RESEARCH PROGRESS AND PLANS (January 1 to June 30, 1990)

Research progress, recorded during the period from January 1, 1990 to June 30, 1990 is summarized and future plans are described here for each of the eleven projects.

Program 1 Environment Enhanced Fatigue of Advanced Aluminum Alloys and Composites

Donald C. Slavik and Richard P. Gangloff

Objective

The objective of this PhD research is to characterize and understand the environmental fatigue crack propagation behavior of advanced, high stiffness and strength, aluminum alloys and metal matrix composites. Those gases and aqueous electrolytes which are capable of producing atomic hydrogen by reactions on clean crack surfaces are emphasized. We seek quantitative characterizations of the behavior of new materials to provide data for damage tolerant component life prediction. We seek mechanistic models of crack tip damage processes which are generally applicable to structural aluminum alloys. Such models will enable predictions of cracking behavior outside of the data, metallurgical improvements in material cracking resistance, and insight on hydrogen compatibility.

Environmental and Mean Stress Interactions
in Fatigue Crack Growth of P/M Aluminum Alloy 644B

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Abstract

The near-threshold fatigue crack propagation behavior of advanced aluminum alloys and metal matrix composites, in gaseous and aqueous environments that produce embrittling hydrogen, is poorly understood. The general objective of this research is to characterize material microstructure-chemical environment-fatigue crack propagation properties, to understand crack tip damage mechanisms, and to develop predictive models.

An immediate challenge is to isolate environmental effects on extrinsic crack closure and on intrinsic hydrogen damage which govern crack growth rates (da/dN). High R-ratio (K_{min}/K_{max}) environmental fatigue crack growth experiments can establish intrinsic crack propagation resistance above crack closure levels and as affected by stress intensity range (ΔK) and K_{max}, however, limited results are recorded in this regard. Such information is important in damage tolerant design and for understanding the relative contributions of maximum stress and cyclic strain within the crack tip process zone. The objective of our initial experiments is to examine the effect of R on intrinsic near-threshold crack growth in an Al-Li based alloy in water vapor.

The fine grained powder metal alloy, 644B (Al-2.6Li-1.0Cu-0.5Mg-0.5Zr by wt % and donated by Allied Signal), was selected for study. Crack closure loads are monitored with a crack mouth mounted displacement gauge. Intrinsic fatigue crack growth rate experiments with programmed ΔK and K_{max} are performed in water vapor, moist air, oxygen, and dynamic vacuum. The water vapor environment and fine grain size were selected for reduced roughness induced closure. Experiments in water vapor employ two constant K_{max} levels of 17 MPa$\sqrt{m}$ and 8.5 MPa$\sqrt{m}$ with decreasing ΔK. A constant ΔK of 2 MPa$\sqrt{m}$ with decreasing K_{max} is also employed. Crack growth rate data are reproducible and consistent with literature results. Crack closure is surprisingly important at stress intensities of 5 to 6.5 MPa$\sqrt{m}$, presumably due to unexpected faceted cracking in the P/M alloy. Above this closure level, intrinsic crack growth rates increase mildly for a two-fold increase in K_{max}. This result is consistent with limited literature data. The mild effect of K_{max} on da/dN can be rationalized with analytical stress distributions around a crack tip. Significant variations in K_{max} may not alter the opening stress distribution within the process zone.

Future work aims to broadly characterize crack growth in a variety of aluminum alloys and composites in both gaseous and aqueous NaCl environments; to further examine the interaction of cyclic strain, maximum stress and hydrogen within the crack tip process zone; and to design experiments to elucidate crack tip damage mechanisms.

Environmental and Mean Stress Interactions in Fatigue Crack Growth of P/M 644B

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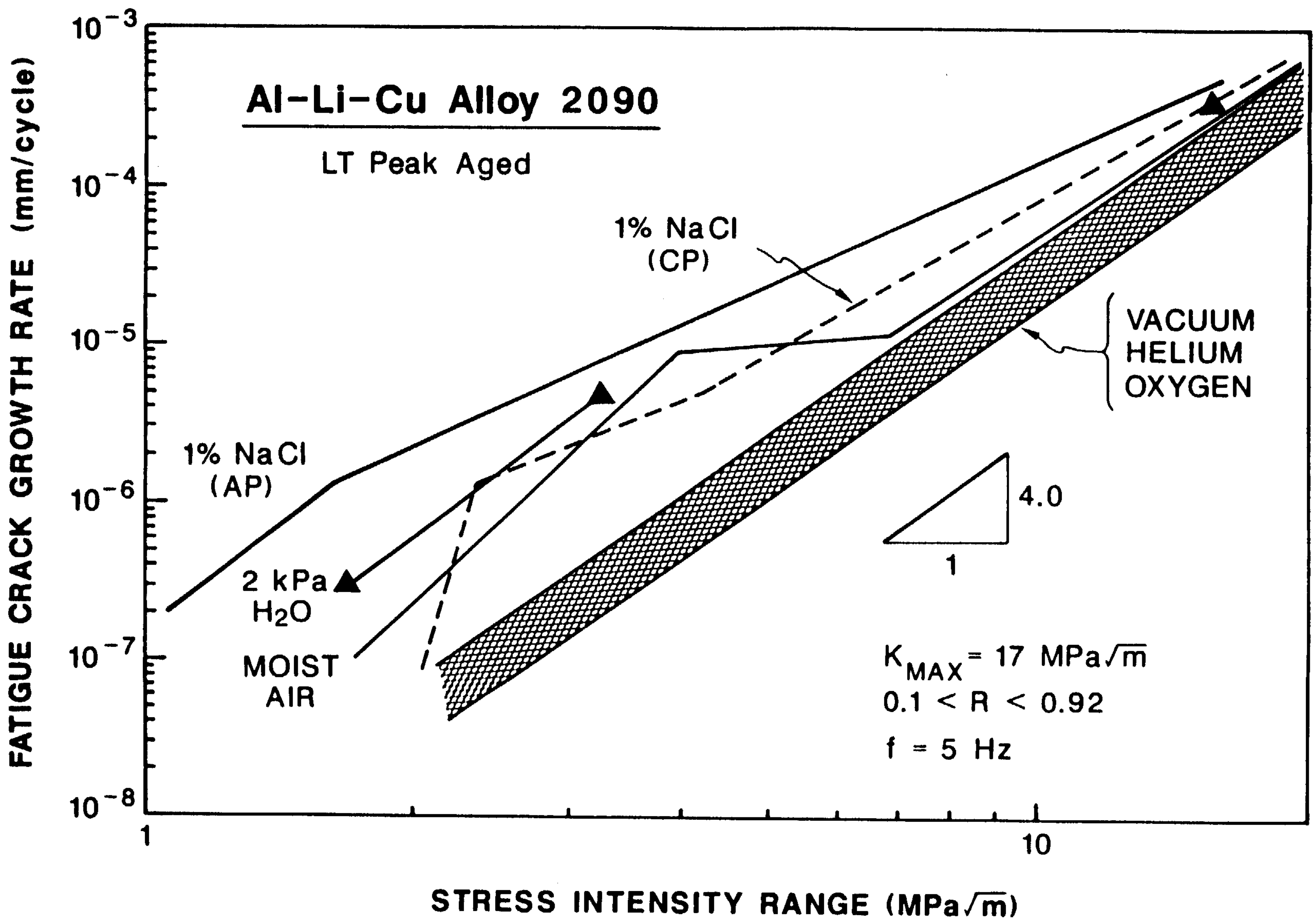
University of Virginia

Support Provided by NASA
Langley Research Center

D. L. Dicus Project Monitor


Al-Li-Cu Alloy 2090
LT Peak Aged
1% NaCl (CP)
VACUUM
HELIUM
OXYGEN
1% NaCl (AP)
2 kPa H_2O
MOIST AIR
4.0
1
K_{MAX} = 17 MPa$\sqrt{m}$
0.1 < R < 0.92
f = 5 Hz
FATIGUE CRACK GROWTH RATE (mm/cycle)
STRESS INTENSITY RANGE (MPa$\sqrt{m}$)
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
1
10

Background

- Intrinsic 2090 & 7075 corrosion fatigue established

- Vacuum, He, & Oxygen
  - Faceted cracking along {111} slip planes in 2090

- Water Vapor & Air
  - Cleavage cracking at low ΔK along {100}
  - Inter-subgranular cracking at high ΔK
  - Transition related to sub-boundary size to cyclic process zone

Questions on the Environmental Effect Near ΔK_{th}

- **What is the environmental fatigue crack growth rate behavior of advanced alloys and composites?**
  - **Intrinsic**
  - **Extrinsic**

- **What are the relevant crack tip mechanistic parameters controlling environmental fracture?**
  - $\Delta\varepsilon_p$
  - σ_{normal}
  - **Dislocation structures**
  - **Dissolved Hydrogen**

- **How does stress ratio contribute to crack tip damage?**
  - **Closure issue**
  - **Damage issue**
  - **Technological issue**

Available Materials

- Allied Signal Alloy 644 B

- 2009 with SiC Reinforcement
  - 15 vol % whisker
  - 20 vol % particulate
  - Powder Matrix

- 2090 and 2091
  - Recrystallized
  - Unrecrystallized

- High Purity Al-Cu Alloy

- 7075 and 2024

Alloy 644B

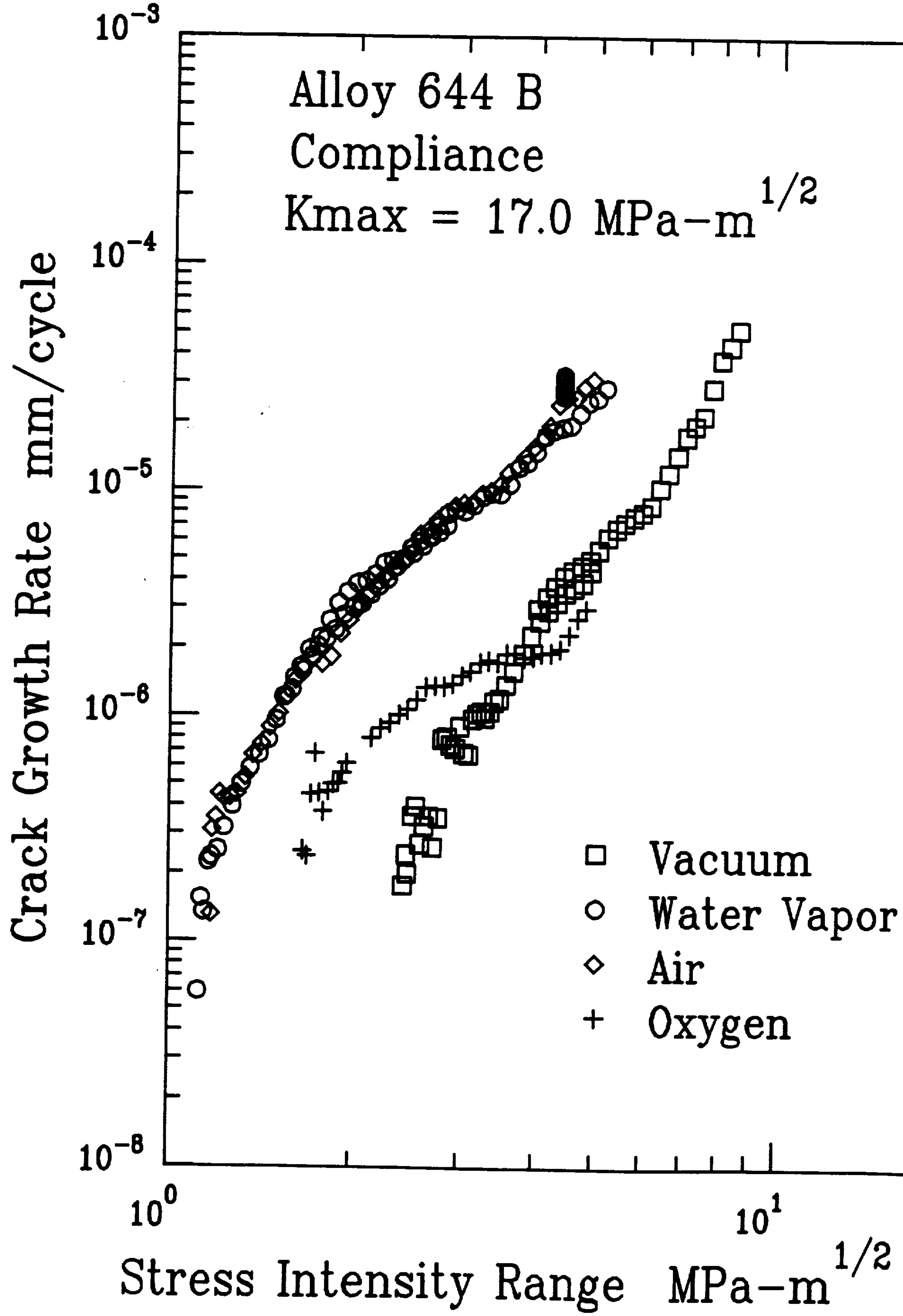
- $Al-2.6Li-1.0Cu-0.5Mg-0.5Zr$ (weight %)
- Major strengthening phases δ' and Al_3Zr
- Rapidly solidified process
- Ribbons 100μm - 25μm - 500μm
- Grains 2μm - 2μm - 10μm
- Fine grain size material to minimize roughness induced crack closure

Objectives of 644B Experiments

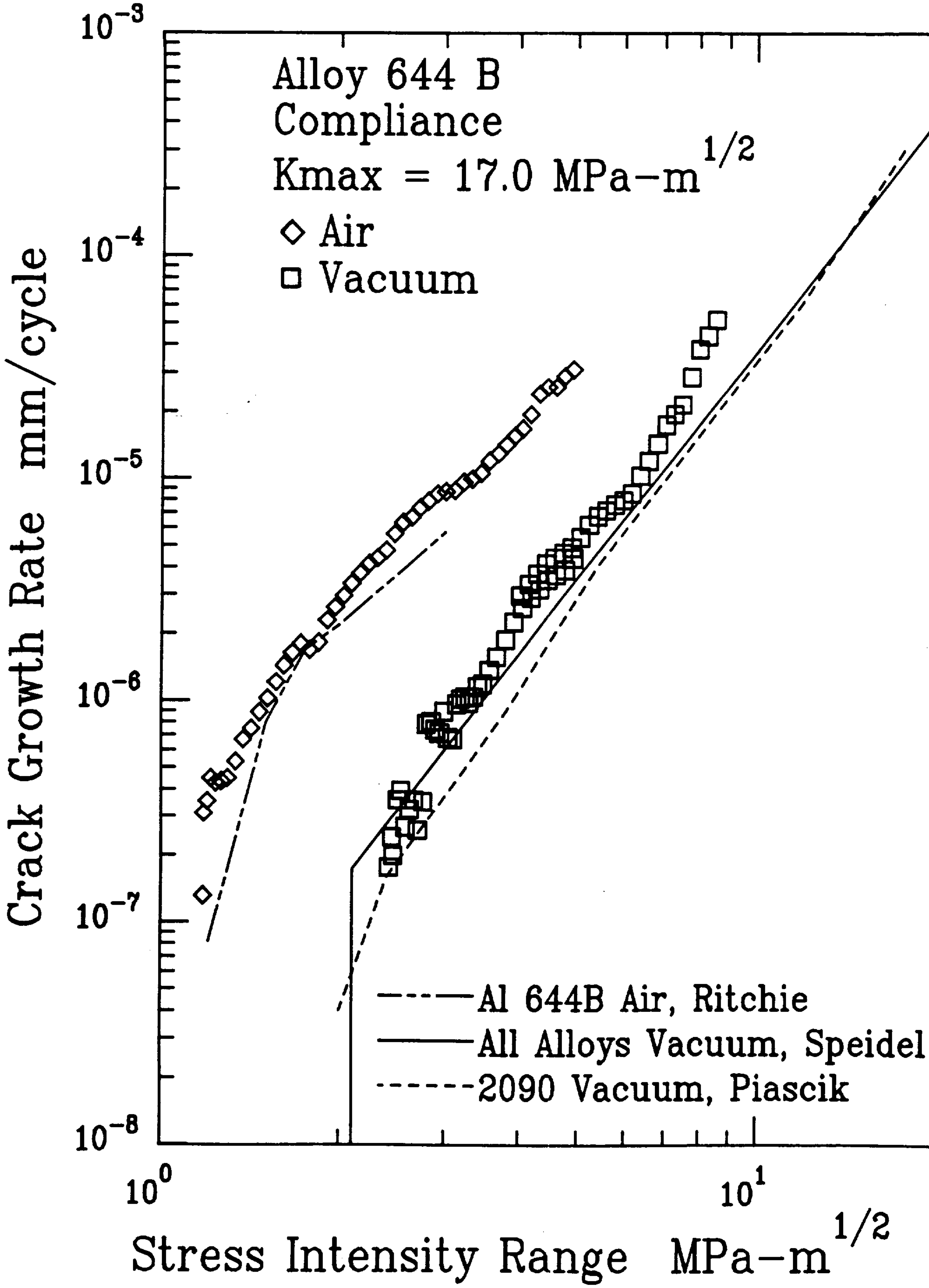
- Perform environmental fatigue experiments and learn issues

- Measure crack closure levels
  - Compact tension specimen geometry
  - Introduce compliance to gas/vacuum system

- Examine mean stress damage effects
  - Identify closure behavior
  - Examine R effect on intrinsic crack growth



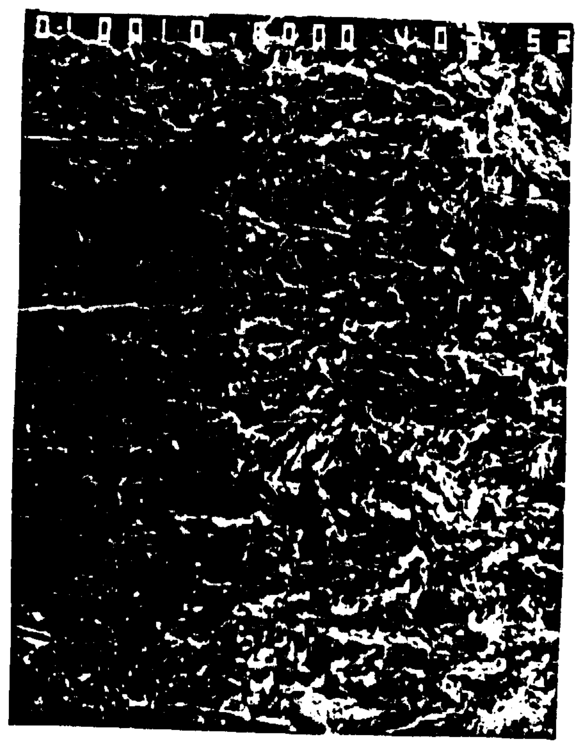
Alloy 644 B
Compliance
Kmax = 17.0 MPa-m^1/2
Crack Growth Rate mm/cycle
Stress Intensity Range MPa-m^1/2
10^-3
10^-4
10^-5
10^-6
10^-7
10^-8
10^0
10^1
Vacuum
Water Vapor
Air
Oxygen



Alloy 644 B
Compliance
Kmax = 17.0 MPa-m^1/2
◇ Air
□ Vacuum
Al 644B Air, Ritchie
All Alloys Vacuum, Speidel
2090 Vacuum, Piascik
Crack Growth Rate mm/cycle
Stress Intensity Range MPa-m^1/2
10^-3
10^-4
10^-5
10^-6
10^-7
10^-8
10^0
10^1

644B Fracture Surface

Water Vapor to Vacuum Test



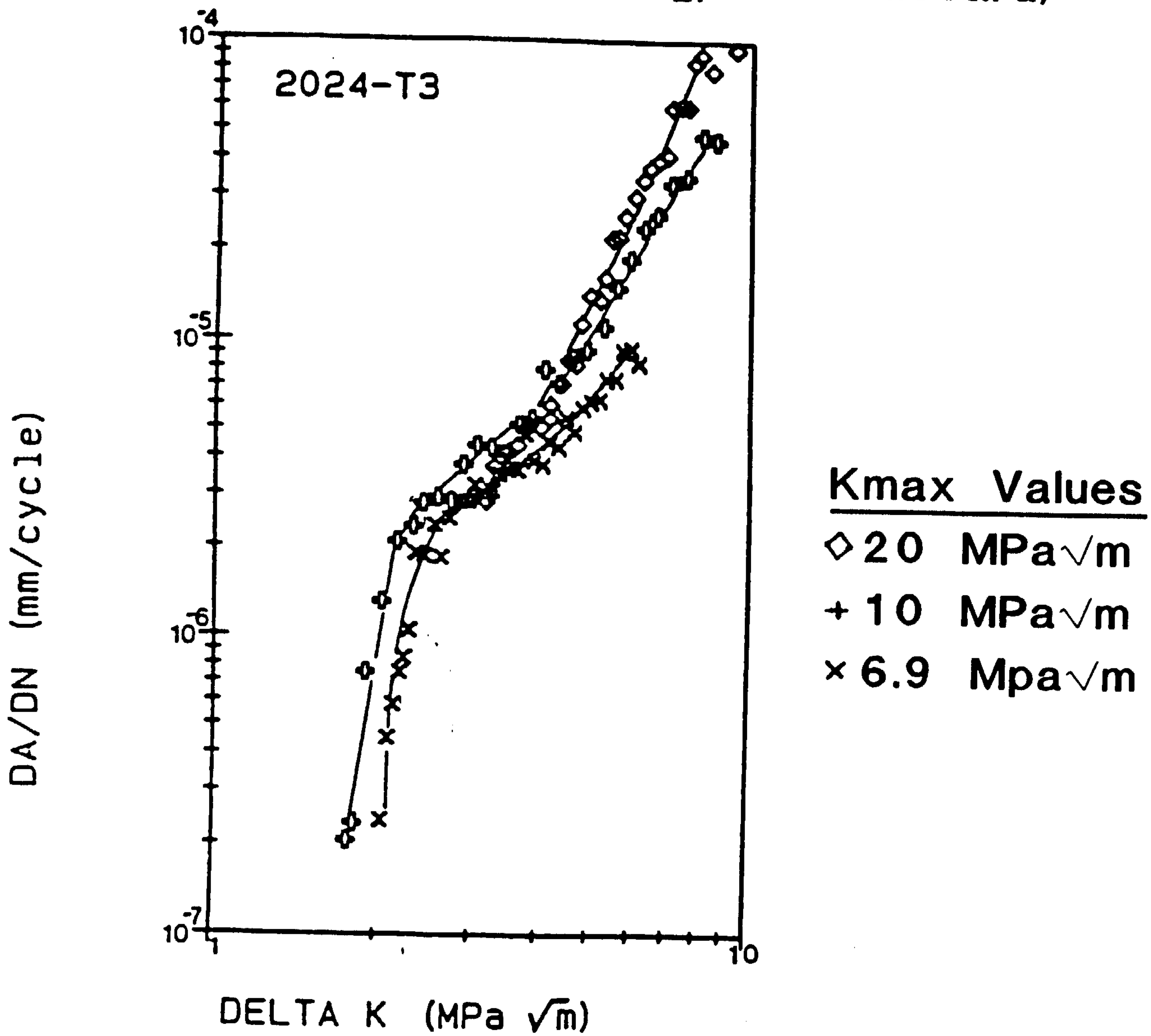
0.1 mm

Mean Stress Effects

- Literature
  - What has been done done apart from crack closure to examine mean stress damage?
- Mechanisms
  - How do crack tip parameters change with Kmax?
- Alloy 644B
  - Is roughness induced crack closure limited due to the alloys small grain size?

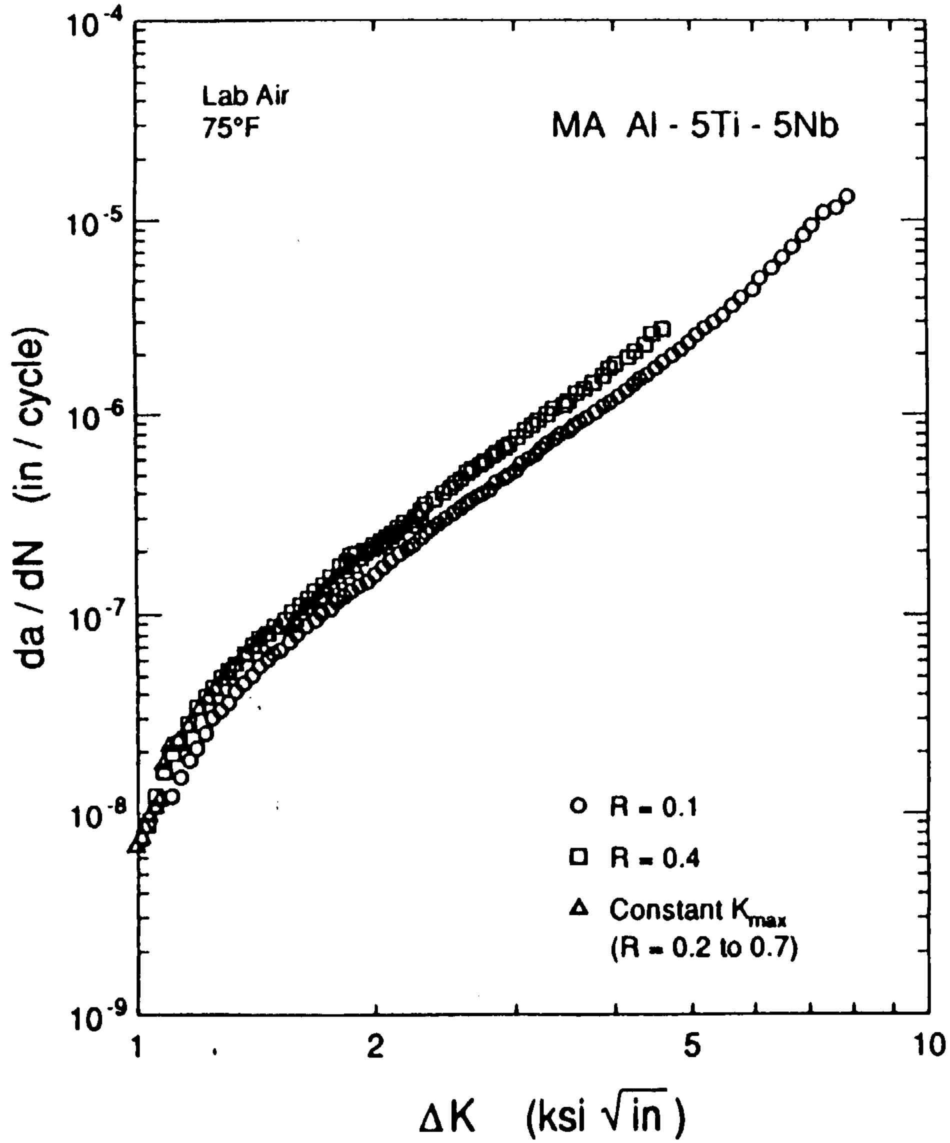
Intrinsic Crack Growth?

(Herman, Hertzberg, and Jaccard)



Intrinsic Crack Growth?

(Bray and Wilsdorf)



Why A Mean Stress Effect

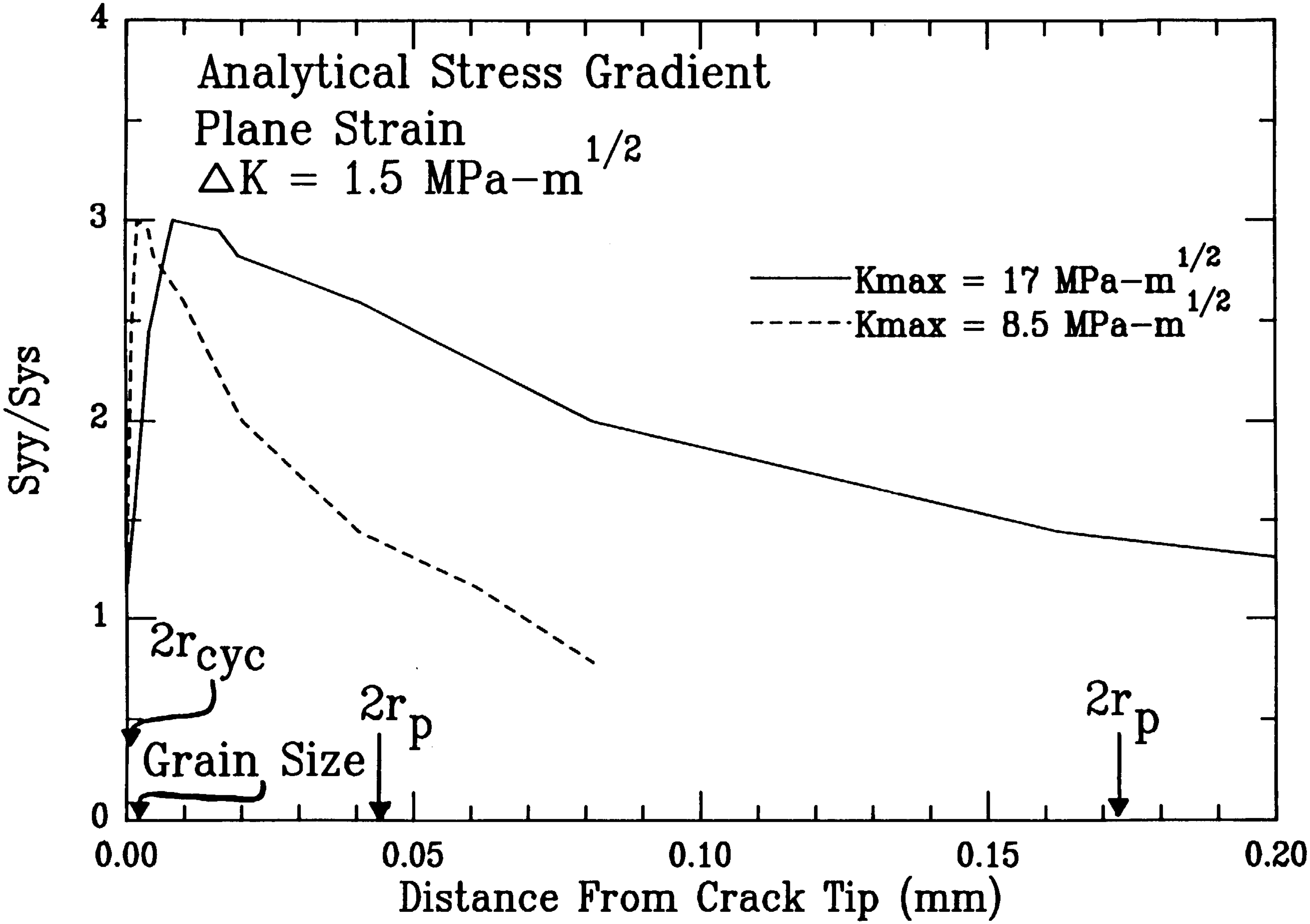
- Increased σmax increases mechanical damage
- Increased σmax increases hydrogen accumulation

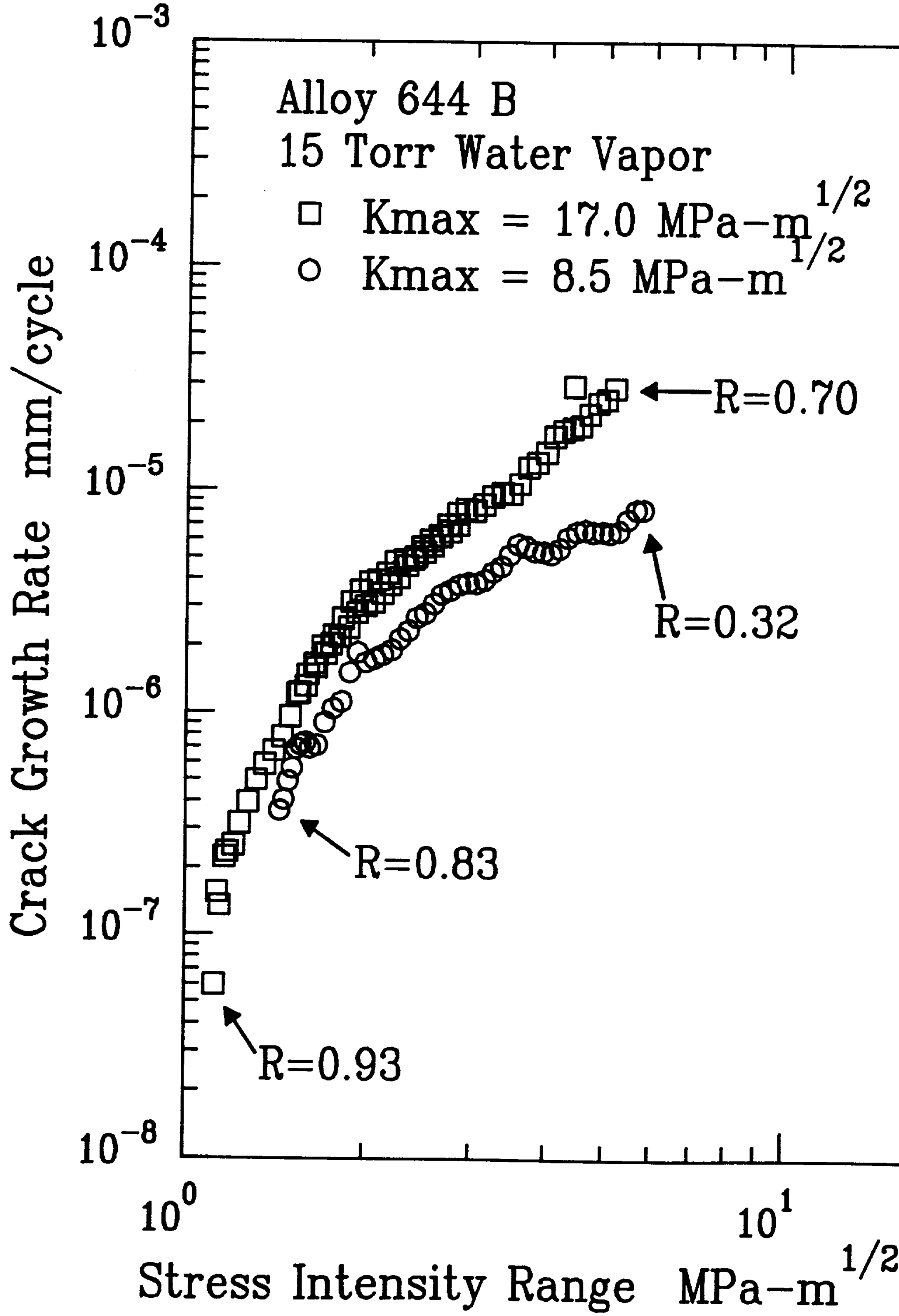
Why Not A Mean Stress Effect

- Increased R does not appreciably change stress distribution in the process zone

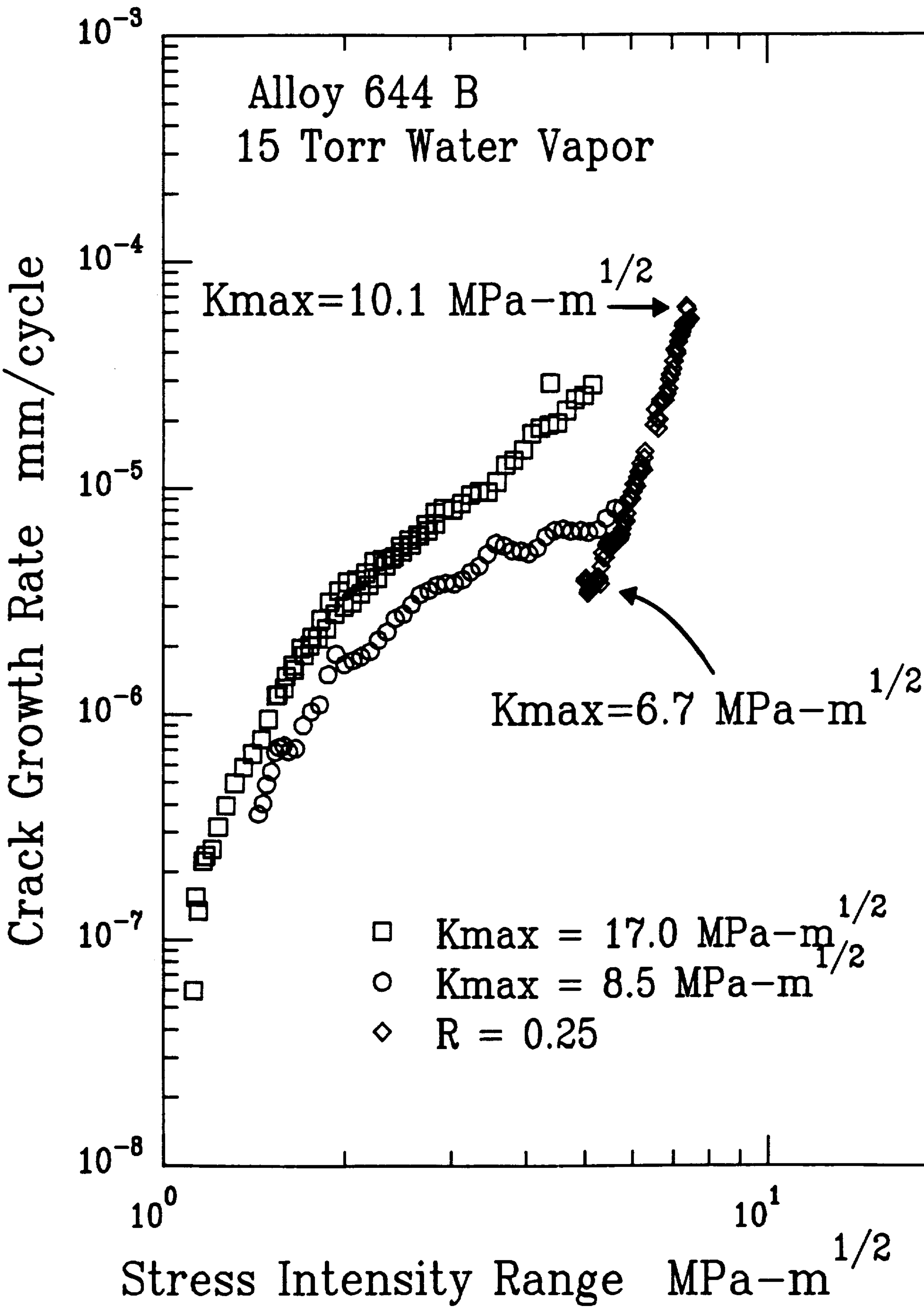
Problems

- What are $\Delta \varepsilon p$ and σmax in the process zone?
- What is the effect of R on the microscopic stress distribution?


Analytical Stress Gradient
Plane Strain
ΔK = 1.5 MPa-m^1/2
Kmax = 17 MPa-m^1/2
Kmax = 8.5 MPa-m^1/2
Syy/Sys
Distance From Crack Tip (mm)
2r_cyc
Grain Size
2r_p
2r_p
0
1
2
3
4
0.00
0.05
0.10
0.15
0.20



Alloy 644 B
15 Torr Water Vapor
Kmax = 17.0 MPa-m^1/2
Kmax = 8.5 MPa-m^1/2
R=0.70
R=0.32
R=0.83
R=0.93
Crack Growth Rate mm/cycle
Stress Intensity Range MPa-m^1/2
10^-3
10^-4
10^-5
10^-6
10^-7
10^-8
10^0
10^1



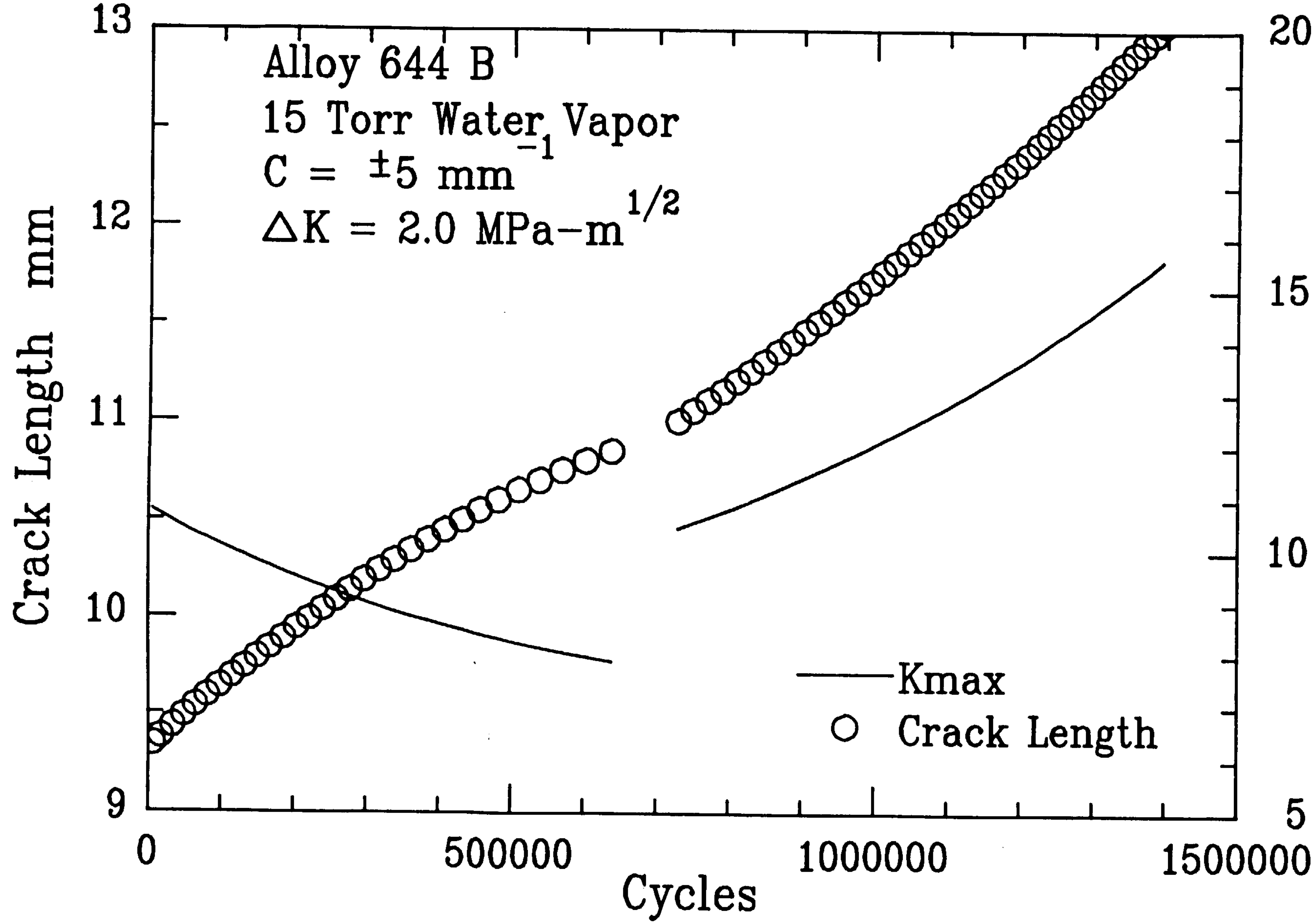
Alloy 644 B
15 Torr Water Vapor
Kmax=10.1 MPa-m^1/2
Kmax=6.7 MPa-m^1/2
Kmax = 17.0 MPa-m^1/2
Kmax = 8.5 MPa-m^1/2
R = 0.25
Crack Growth Rate mm/cycle
Stress Intensity Range MPa-m^1/2
10^-3
10^-4
10^-5
10^-6
10^-7
10^-8
10^0
10^1

Need for Appropriate Experiment

- Constant $\Delta K = 2.0$ MPa$\sqrt{m}$
- Variable Kmax = 15.6 MPa$\sqrt{m}$ to 8.0 MPa$\sqrt{m}$

Experimental Difficulties

- Slow crack growth rates make experiment difficult
- Unexpected roughness of 644B
  - Kopen = 5-6.5 MPa$\sqrt{m}$
- Is a Clip gage opening load an appropriate measure of the crack tip opening?


Alloy 644 B
15 Torr Water Vapor
C = ±5 mm^{-1}
ΔK = 2.0 MPa-m$^{1/2}$
Crack Length mm
Kmax MPa-m$^{1/2}$
Cycles
Kmax
Crack Length
13
12
11
10
9
20
15
10
5
0
500000
1000000
1500000

Conclusions

- Kmax has limited influence on the intrinsic damage of Alloy 644B in water vapor.

- Kclose of 5-6.5 MPa$\sqrt{m}$ was observed in Alloy 644B. Roughness induced closure may be significant.

- Kmax may have a small effect on the stress distributions very near the crack tip. This can explain the limited influence of Kmax on the intrinsic crack growth rates.

- Determining the effect of Kmax on intrinsic rates in hydrogen environments is a complex experiment.

Future Work

What is the near threshold fatigue crack growth behavior of composites and advanced Al alloys in aggressive hydrogen environments?

- Experimental
  - Gripping system and closure monitoring for aqueous environments
  - Consider novel alloys
    - + Aluminum-Lithium Alloys
    - + Metal Matrix Composites
    - + Conventional Aluminum Alloys

Future Work

What is the crack tip process zone damage mechanism and associated da/dN-ΔK model?

- "Large" cracks in a fine grain alloy
  - Closure measurements
- "Small" cracks in a large grain alloy
  - Al-Cu model alloys
- Fractographic characterization for crack path micromechanism determinations
- Review crack tip stress/strain fields
  - Cyclic loading analytical results
  - SEM/fatigue loading stage observations