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Elevated Temperature Fracture of RS/PM Aluminum Alloy 8009

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Abstract

Dispersion strengthened, powder metallurgy aluminum alloys produced by rapid solidification and mechanical alloying techniques are candidate materials for next generation aerospace structures at intermediate elevated temperatures (150 - 225 °C). One of the most promising alloys identified from this class is the rapidly solidified, powder processed, Al-8.5Fe-1.3V-1.7Si (wt.%) alloy 8009 produced by Allied-Signal, Inc. Preliminary study of AA 8009 indicated excellent elevated temperature tensile strength retention due to thermal stability of the ultrafine grain structure and the high volume fraction $Al_{12}(Fe,V)_3Si$ silicide. In the initial stages of this study, it was shown, however, that damage tolerance for 8009 decreases with increasing temperature and decreased loading rate. Similar degradation has been observed in other alloys of this class. The cause of this degradation is uncertain, however several mechanisms have been proposed including: dynamic strain aging due to excess solid solution iron, extrinsic delamination toughening, environmental embrittlement due to water vapor or oxygen reactions with aluminum, embrittlement by retained hydrogen from processing, or temperature enhanced localized deformation unique to ultrafine grain size alloys with a high volume fraction of strengthening dispersoids. The current objective of this study is to determine the mechanism(s) by which the damage tolerance of AA 8009 decreases with increasing temperature and decreasing loading rate.

Recent work has focused on confirming the intrinsic nature of the elevated temperature damage tolerance degradation of 8009 and on determining the role of the moist air environment and retained hydrogen from processing in this unusual fracture behavior. Monotonic increasing load plane strain fracture toughness, K_{IC}, was determined for cross-rolled 8009 plate as a function of temperature. A large decrease in fracture toughness was observed with increasing test temperature independent of specimen orientation (K_{IC}: 30 MPa√m at 25 °C, 10 MPa√m at 175 °C). This decrease occurred despite the absence of prior particle boundary delamination in specimens at both temperatures like that seen in the LT orientation of the extruded material at 25 °C. This confirms that the toughness decrease with temperature previously observed in extruded AA 8009 was intrinsic to the material and decreased extrinsic delamination toughening had, at most, a minor effect on K_{IC}.

Fracture mechanics characterizations of monotonic increasing and sustained load damage tolerance were conducted at 175 °C in air and high vacuum (< 30 μPa), for material as-processed and after an extended vacuum heat treatment. K-Δa R-curves were determined for extruded and plate 8009. Results indicated no effect of environment or the 75 hour 330 °C vacuum heat treatment on the fracture behavior of the 8009 in either plate or extruded form. The critical stress intensity for fracture initiation, K_{IC}, was approximately 16 MPa√m for all environment and heat treatment conditions in the extruded material at 175 °C (K_{IC} = 10 MPa√m for plate), reduced from a K_{IC} of 30 MPa√m at 25 °C. Likewise the slopes of the R-curves, an indication of material resistance to stable crack growth, are

similar for all conditions at 175°C and are much reduced from values at 25°C. Additionally, K - da/dt sustained load crack growth results indicated subcritical crack growth at 175°C in vacuum, similar to results in air. Determination of the hydrogen content of the 8009; as received, after elevated temperature testing, and after vacuum heat treatment; indicated that hydrogen contents were similar in all cases, and hydrogen was not mobile at temperatures as high as 330°C in this material. These results imply that the degradation of damage tolerance of AA 8009 with increasing temperature is not due to embrittlement from a moist air environment or retained hydrogen from processing.

Stereo pair, matching fracture surface SEM fractography was performed on failed specimens and indicated a locally plastic fracture mode for experiments at 25 and 175°C, in air and vacuum. The nature of the fracture mode varied with temperature and environment, however. At 25°C, the fracture surface contained a dual distribution of dimples, .5 to 2 μm and 4 to 8 μm in diameter. At 175°C, fracture surfaces of specimens tested in air and vacuum had a uniform distribution of shallow dimples 2 to 4 μm in diameter. Specimens tested in vacuum also had a large number of submicron particles apparent on the fracture surface. The explanation for these differences is unknown at this time.

Future work will focus on interpretation of the elevated temperature fracture behavior of AA 8009 through microscopy of failed fracture mechanics specimens and sectioned notched bars from interrupted tensile experiments. With an understanding of the evolution of fracture in 8009, mechanisms will be proposed to account for the effect of temperature and loading rate in degrading the damage tolerance of this material.

ELEVATED TEMPERATURE FRACTURE OF RS/PM ALUMINUM ALLOY 8009

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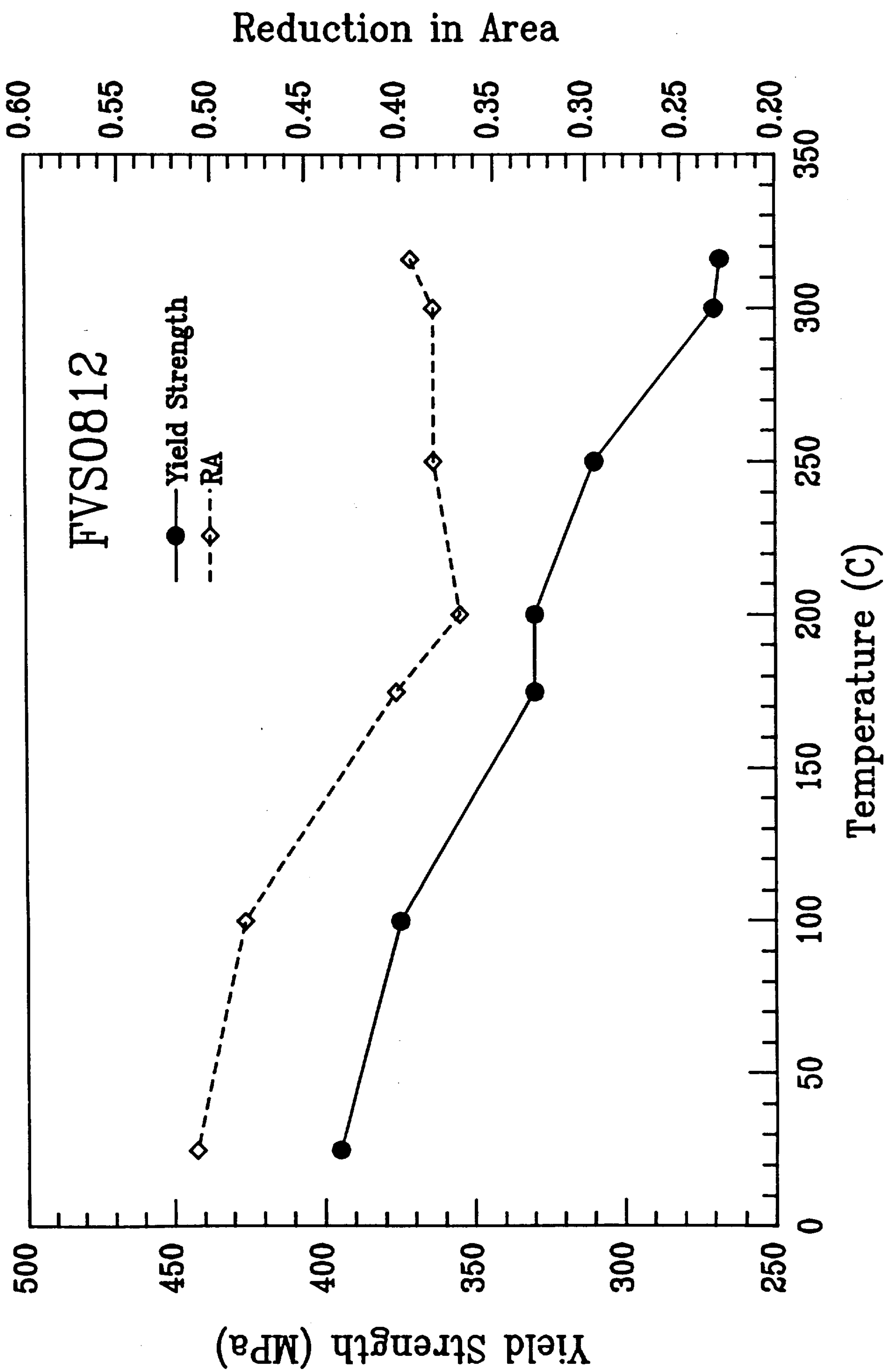
C. E. Harris, Project Monitor

HIGH TEMPERATURE PM ALUMINUM ALLOYS

■■ Structural Applications – HSCT

Mach 2.0: 100°C Long Term
Temperature Requirement
-- 135°C Peak

Mach 2.4: 175°C Long Term
-- 200°C Peak



FVS0812
Yield Strength
RA
Reduction in Area
0.60
0.55
0.50
0.45
0.40
0.35
0.30
0.25
0.20
Yield Strength (MPa)
500
450
400
350
300
250
Temperature (C)
0
50
100
150
200
250
300
350

TEM micrograph of FVS0812 Al alloy

PROCEDURES

- Measured Parameters

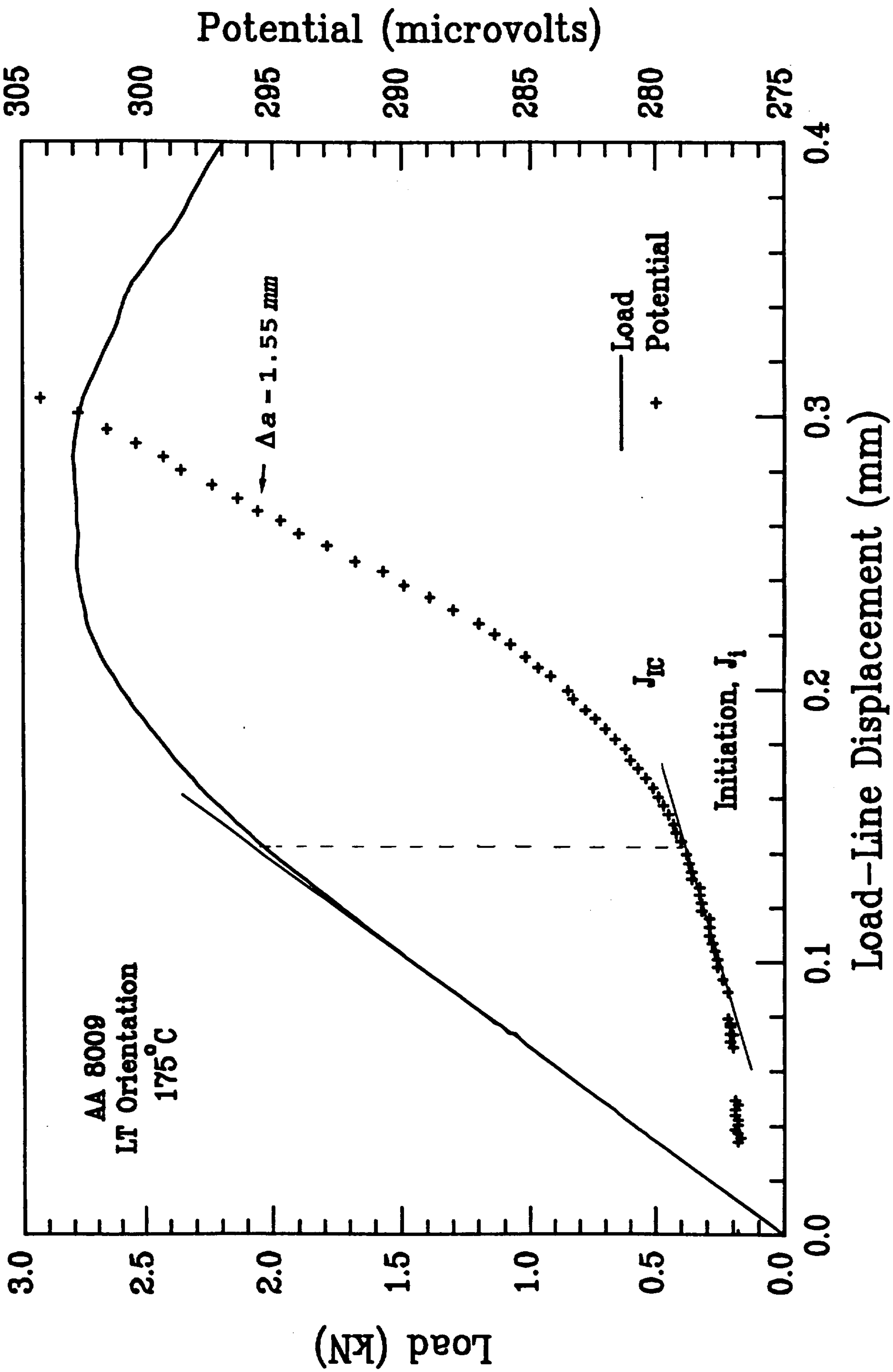
  LEFM: $K-\Delta a$ .... P, a

  $K-da/dt$ ...... P, a, t

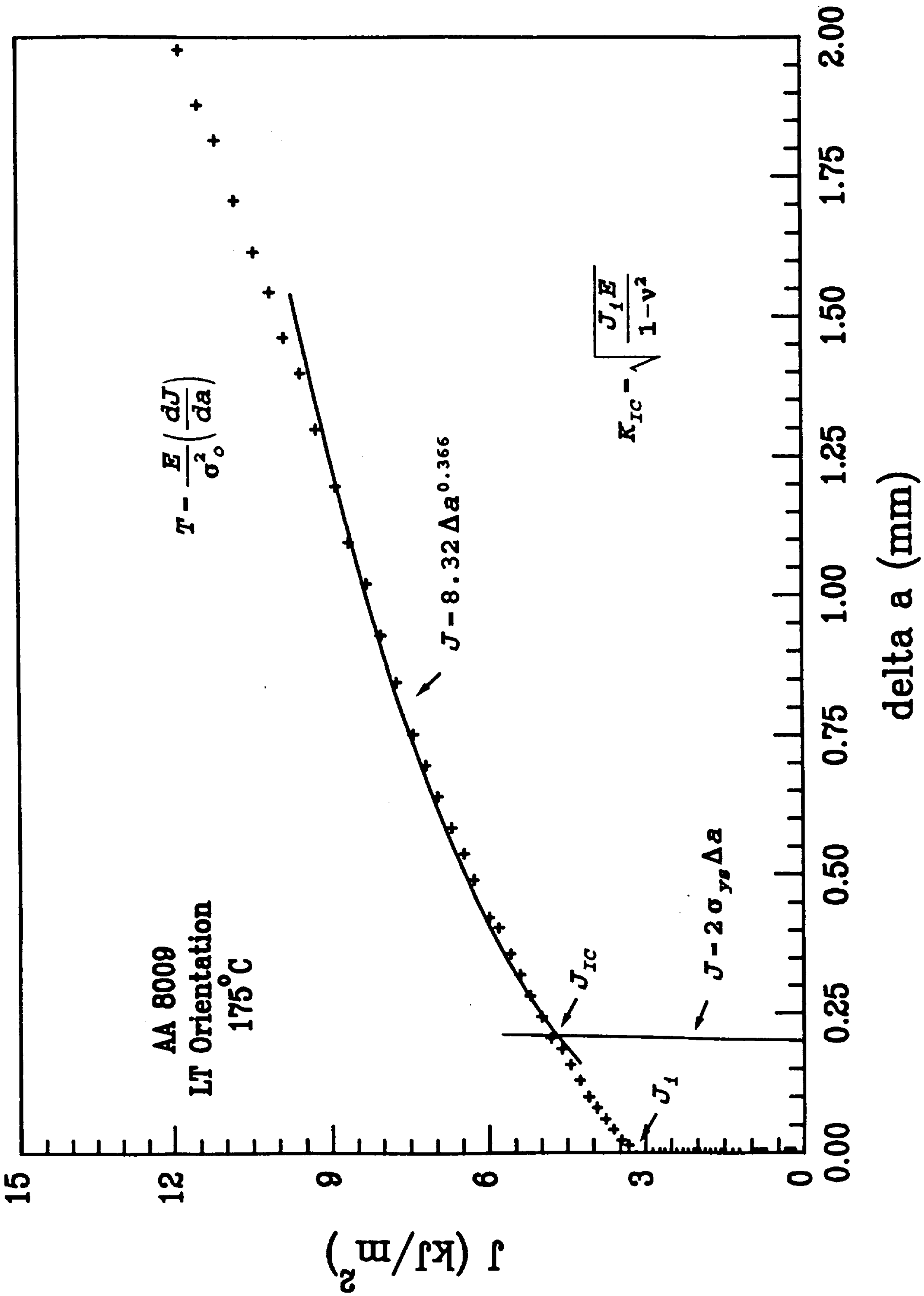
  EPFM: $J-\Delta a$ .... P, a, δ

  $J-da/dt$ ...... P, a, δ, t

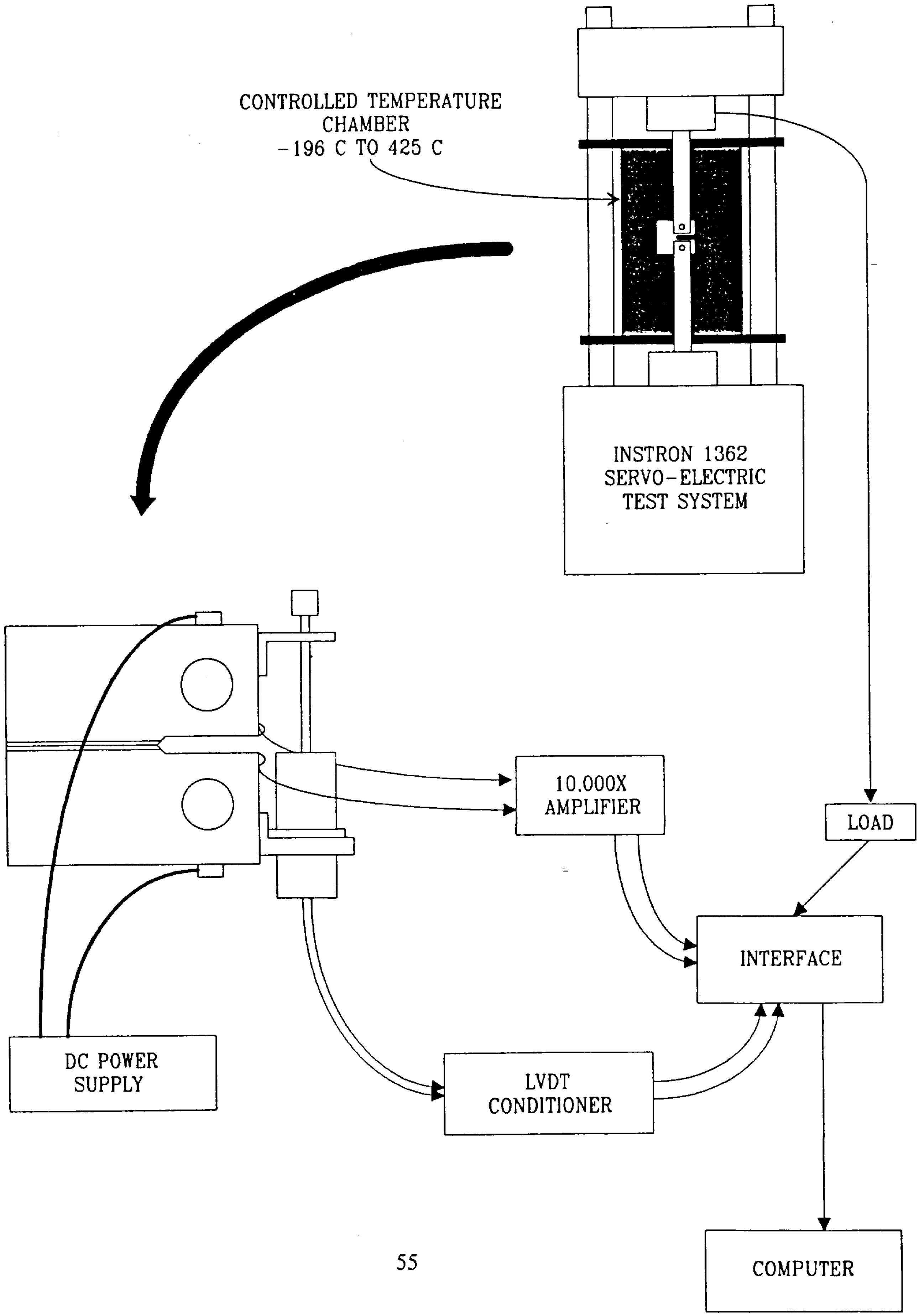
- a from DC potential drop technique

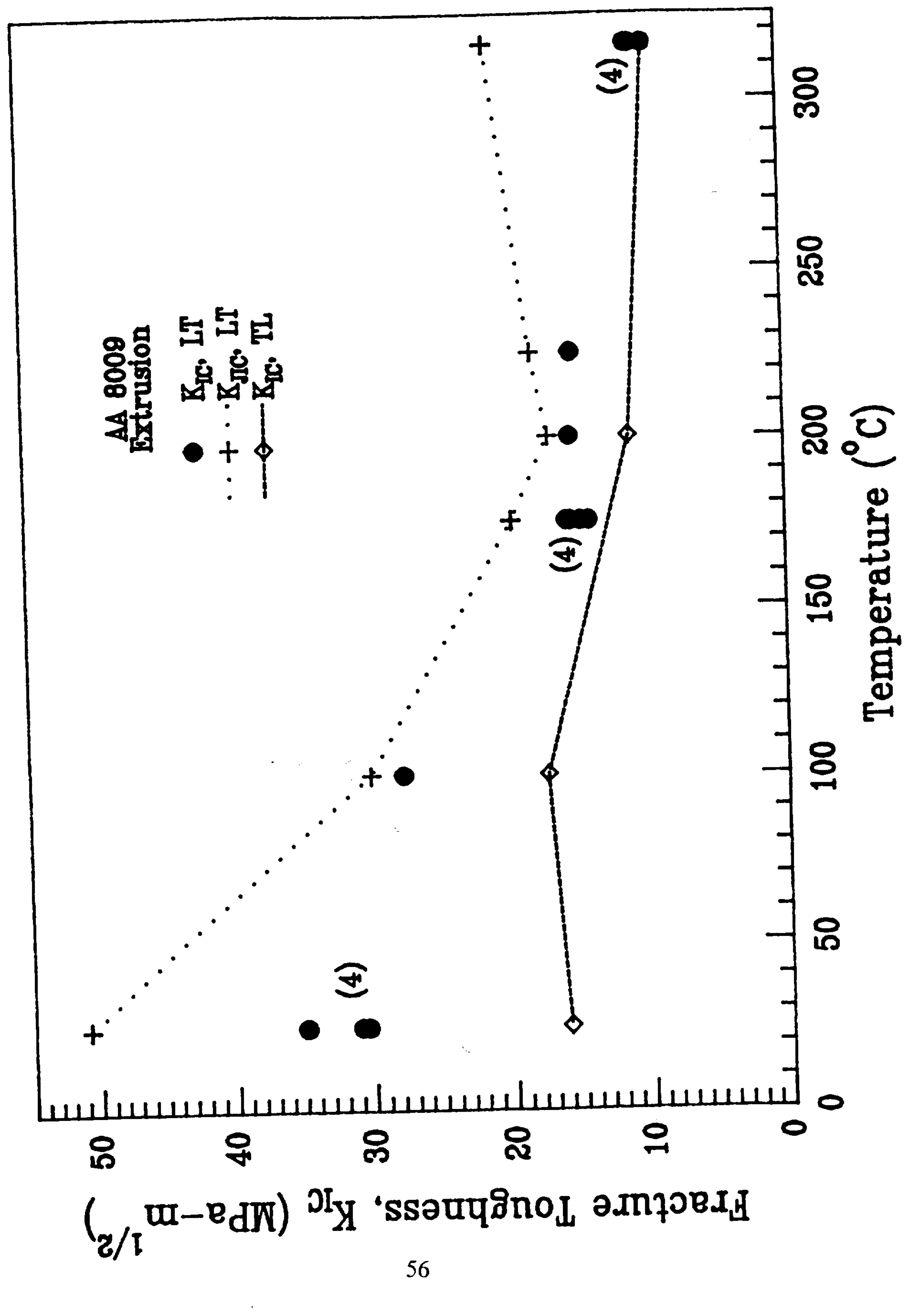


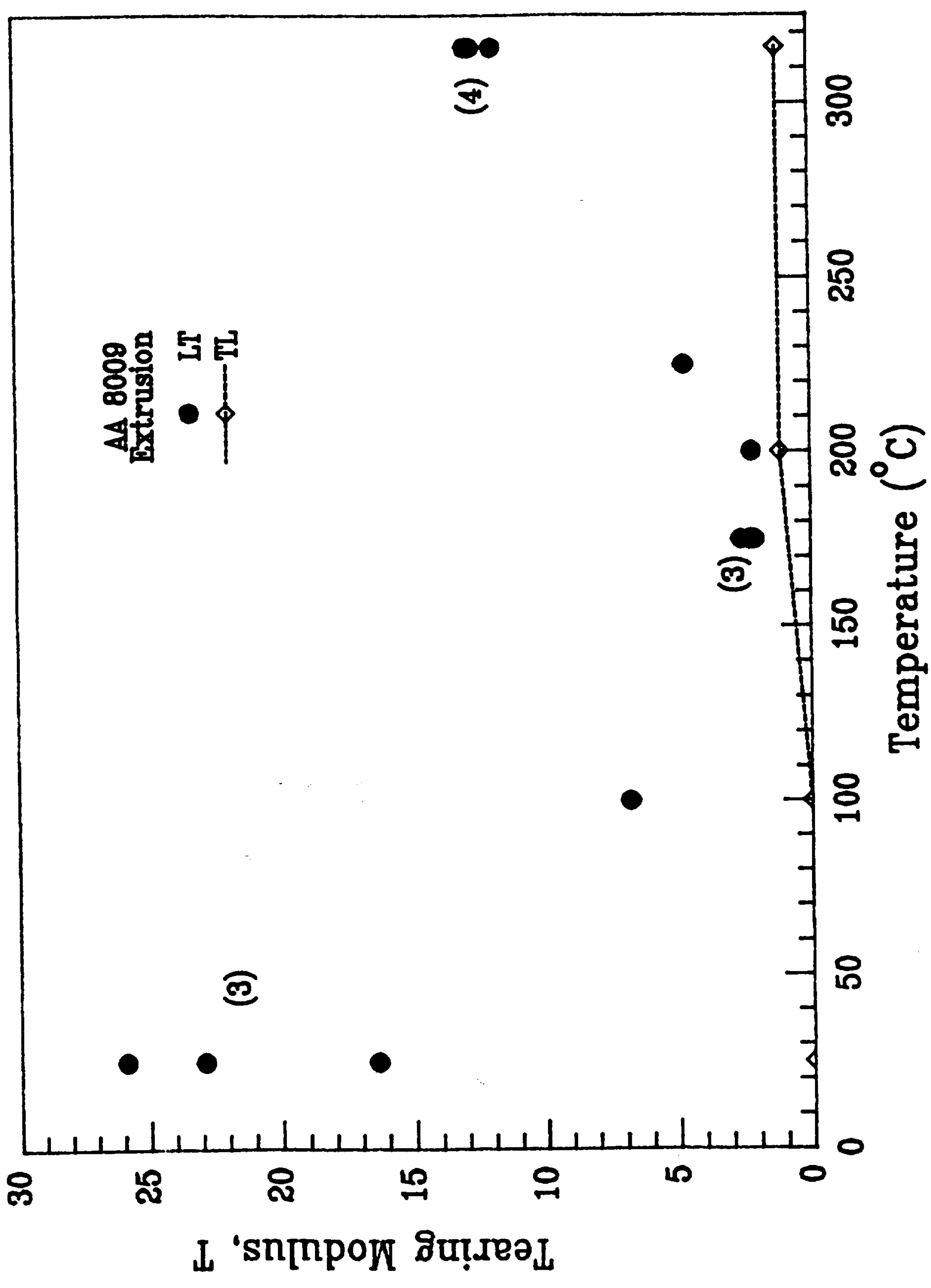
Potential (microvolts)
305
300
295
290
285
280
275
Load (kN)
3.0
2.5
2.0
1.5
1.0
0.5
0.0
Load-Line Displacement (mm)
0.0
0.1
0.2
0.3
0.4
AA 8009
LT Orientation
175°C
Δa - 1.55 mm
Load
Potential
J_{IC}
Initiation, J_i

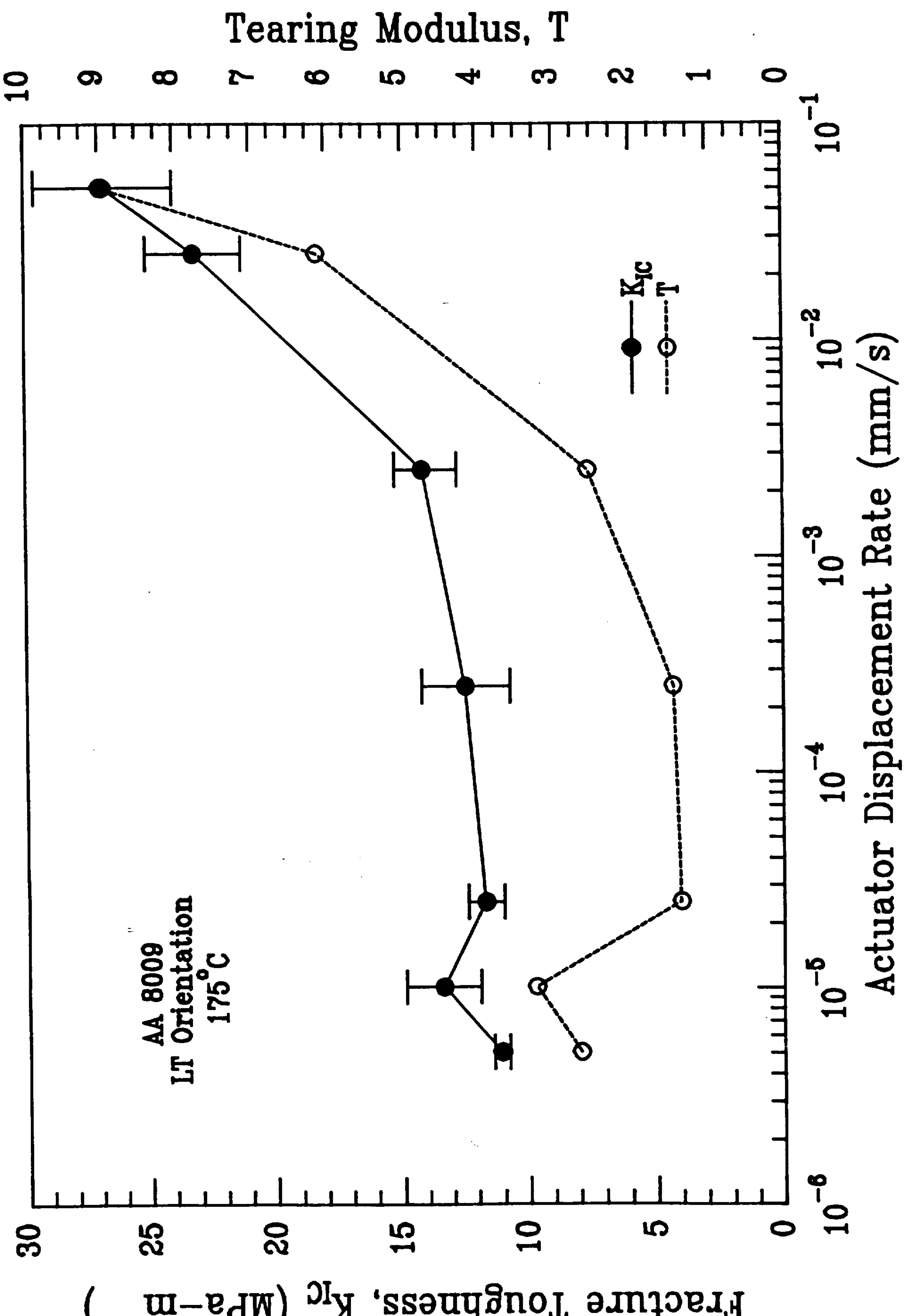


AA 8009
LT Orientation
175°C
J (kJ/m²)
delta a (mm)
$T = \frac{E}{\sigma_o^2}\left(\frac{dJ}{da}\right)$
$J = 8.32\,\Delta a^{0.366}$
$K_{IC} = \sqrt{\frac{J_I E}{1-\nu^2}}$
$J = 2\,\sigma_{ys}\,\Delta a$
J_{IC}
J_I
0 3 6 9 12 15
0.00 0.25 0.50 0.75 1.00 1.25 1.50 1.75 2.00


CONTROLLED TEMPERATURE
CHAMBER
-196 C TO 425 C
INSTRON 1362
SERVO-ELECTRIC
TEST SYSTEM
10,000X
AMPLIFIER
LOAD
INTERFACE
DC POWER
SUPPLY
LVDT
CONDITIONER
COMPUTER


AA 8009
Extrusion
K_{IC}, LT
K_{JIC}, LT
K_{IC}, TL
(4)
(4)
(4)
Temperature (°C)
Fracture Toughness, K_{IC} (MPa-m$^{1/2}$)
0
50
100
150
200
250
300
0
10
20
30
40
50


AA 8009
Extrusion
LT
TL
(3)
(3)
(4)
Temperature (°C)
Tearing Modulus, T
0
50
100
150
200
250
300
0
5
10
15
20
25
30



Tearing Modulus, T
10
9
8
7
6
5
4
3
2
1
0
AA 8009
LT Orientation
175°C
K_{IC}
T
10^{-6}
10^{-5}
10^{-4}
10^{-3}
10^{-2}
10^{-1}
Actuator Displacement Rate (mm/s)
30
25
20
15
10
5
0
Fracture Toughness, K_{IC} (MPa-m$^{1/2}$)

FRACTURE MECHANICS PARAMETERS FOR ELEVATED TEMPERATURE CRACKING KINETICS

"CREEP BRITTLE"---Crack growth is faster than the crack tip creep zone expansion rate

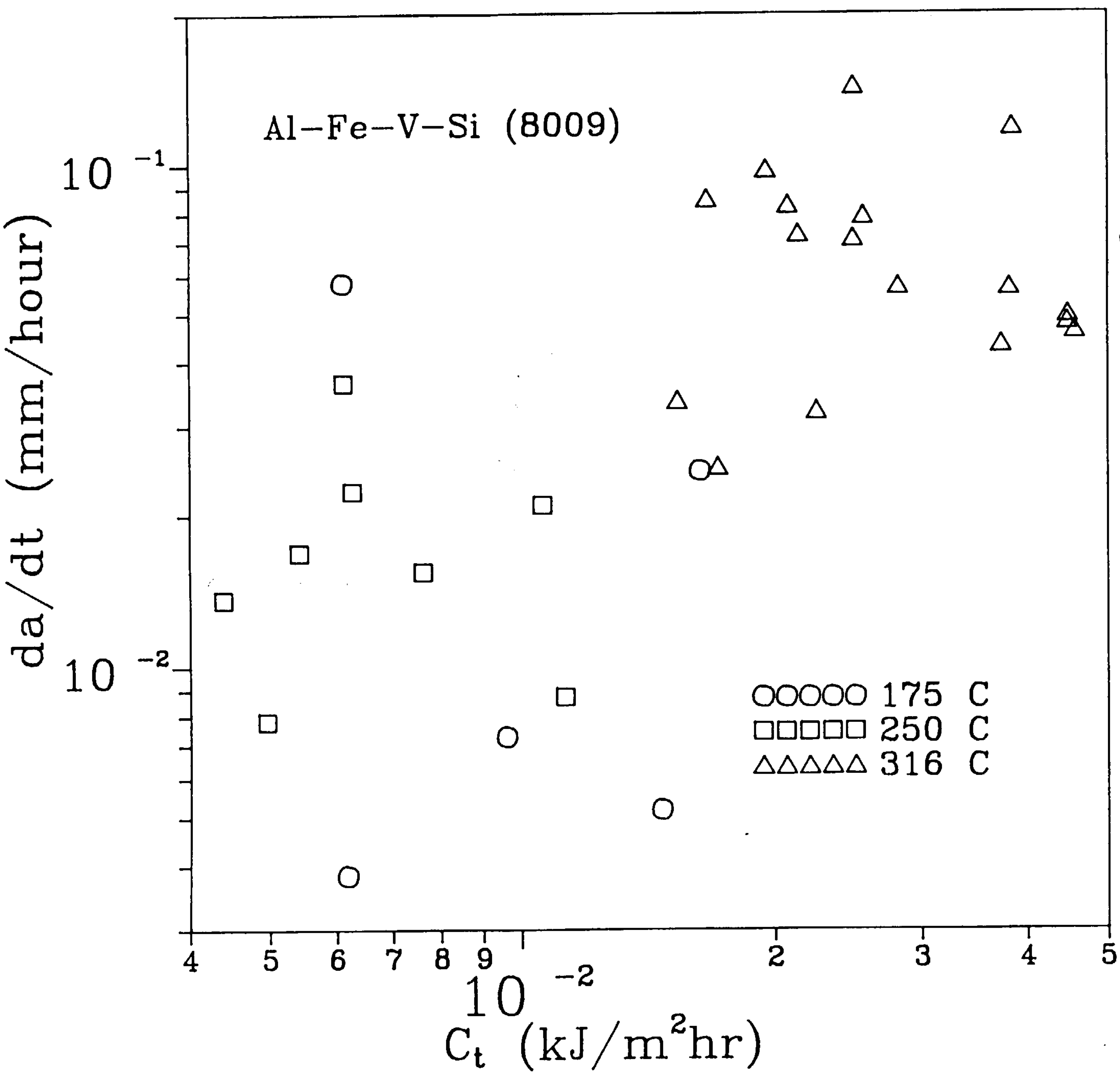
- oo Stress Intensity Factor
- oo J-integral

"Creep Ductile"---Process zone or ligament deformation occur at substantial rate compared to da/dt

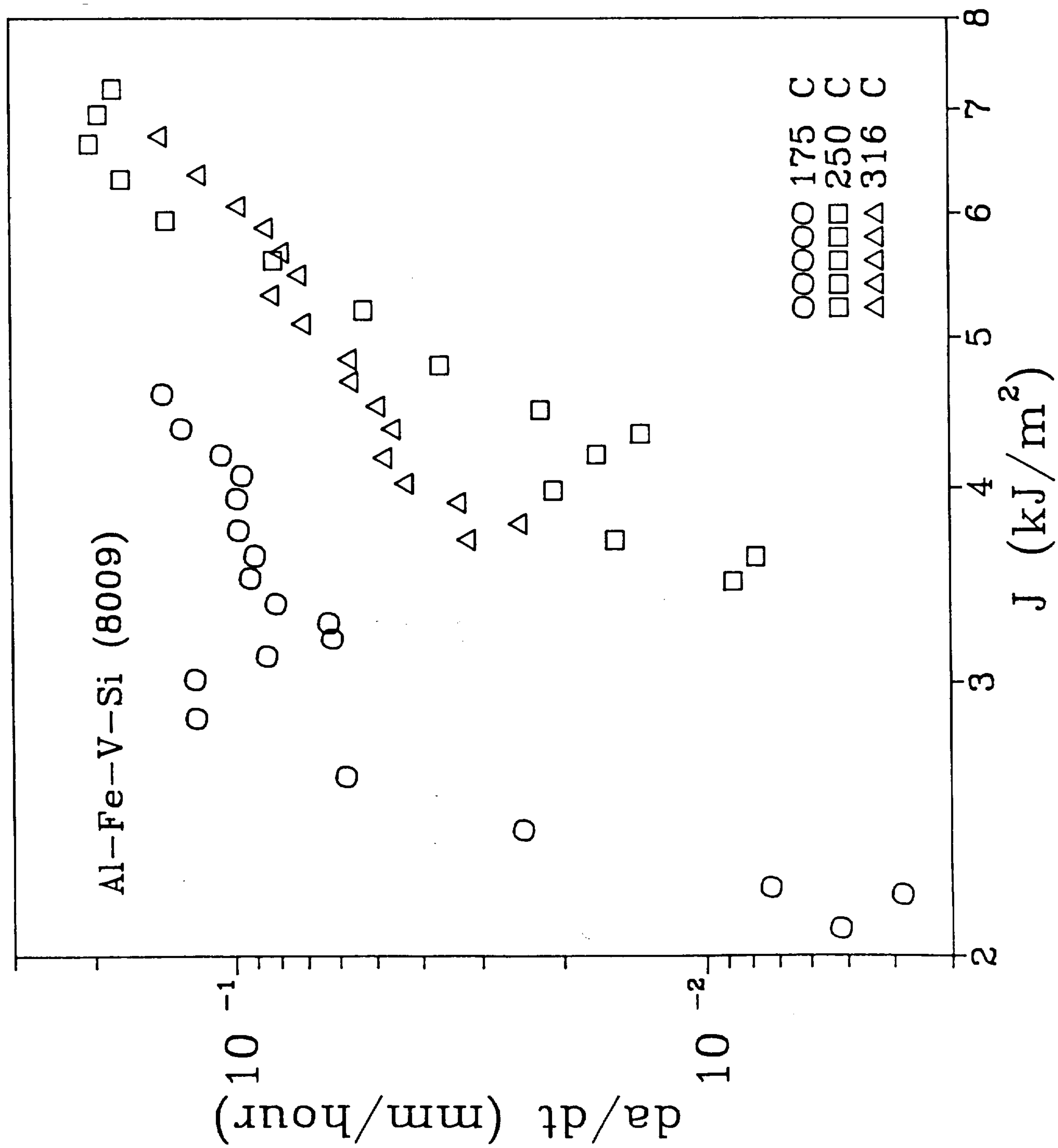
- oo $C^*(t)$ Path independent energy rate integral and amplitude of HRR strain rate field for large scale primary and steady state creep

- oo $C(t)$ Amplitude of HRR strain rate field for small scale transient to extensive creep regimes

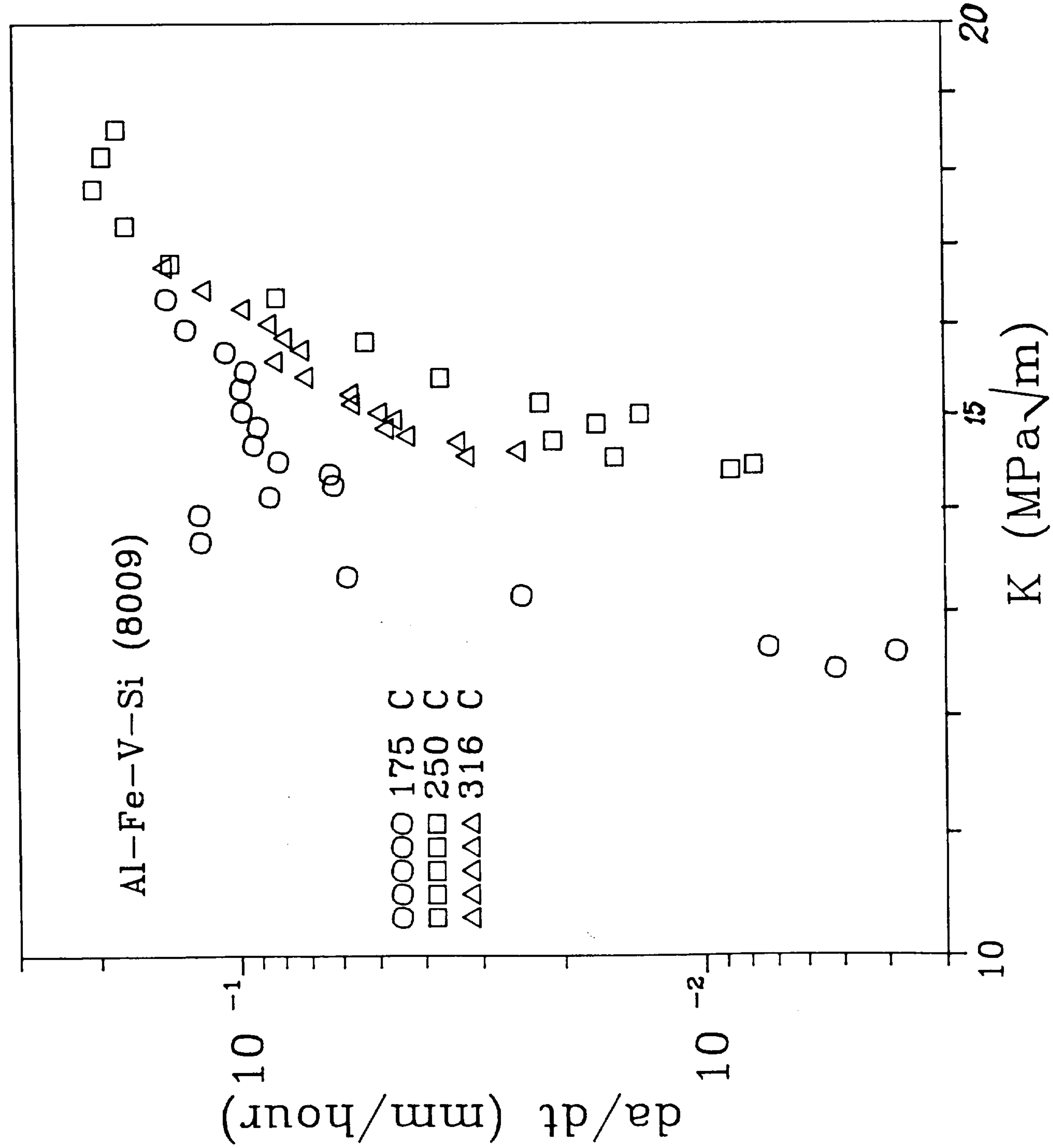
- oo C_t Energy dissipation rate integral relating creep zone expansion rate for small scale transient to extensive creep regimes



Al–Fe–V–Si (8009)
da/dt (mm/hour)
10^{-1}
10^{-2}
○○○○○ 175 C
□□□□□ 250 C
△△△△△ 316 C
4
5
6
7
8
9
2
3
4
5
10^{-2}
C_t (kJ/m^{2}hr)



Al–Fe–V–Si (8009)
175 C
250 C
316 C
J (kJ/m^2)
da/dt (mm/hour)
10^{-1}
10^{-2}
2
3
4
5
6
7
8



Al–Fe–V–Si (8009)
175 C
250 C
316 C
K (MPa√m)
10
15
20
da/dt (mm/hour)
10^-1
10^-2

POSSIBLE CAUSES

Delamination Toughening

-- Extrinsic

Creep

-- Novel Mechanism Due To Ultra Fine Microstructure

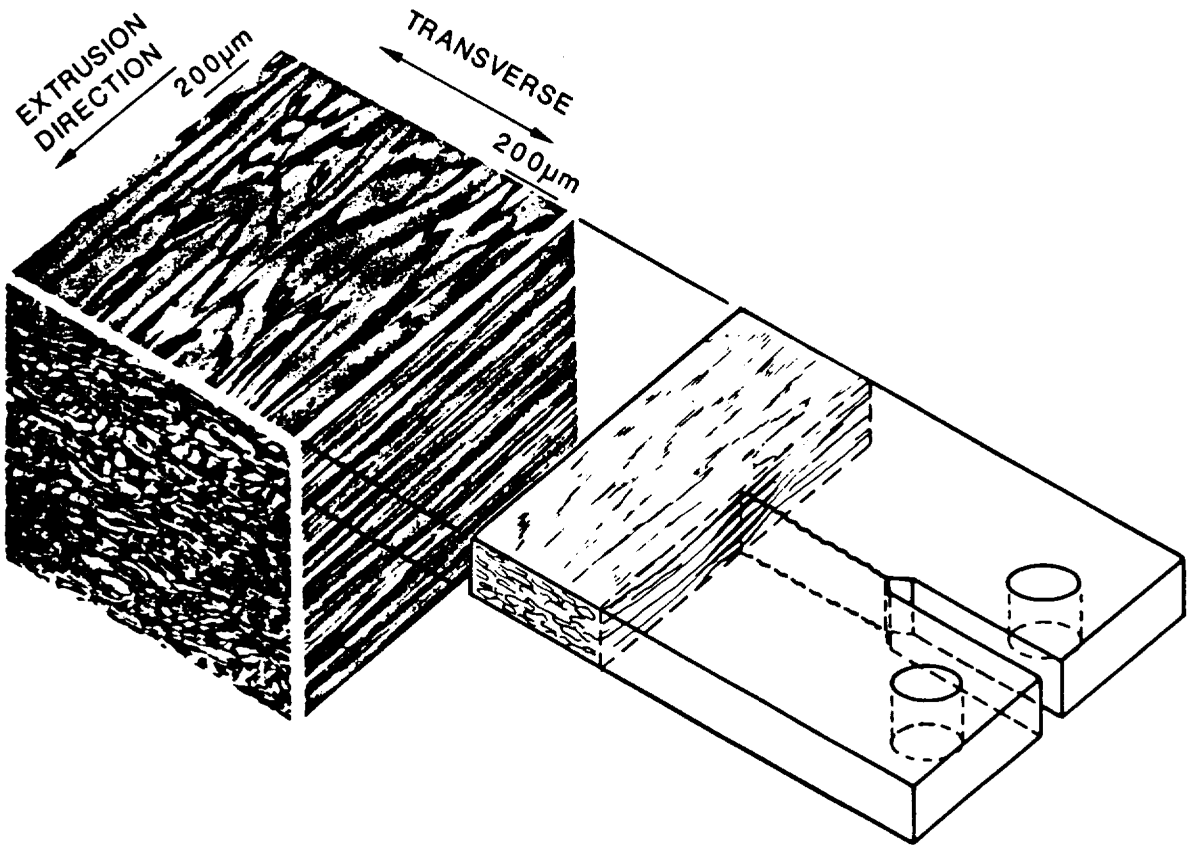
Environment

-- Oxidation

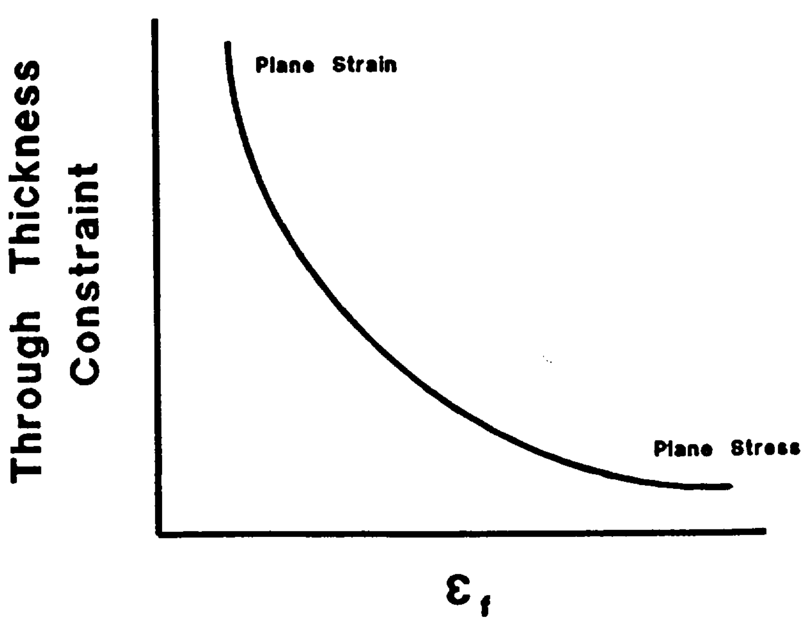
-- Hydrogen Embrittlement

Dynamic Strain Aging

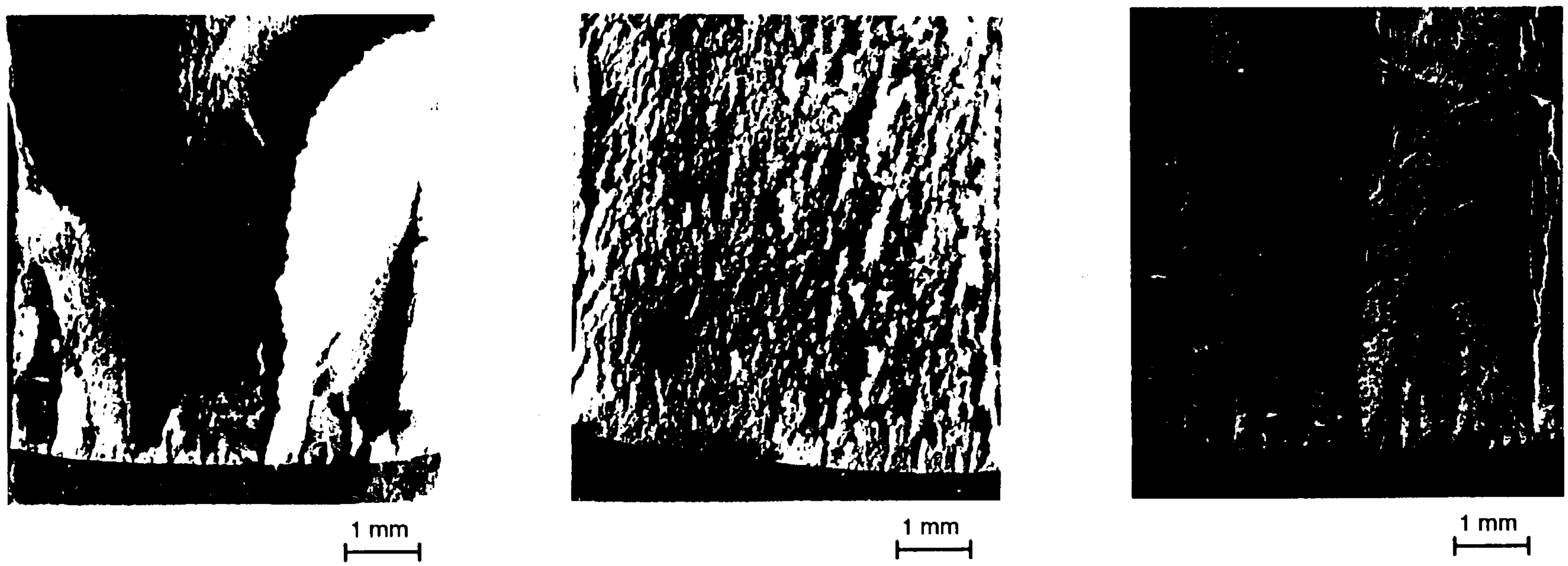
-- Greater than equilibrium substitutional solute concentration



EXTRUSION DIRECTION
200μm
TRANSVERSE
200μm

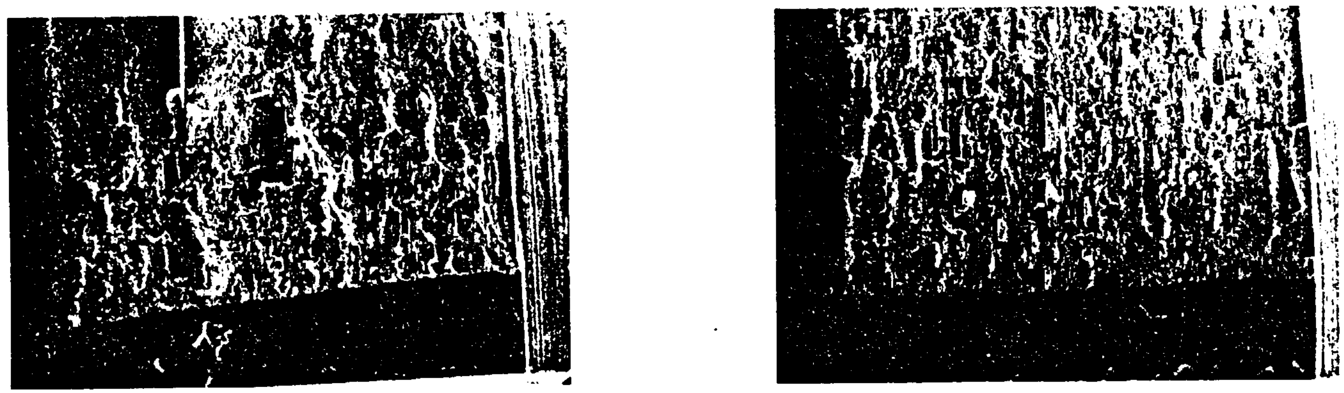


Through Thickness Constraint
Plane Strain
Plane Stress
ε_f



(a) 25 C (b) 200 C (c) 316 C

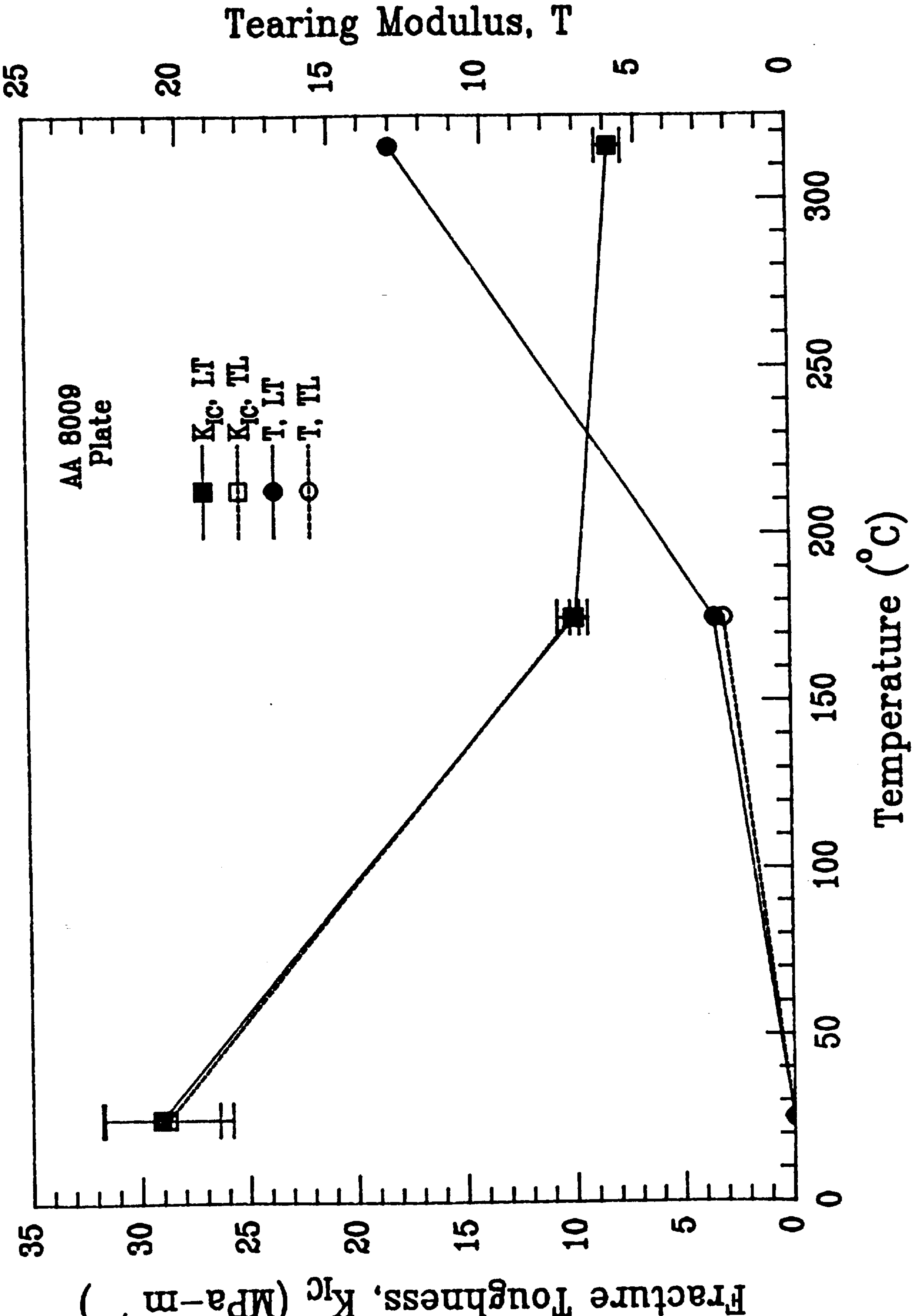
Low magnification SEM photographs of FVS0812 fracture surfaces for different test temperatures.



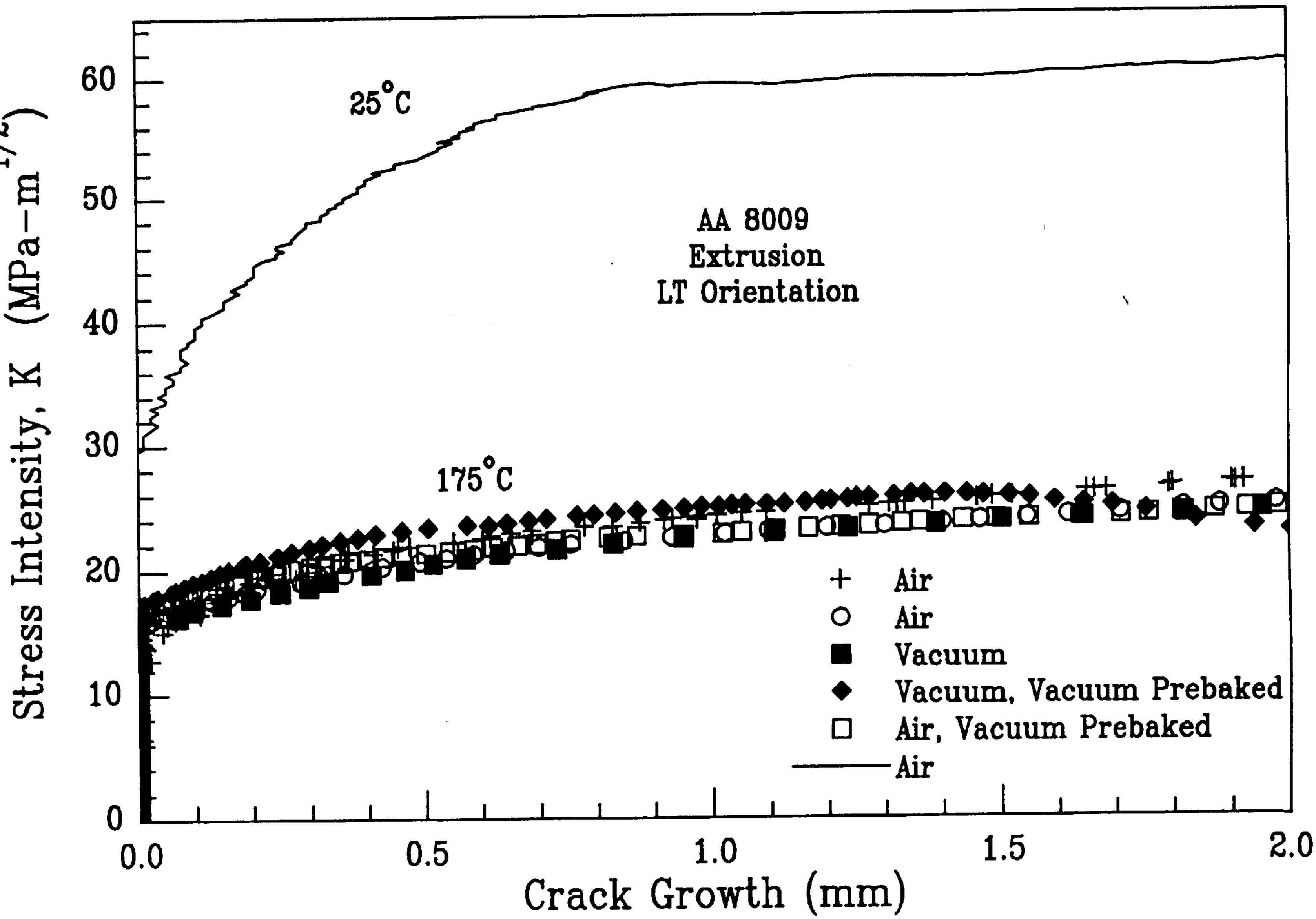
25° C　　　175° C

2 mm

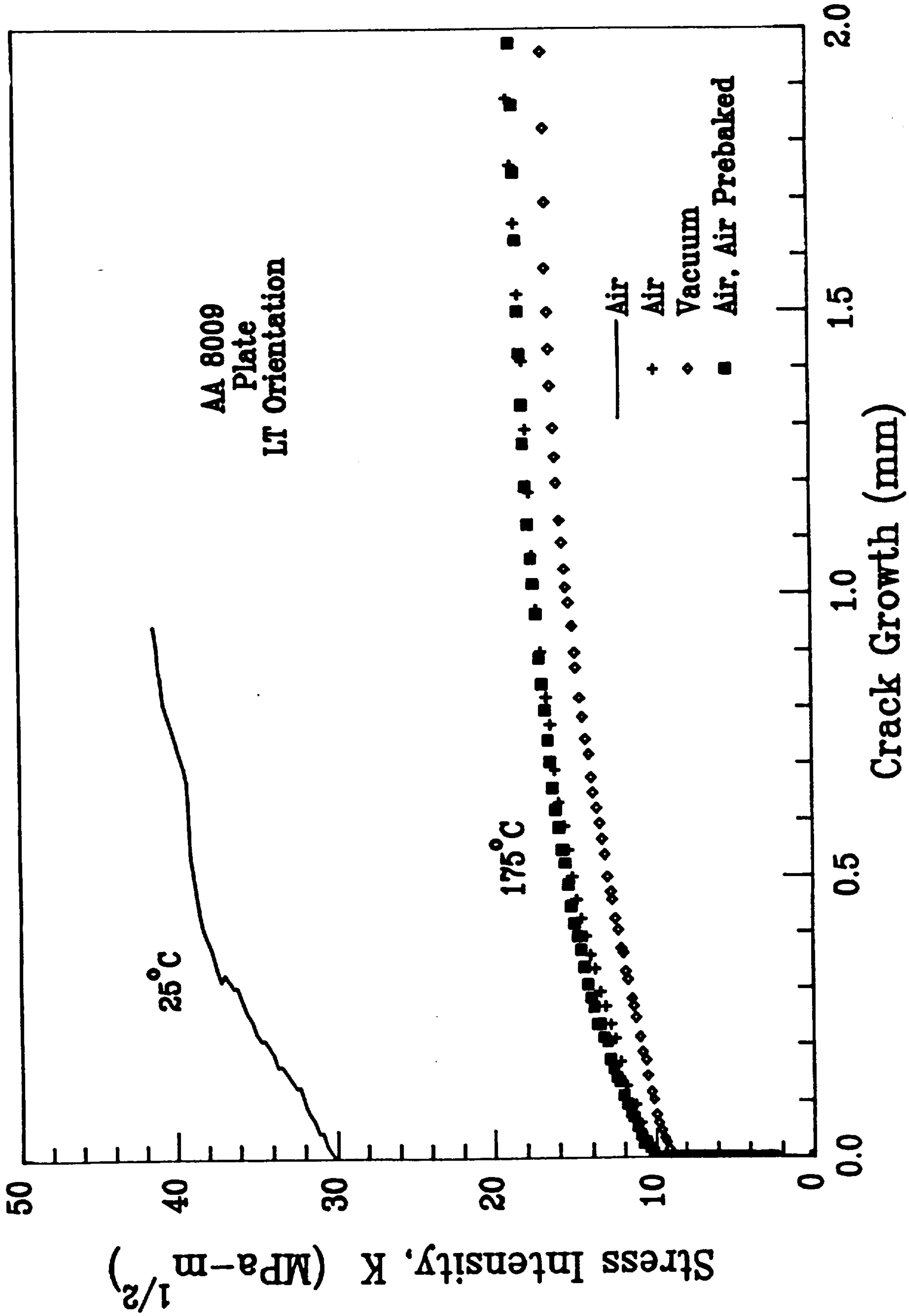
Low magnification SEM photographs of AA 8009 plate fracture surfaces tested in air

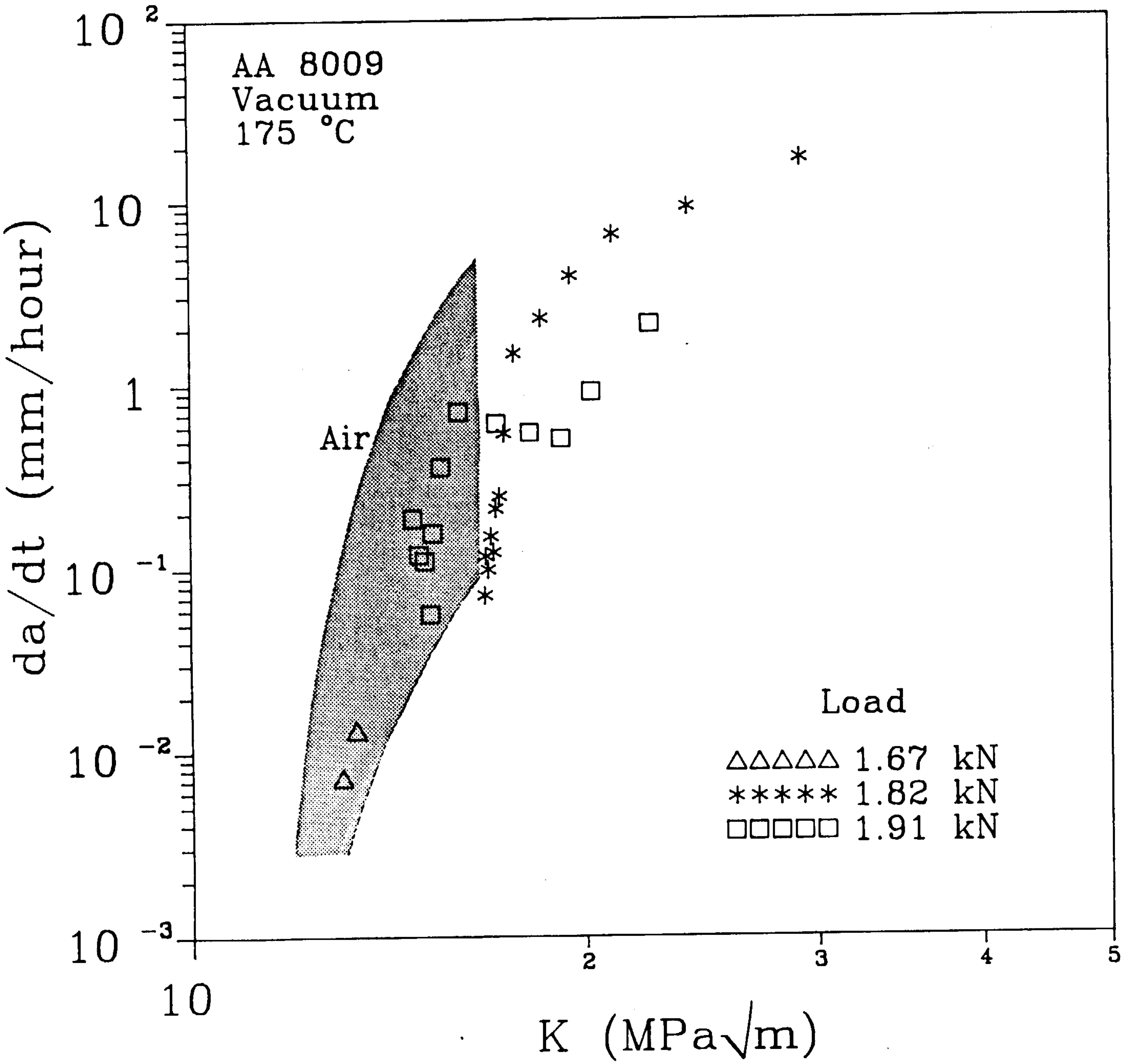


Tearing Modulus, T
25
20
15
10
5
0
AA 8009
Plate
K_{IC}, LT
K_{IC}, TL
T, LT
T, TL
0
50
100
150
200
250
300
Temperature (°C)
35
30
25
20
15
10
5
0
Fracture Toughness, K_{IC} (MPa-m$^{1/2}$)

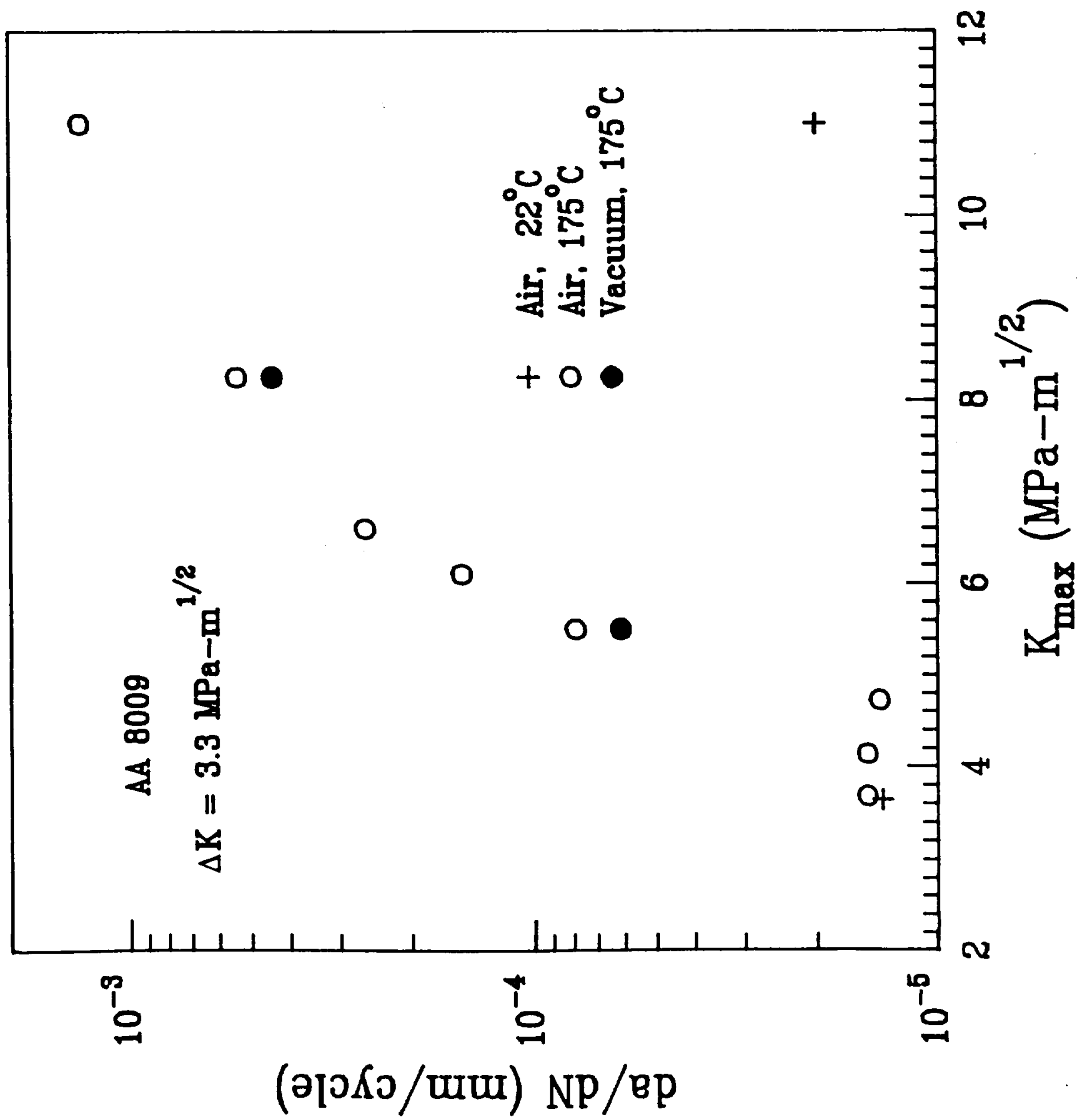


25°C
175°C
AA 8009
Extrusion
LT Orientation
Air
Air
Vacuum
Vacuum, Vacuum Prebaked
Air, Vacuum Prebaked
Air
Stress Intensity, K (MPa-m^1/2)
Crack Growth (mm)
0
10
20
30
40
50
60
0.0
0.5
1.0
1.5
2.0


AA 8009
Plate
LT Orientation
25°C
175°C
Air
Air
Vacuum
Air, Air Prebaked
Crack Growth (mm)
Stress Intensity, K (MPa-m^1/2)
0.0
0.5
1.0
1.5
2.0
0
10
20
30
40
50



AA 8009
Vacuum
175 °C
Air
Load
△△△△△ 1.67 kN
∗∗∗∗∗ 1.82 kN
□□□□□ 1.91 kN
da/dt (mm/hour)
K (MPa√m)


AA 8009
ΔK = 3.3 MPa-m^1/2
+ Air, 22°C
○ Air, 175°C
● Vacuum, 175°C
K_max (MPa-m^1/2)
da/dN (mm/cycle)
2
4
6
8
10
12
10^-5
10^-4
10^-3

HYDROGEN CONTENT

- Hydrogen content of AA 8009 determined by vacuum fusion technique:
  - As received: 4.3 ± 0.3 ppm
  - Vacuum heat treated at 330°C and fractured in vacuum at 175°C: 4.4 ± 0.2 ppm
  - As received and fractured in air at 175°C: 4.3 ± 0.1 ppm
  - Allied–Signal (D. Raybould): ≈ 3 ppm

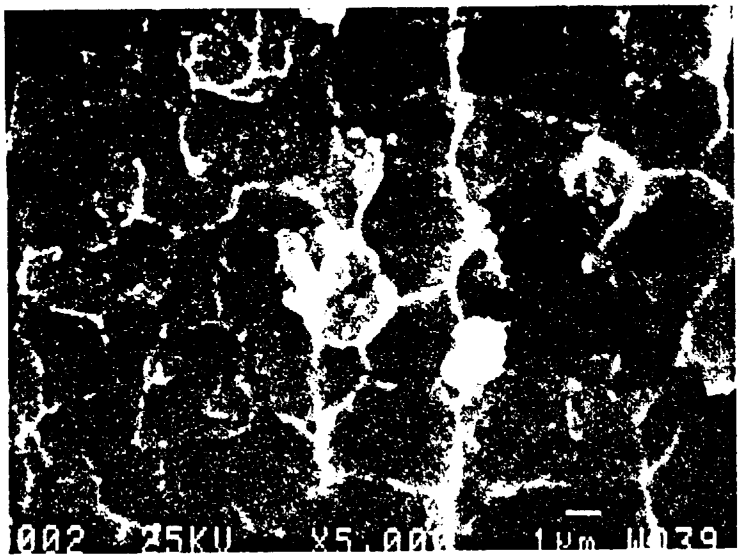
FRACTOGRAPHY

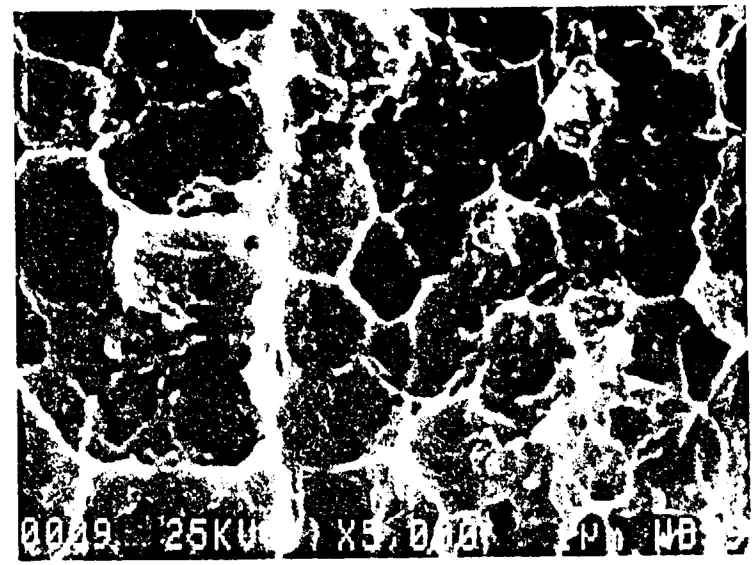
- Precision matching of fracture surfaces, coupled with stereo pairs fractography, indicated a locally plastic fracture mode at 25 and 175°C, in air and vacuum.

  - 25°C: dual distribution of dimples – .5 to 2 μm and 4 to 8 μm

  - 175°C: uniform distribution of shallow dimples – 2 to 4 μm

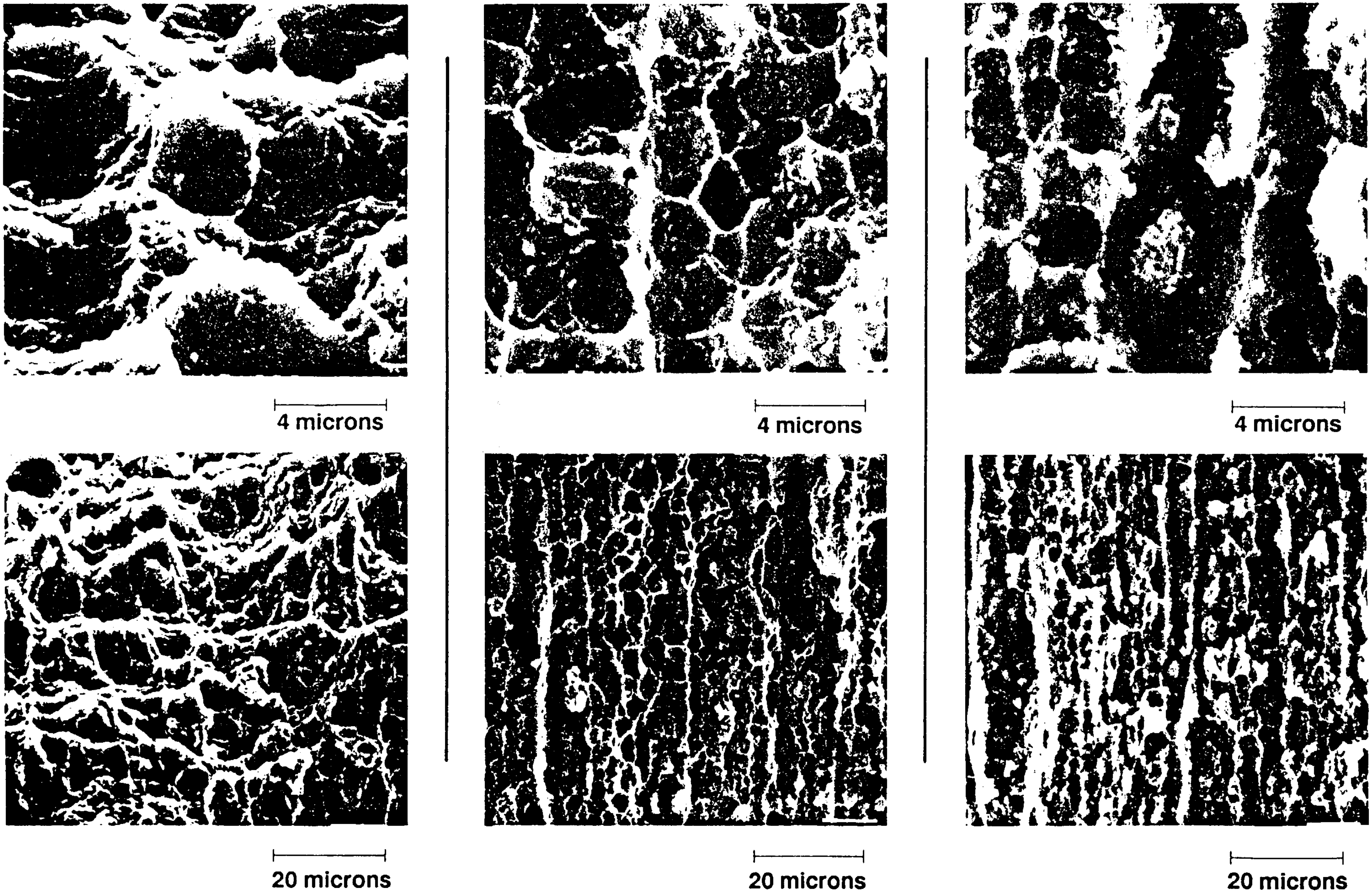
- Oxides critical?
- Boundary cracking?



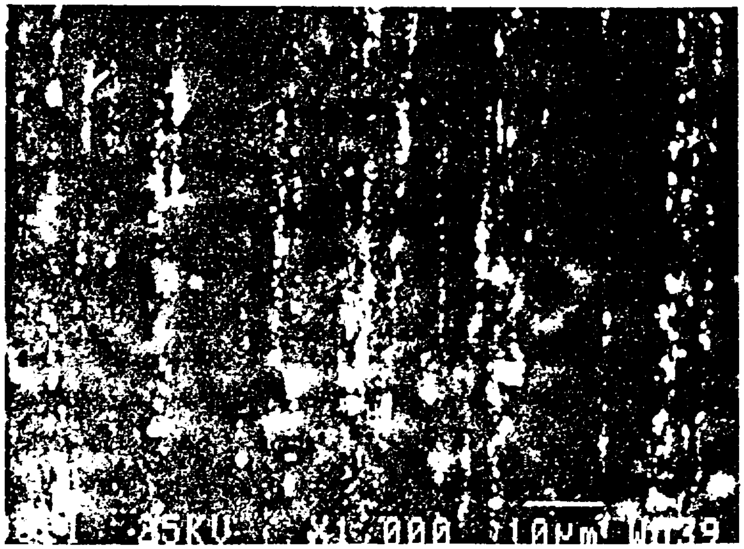


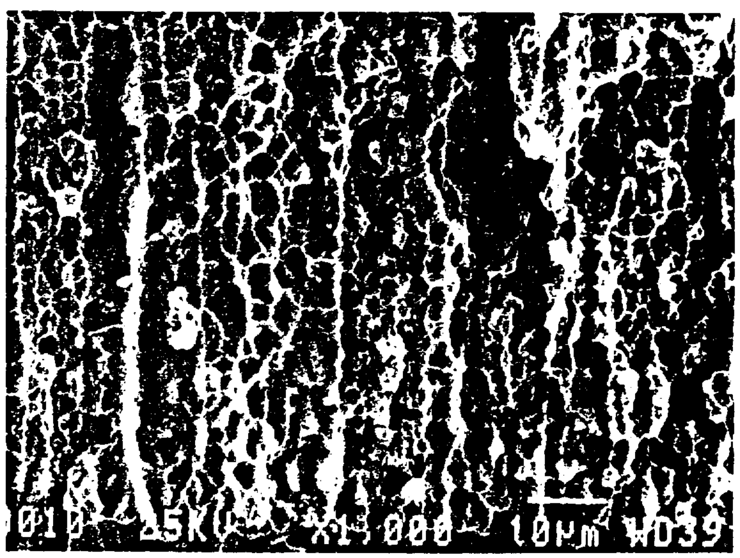
4 microns

High magnification SEM photographs of matching fracture surface features.
Specimens tested in air at 175° C.



25° C, Air | 175° C, Air | 175° C, Vacuum





20 microns

SEM micrographs of AA 8009 plate with oxide distribution and accompanying fracture surface (Fractured in Air, 175°C)

DYNAMIC STRAIN AGING

- None of the proposed mechanisms are supported by microscopic observations

  - Localized solid solution strengthening resulting in localized deformation

    -- could explain similar behavior in MA Al–Ti

TEMPERATURE ENHANCED DEFORMATION

- Temperature enhanced dislocation flow without accompanying grain boundary sliding results in intergranular cavity formation.

  - no microscopic evidence (yet) of intergranular cavity formation

CONCLUSIONS: PHENOMENOLOGY

- Elevated temperature damage tolerance degradation appears generic to the advanced PM aluminum alloys.

- AA 8009 exhibits *intrinsic* ductility and toughness decreases with increasing temperature.

- AA 8009 exhibits decreased toughness with decreasing loading rate at 175°C.

- AA 8009 is susceptible to elevated temperature, time dependent crack growth at K levels less than K_{IC} in both air and vacuum environments. Threshold K for crack growth is equal to slow loading K_{IC}.

- AA 8009 is creep brittle; crack growth rates can be correlated to K, and more properly, J.

- For a given applied J (K), time dependent crack growth rate is high at 175°C and decreases with increasing temperature to 316°C for 8009.

CONCLUSIONS: MECHANISM

- The unusual intrinsic mechanical behavior of AA 8009 is not the result of moist air environmental embrittlement.

- The hydrogen content of AA 8009 does not change with long term, elevated temperature moist laboratory air exposure and retained hydrogen is not mobile at temperatures as high as 330°C.

- Fractography indicated a ductile mode of fracture at 25 and 175°C, in air and vacuum. Differences in feature sizes with temperature, but not environment, were apparent. Oxides from processing may be critical in the fracture evolution.

- Degradation of the damage tolerance of AA 8009 at elevated temperatures is most likely due to dynamic strain aging or a unique temperature dependent deformation mechanism.

FUTURE WORK

- Continue microscopy of failed fracture mechanics specimens and sectioned notched bars from interrupted tensile experiments.

- Develop defendable mechanism for elevated temperature damage tolerance degradation of AA 8009.

- Complete PhD. Dissertation by July 1, 1992.