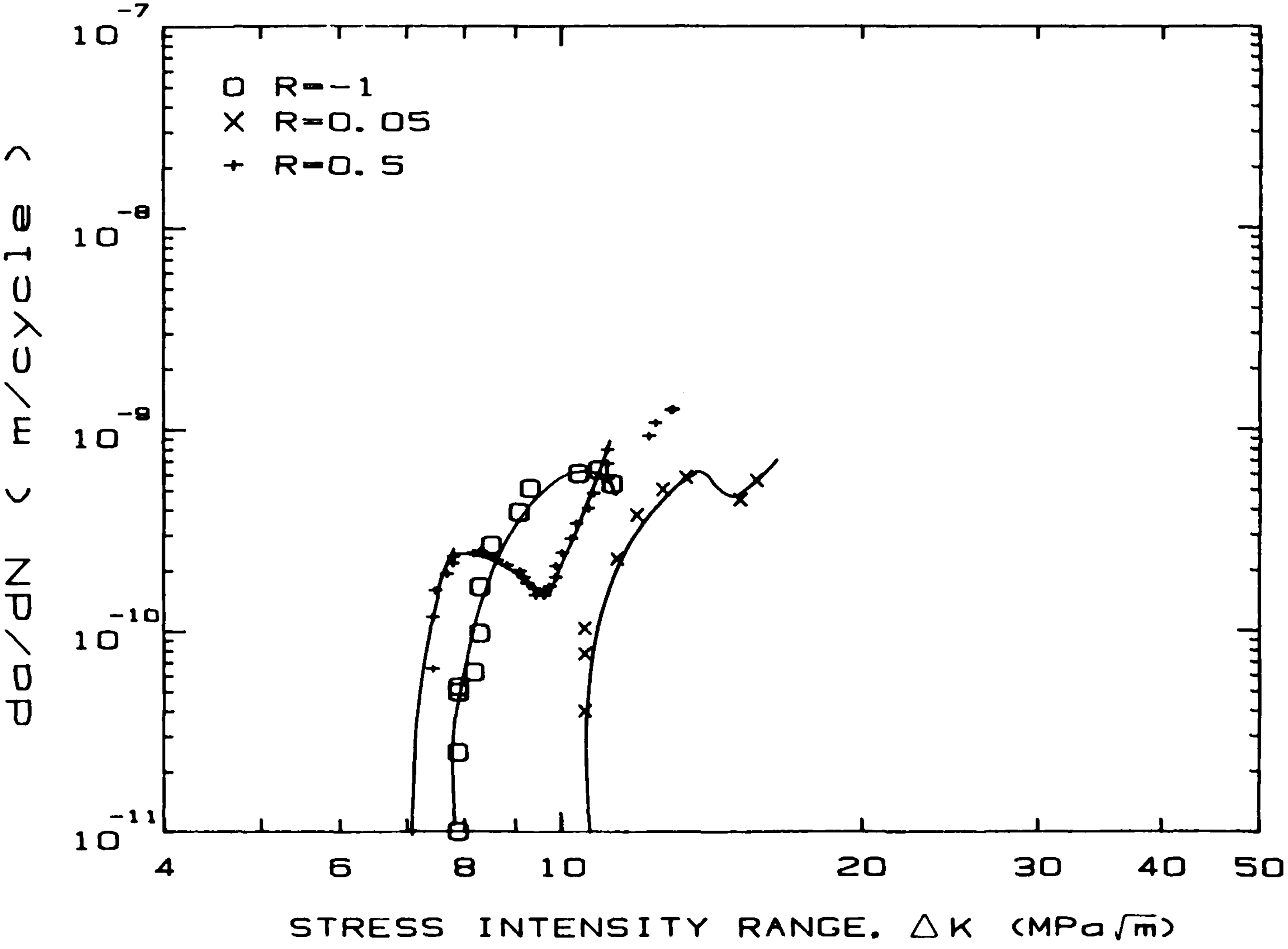

Figure 1. Variation of fatigue crack propagation rate as a function of stress intensity factor range for Inconel X-750 tested at room temperature.

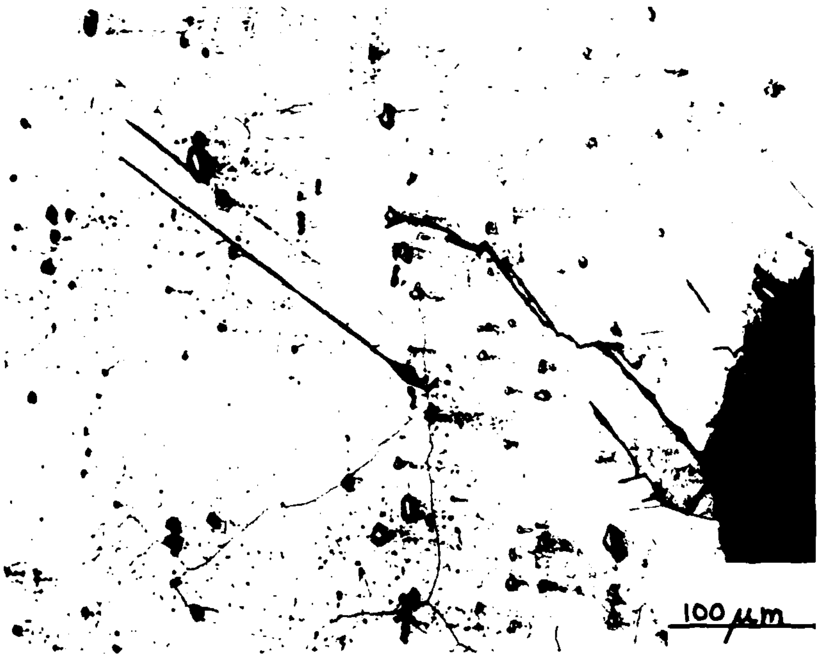

Figure 2. Fatigue cracks emanating from an EDM pit in Inconel X-750 tested at room temperature.

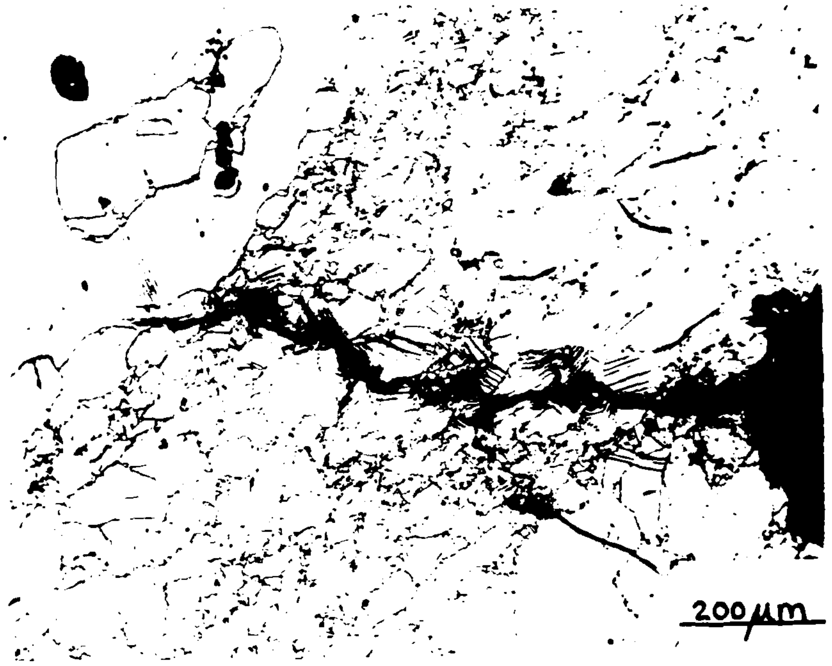

Figure 3. Optical micrograph of fatigue crack emanating from an EDM initiation site in Waspaloy.

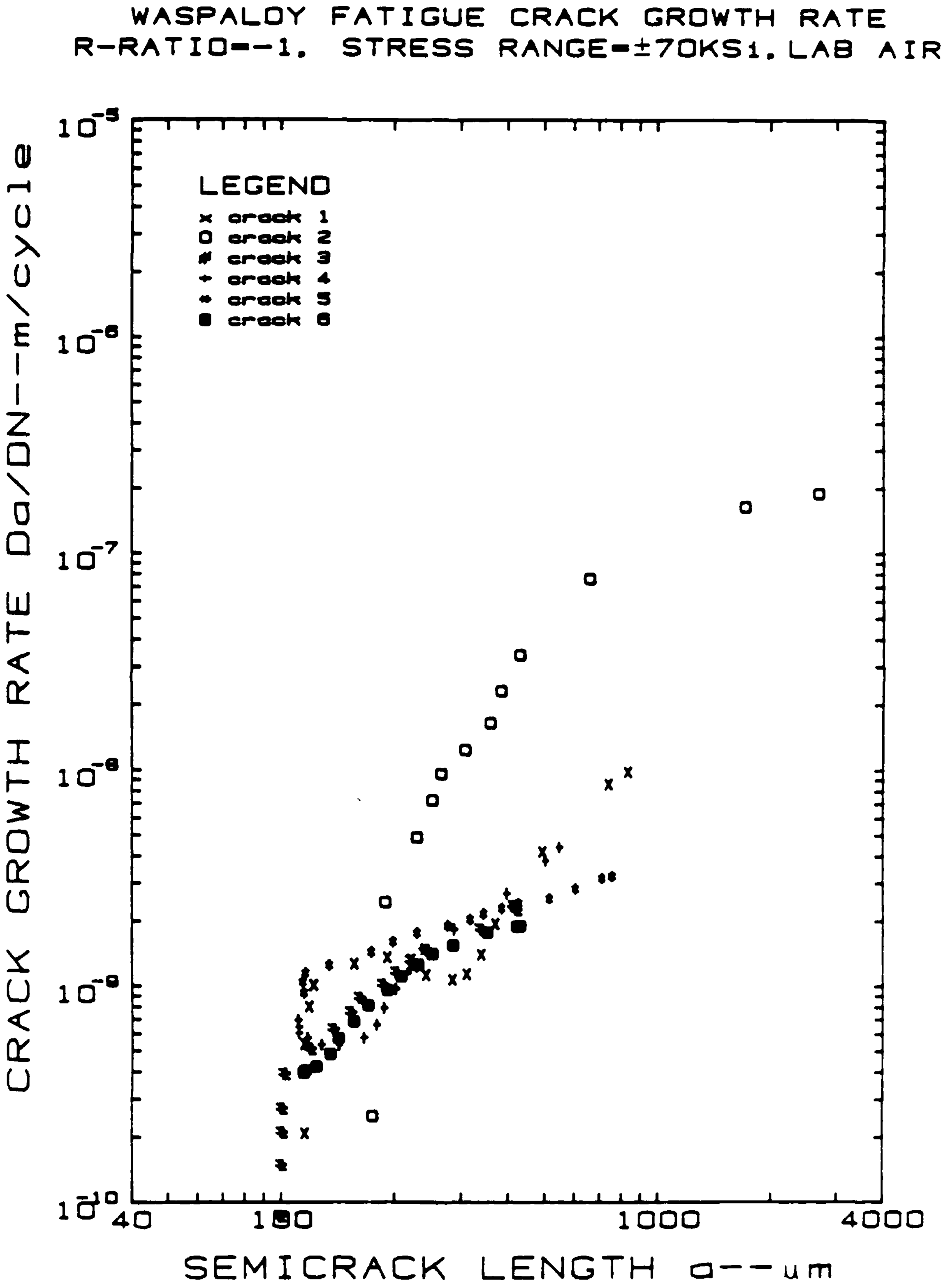

Figure 4. Variation of Fatigue crack propagation rate as a function of semicrack length for Waspaloy tested at room temperature.

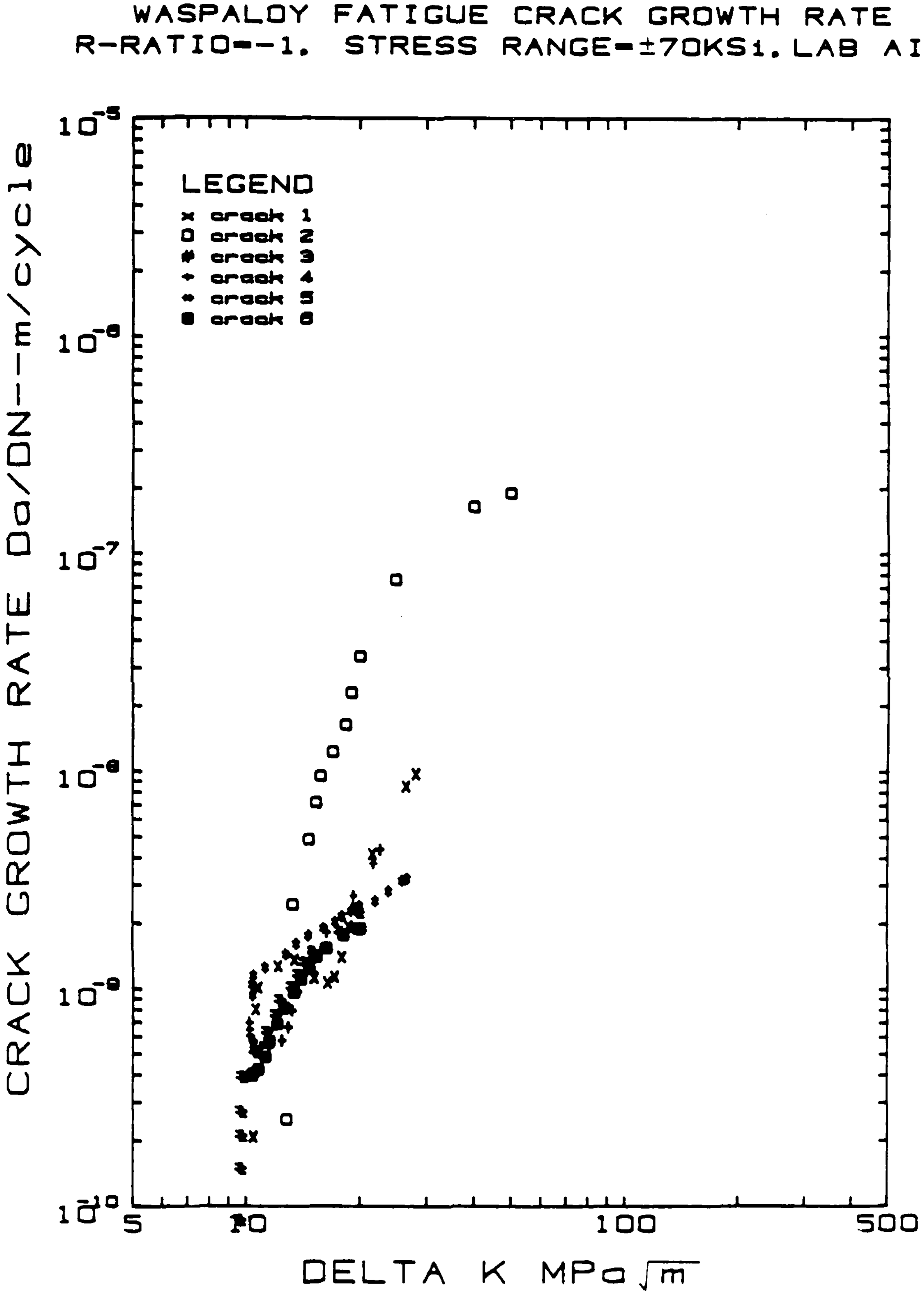

Figure 5. Variation of fatigue crack propagation rate as a function of stress intensity factor range for Wapaloy tested at room temperature.

Figure 6. Laser initiation site in Waspaloy fatigue specimen.

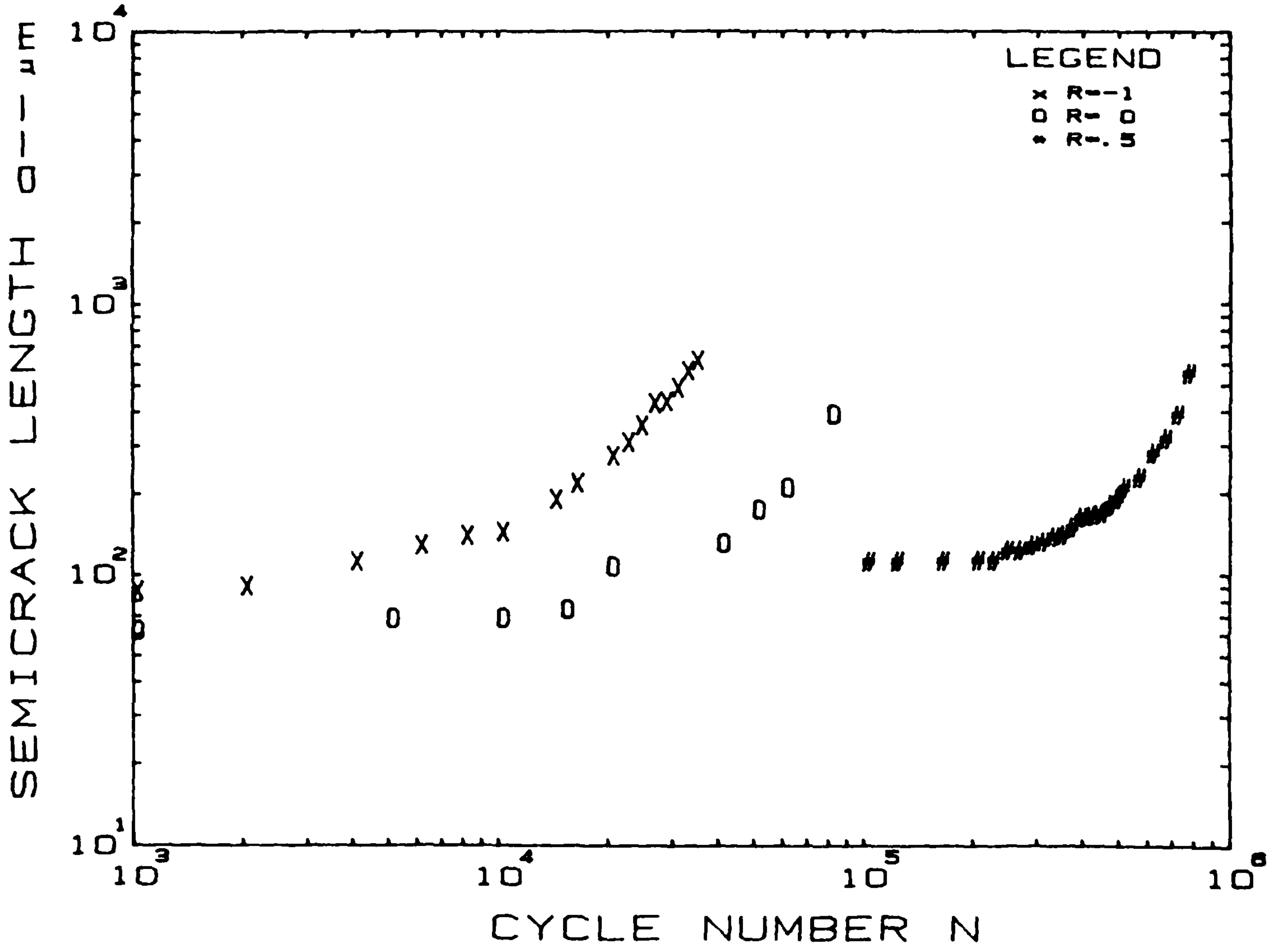

Figure 7. Variation of semicrack length as a function of fatigue cycle number for Rene' 95 tested at room temperature with different R-ratios.

maximum stress= 110 KSi, lab air

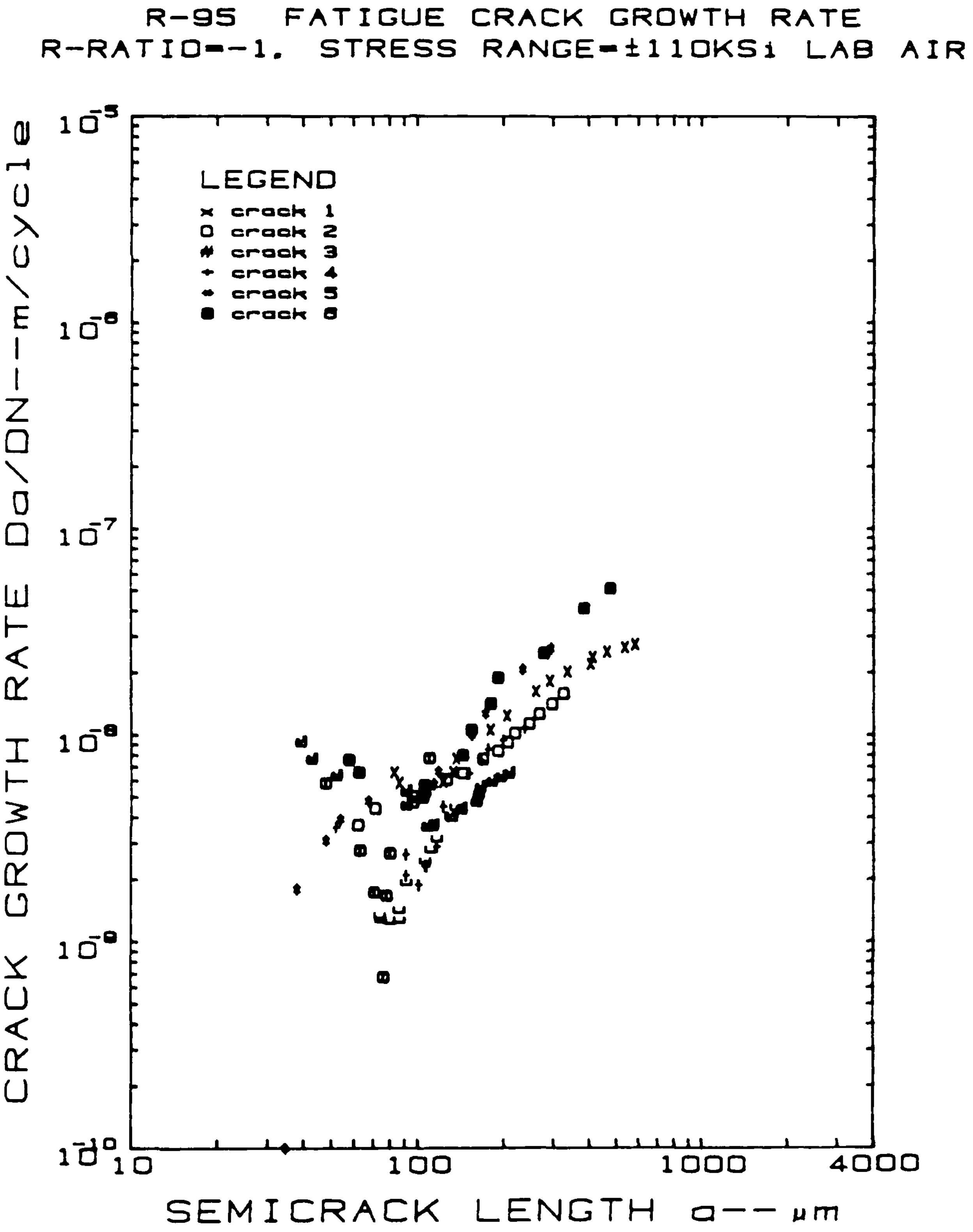

Figure 8. Variation of fatigue crack propagation rate as a function of semicrack length for Rene' 95 tested at room temperature.

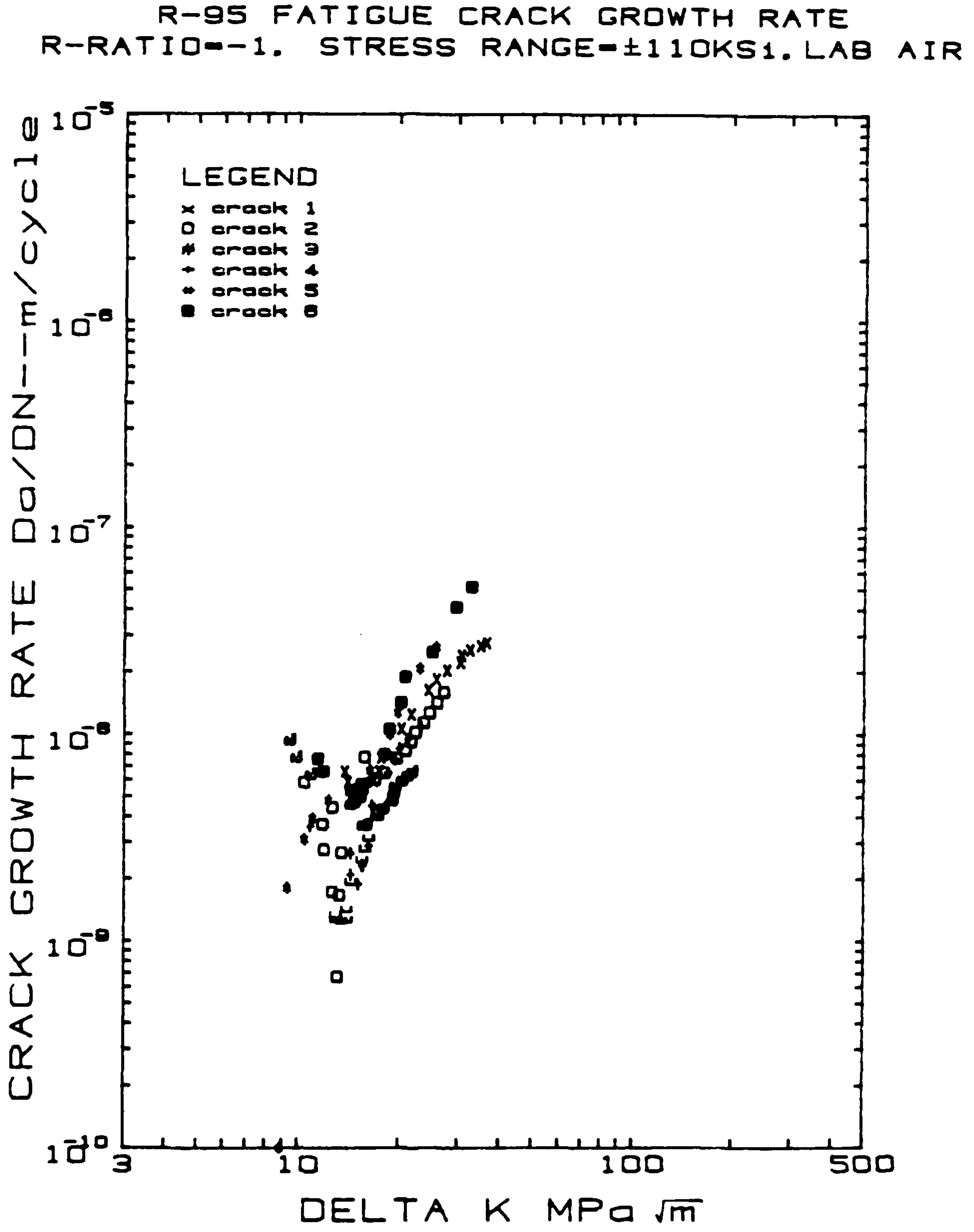

Figure 9. Variation of fatigue crack propagation rate as a function of stress intensity factor range for Rene' 95 tested at room temperature.

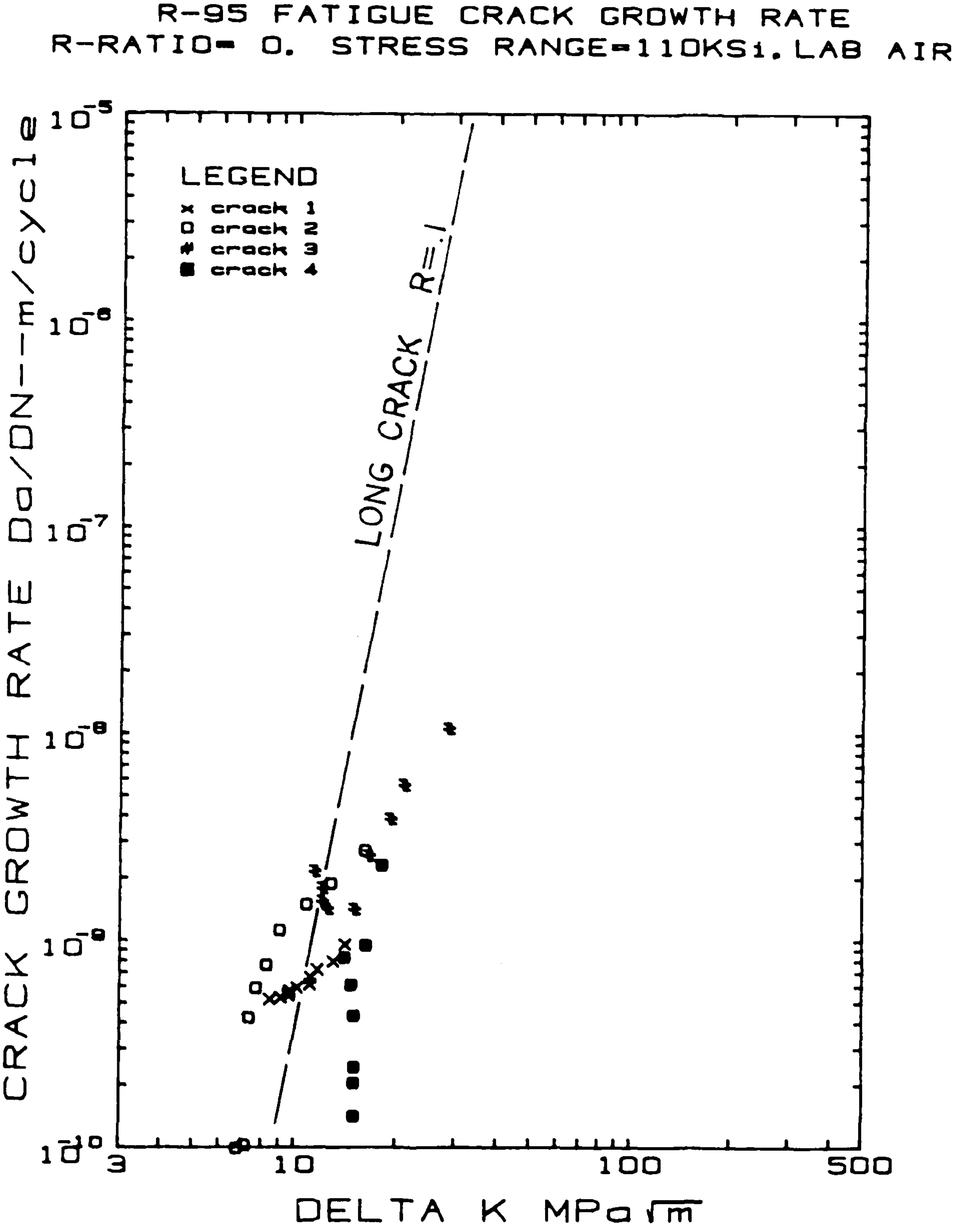

Figure 10. Variation of fatigue crack propagation rate as a function of stress intensity factor range for Rene' 95 tested at room temperature.

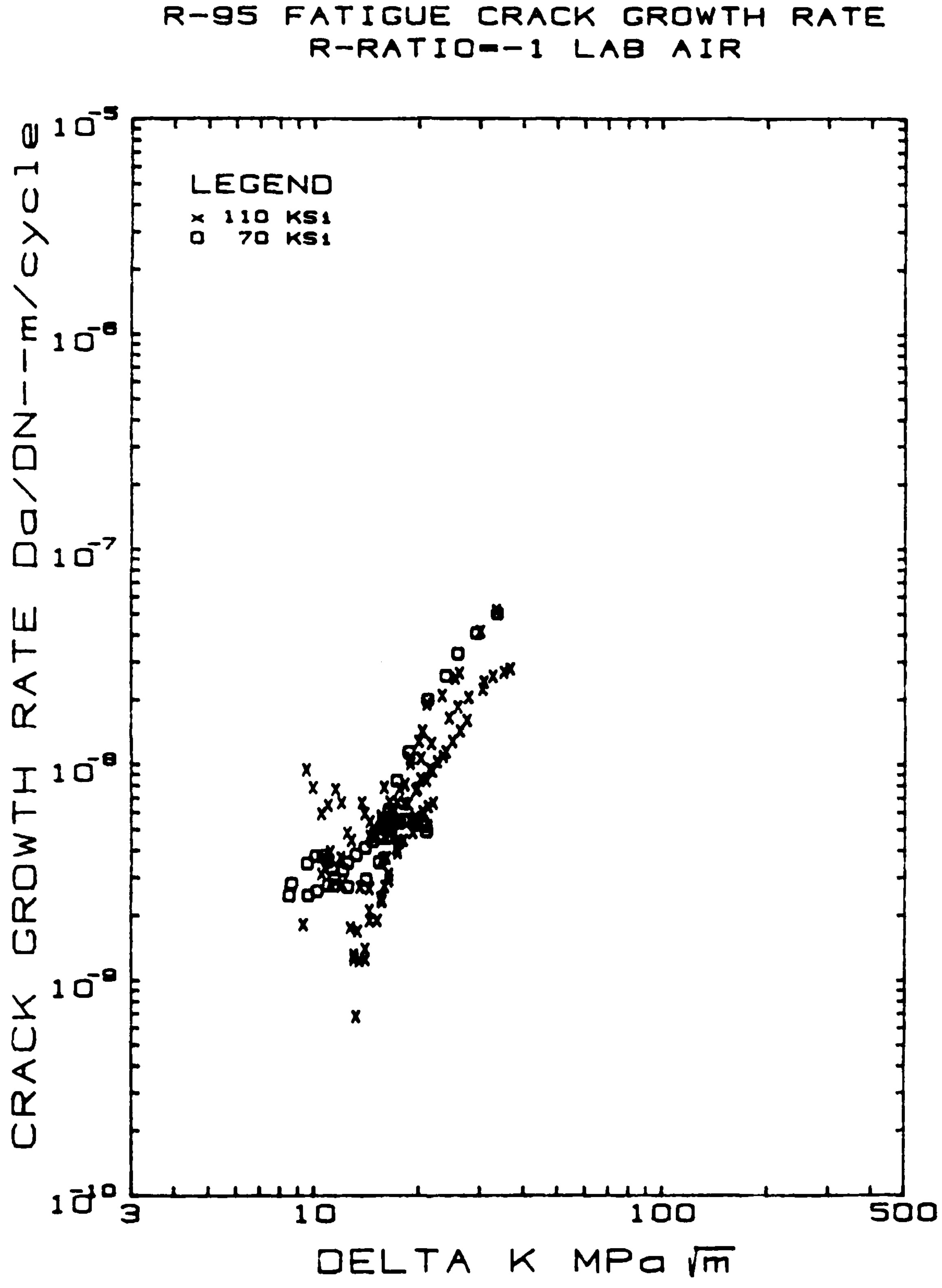

Figure 11. Variation of fatigue crack propagation rate as a function of stress intensity factor range for Rene' 95 tested at room temperature with different stress ranges.

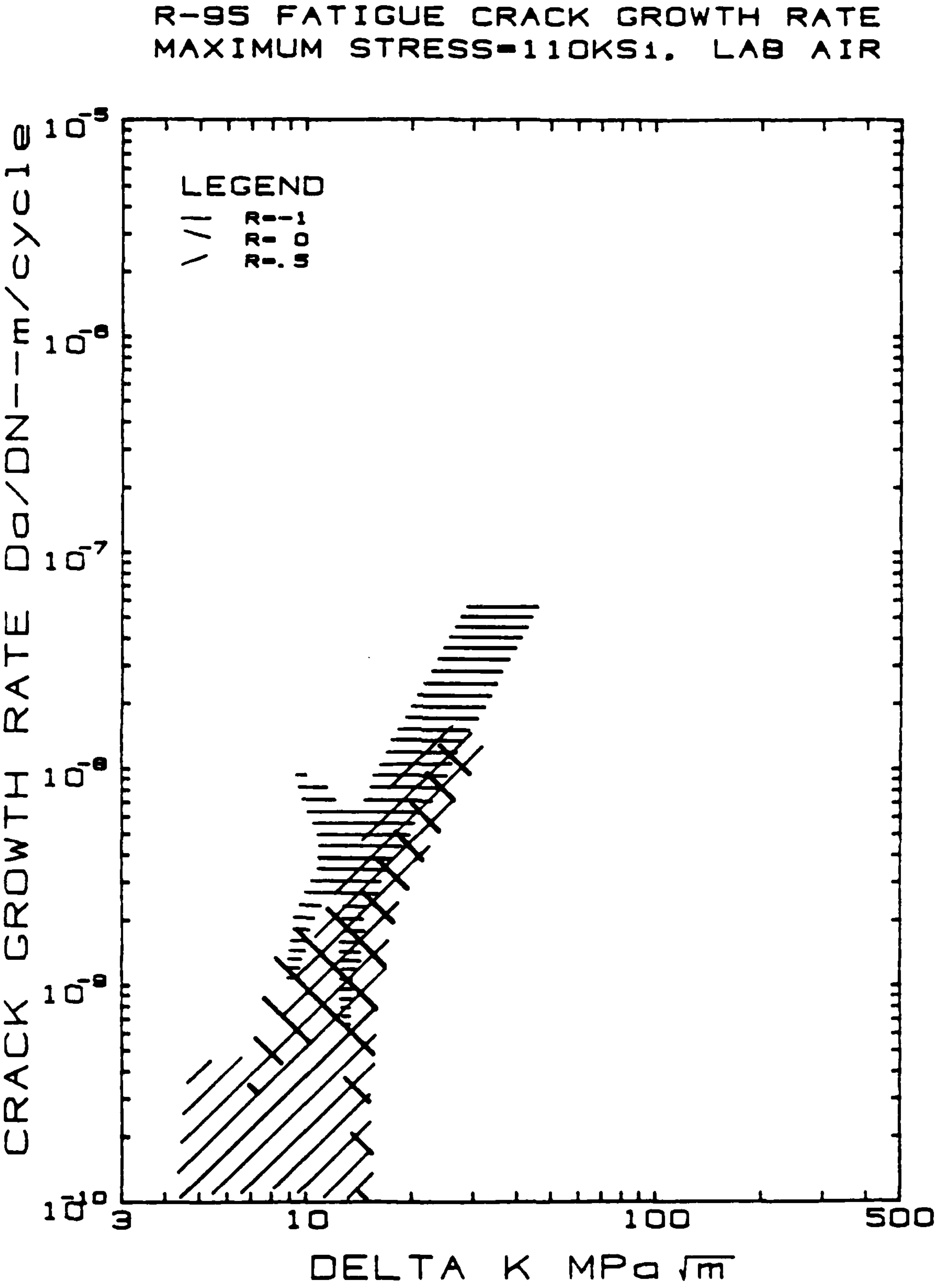

Figure 12. Variation of fatigue crack propagation rate as a function of stress intensity factor range for Rene' 95 tested at room temperature with different R-ratios.

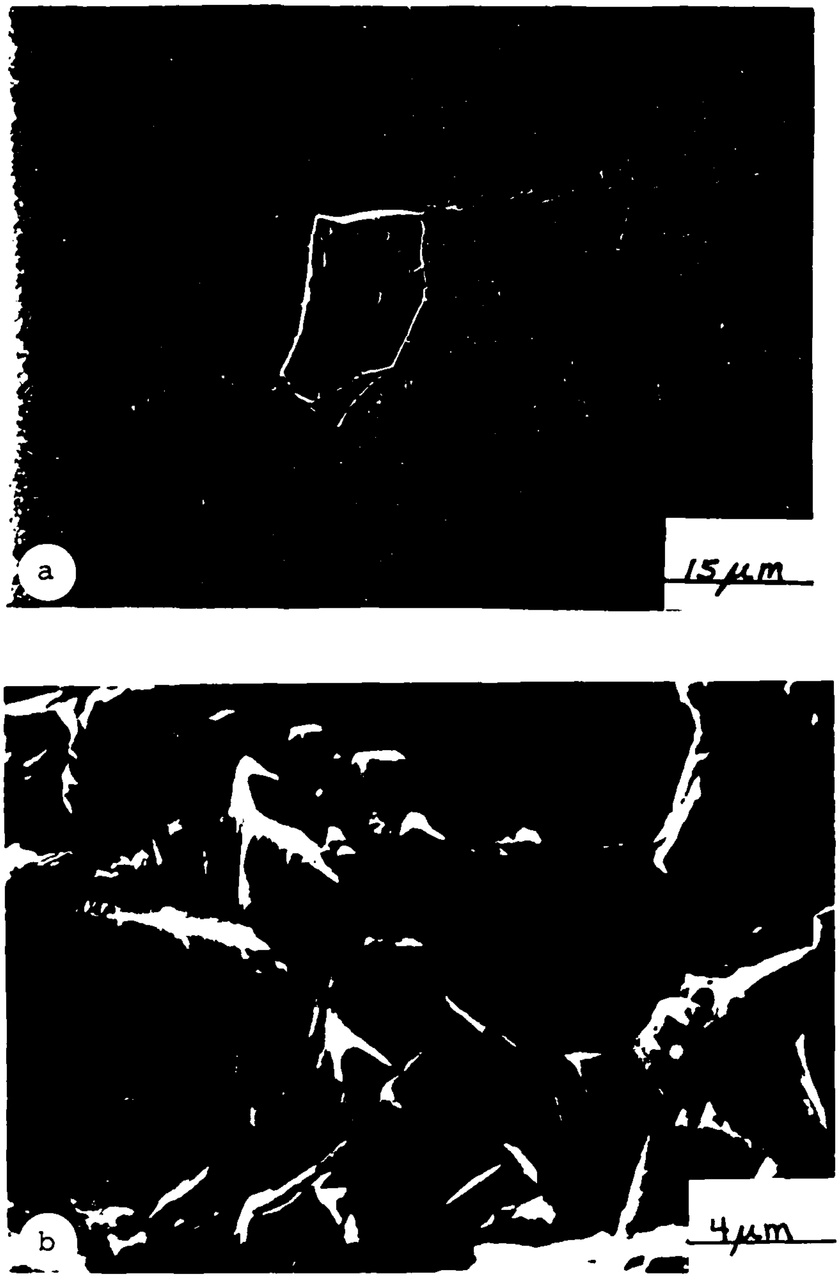

Figure 13. a)Fatigue crack initiated at ceramic inclusion intersecting the specimen surface in Rene' 95.
b)SEM micrograph showing the crystallographic fracture mechanism.

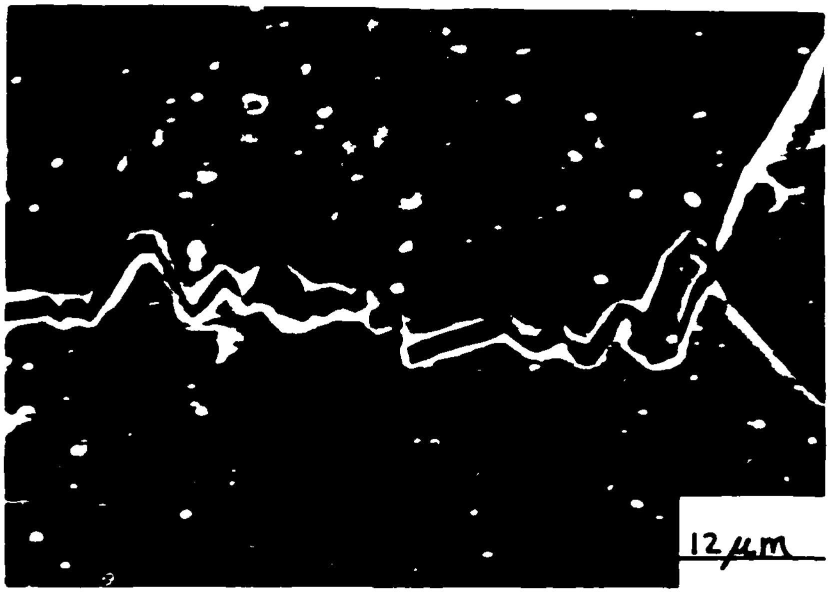

Figure 14. Fatigue cracks were observed to be open at the intersection with the specimen surface. (Rene' 95)

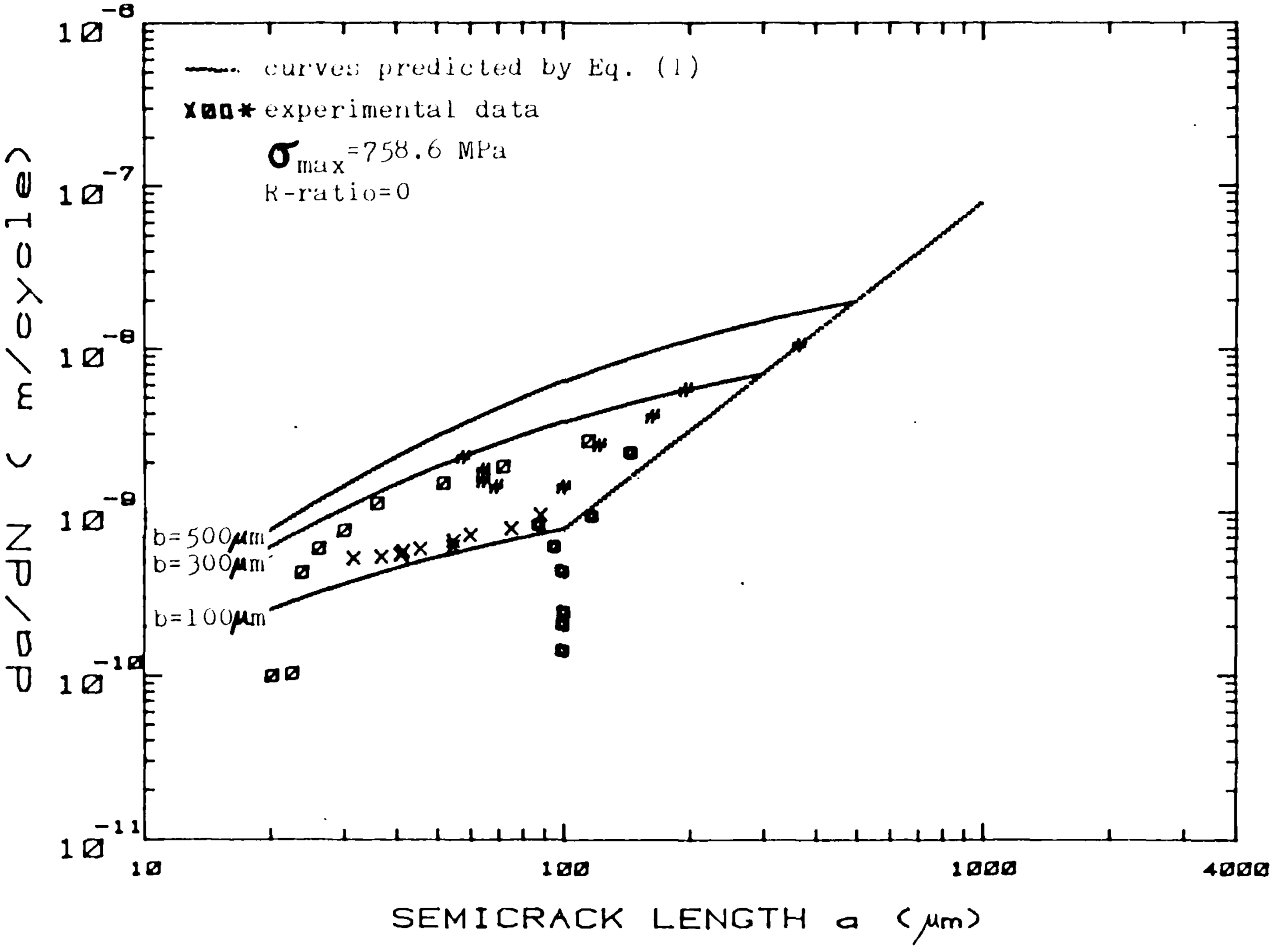

Figure 15. A comparison between experimentally determined crack propagation rates and those predicted by Equation 1.

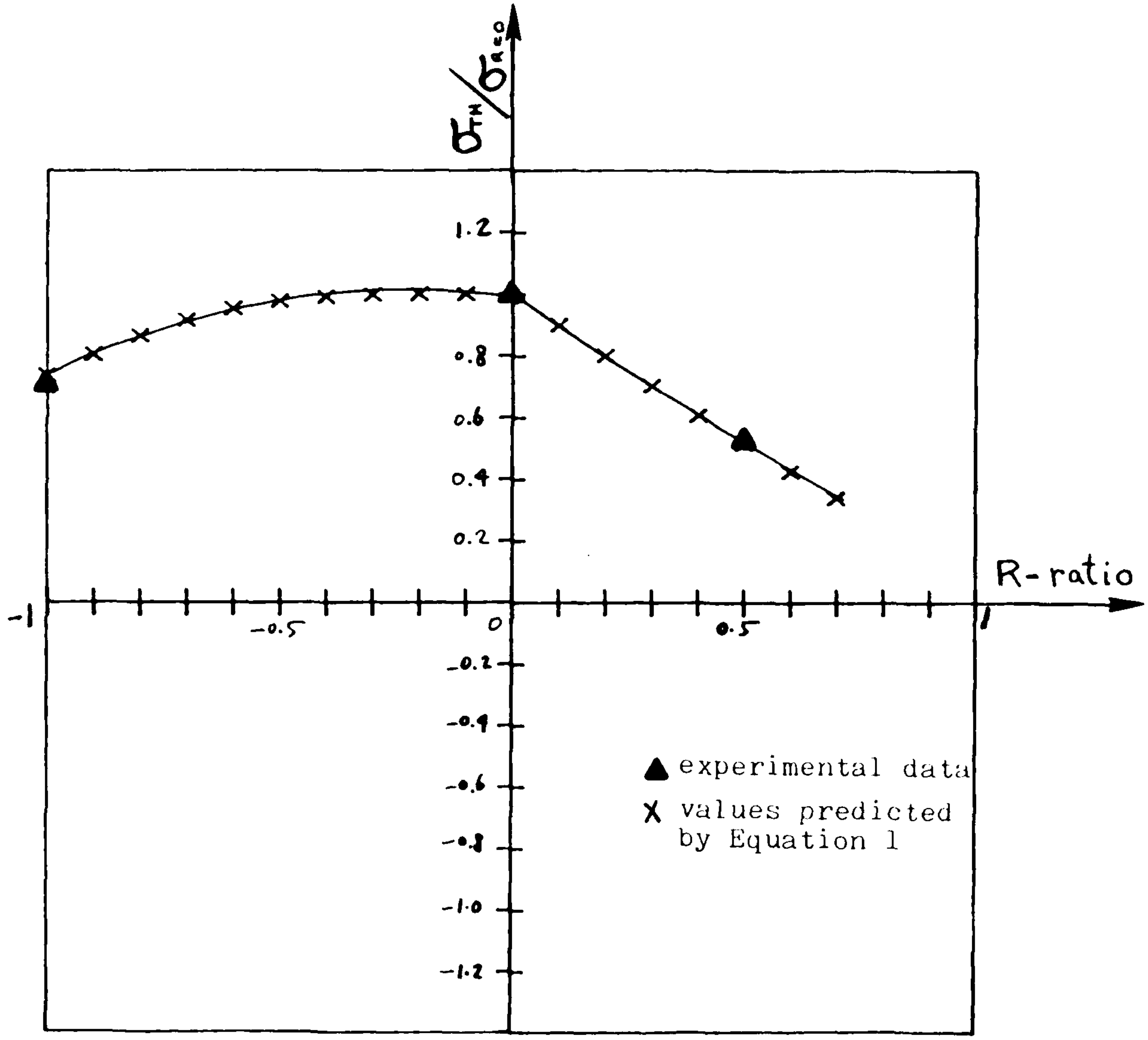

Figure 16. A comparison between experimentally determined values of the threshold stress and those predicted by Equation 1.

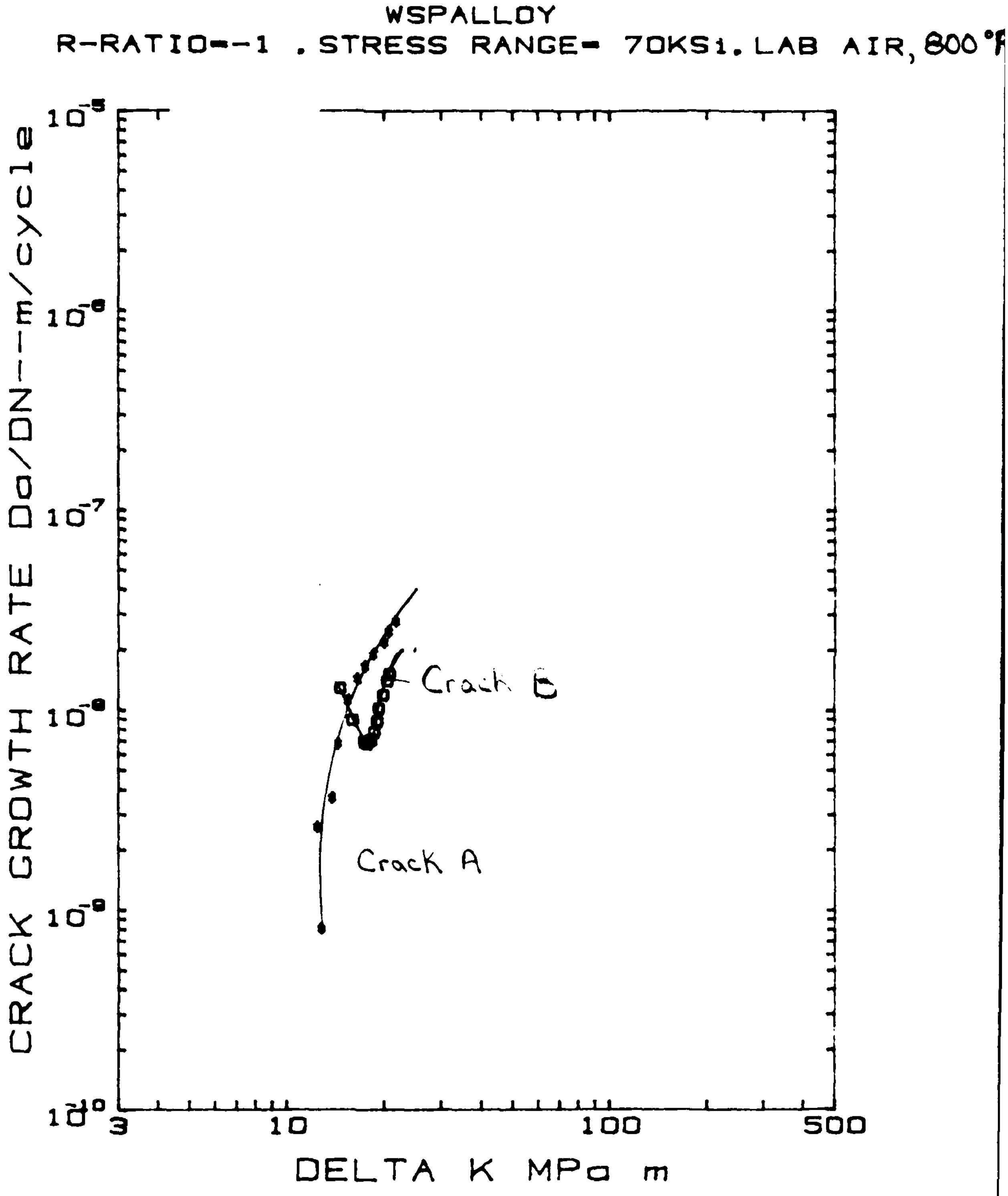

Figure 17. Variation of fatigue crack propagation rate as a function of stress intensity factor range for Waspaloy tested at 800°F.

Figure 16. SEM micrograph of laser initiation site in Waspaloy fatigue specimen.

Figure 19. SEM micrograph of EDM initiation site in Inconel X-750 fatigue specimen.

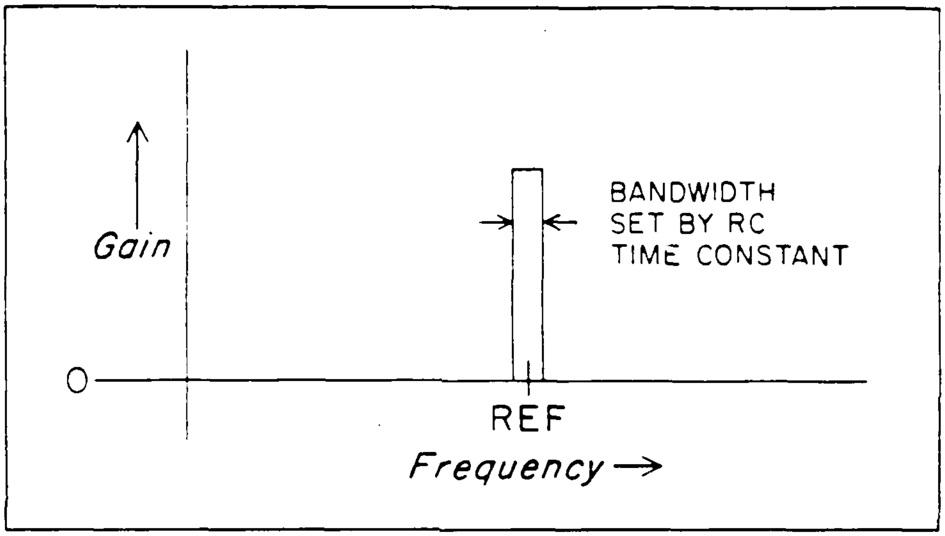

Figure 20. Frequency-amplitude response of an ideal lock-in amplifier.

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