Fatigue crack propagation accelerated by mercury immersion

Japan Atomic Energy Agency

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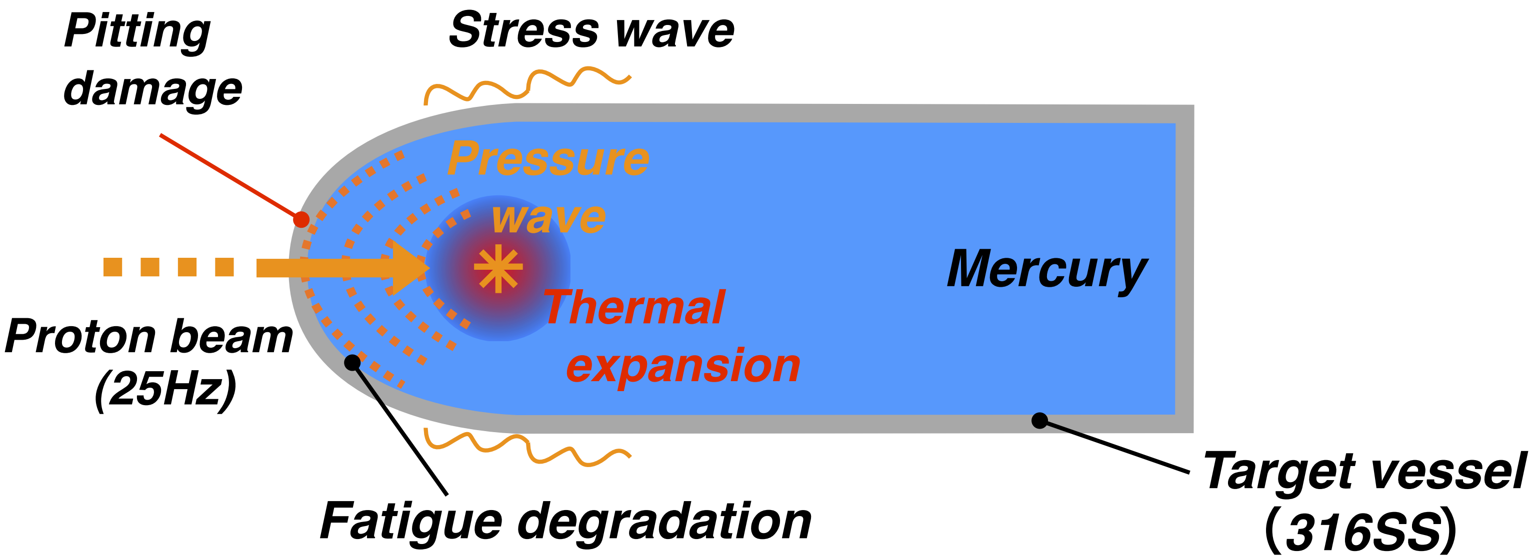
Contents

- **Motivation and purpose**
- **Bending fatigue test in mercury**
  - with large indent — *Briefly explain the previous experiment*
  - **with notch** — *To investigate the fatigue crack propagation*
- **Fatigue crack propagation**
  - **Crack length estimated by FRASTA method with O.D. measurement** *(**FRA**cture **S**urface **T**opography **A**nalysis)*
  - **Crack growth rate VS. Stress intensity factor**
- **Summary**

Motivation



Liquid mercury target

- **Mercury target vessel is exposed to severe environments**

  Radiation damage, Pressure wave, Cavitation damage, Repeated stress

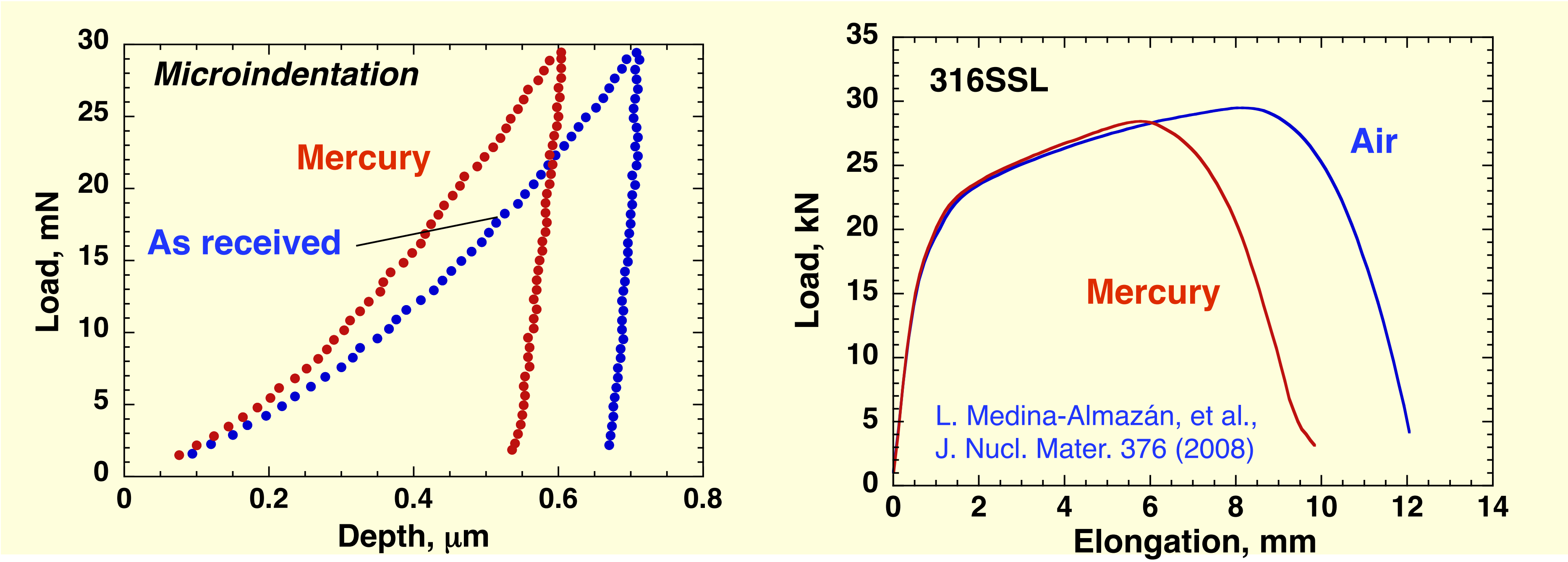
  Remarkably decreases the structural integrity of the target vessel

- **To improve the structural integrity;**

  Surface modification, Microbubble injection into the mercury

- **Liquid Metal Embrittlement (LME) may decrease the structural integrity**

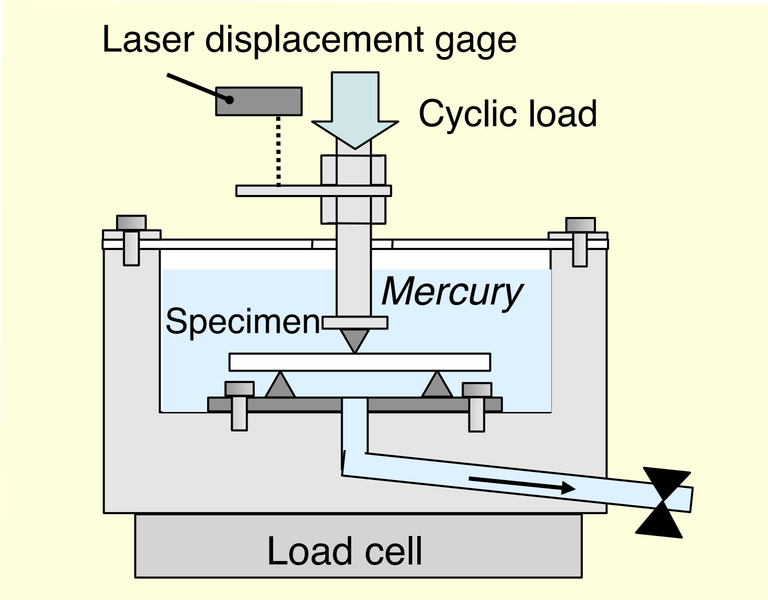
LME between mercury and 316SS



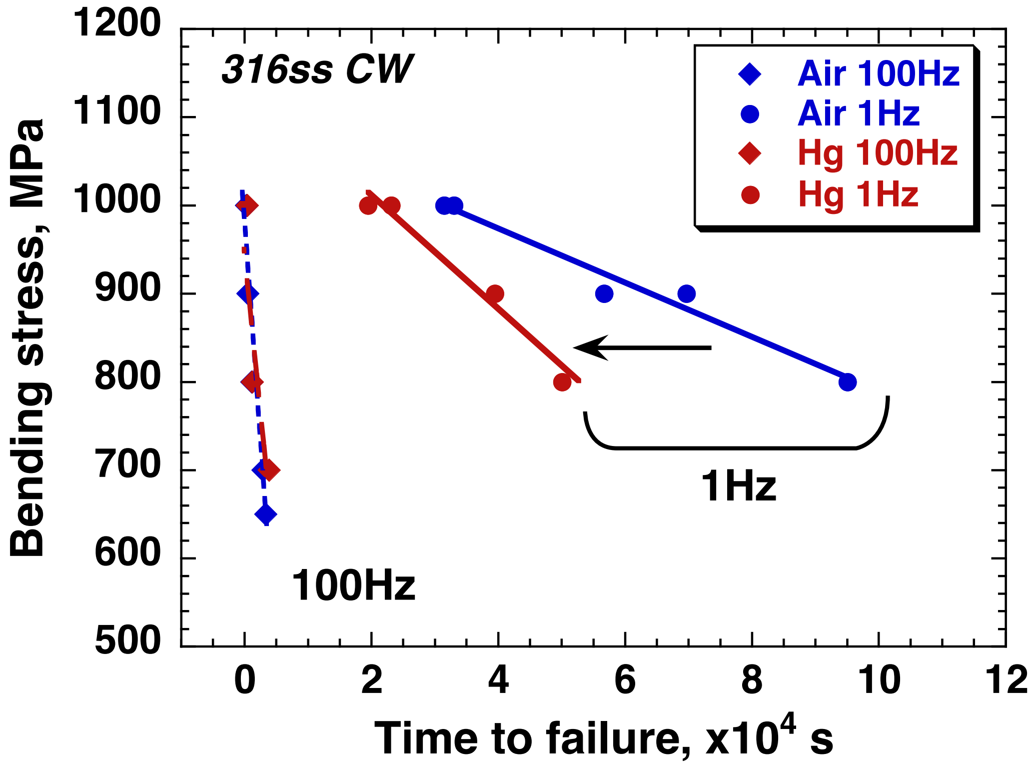
- **LME occurs in the specific combination between the solid and liquid metals**
- **Sub surface layer hardened after mercury immersion**
- **Static elongation decreased by mercury immersion**
- **Degradation of low cycle fatigue strength was reported.**

Strizak, et al, J.Nucl. Mater. 343 (2005), Futakawa, et al., J.Nucl. Mater. 356 (2006).

Fatigue strength in mercury



3-point bending fatigue test

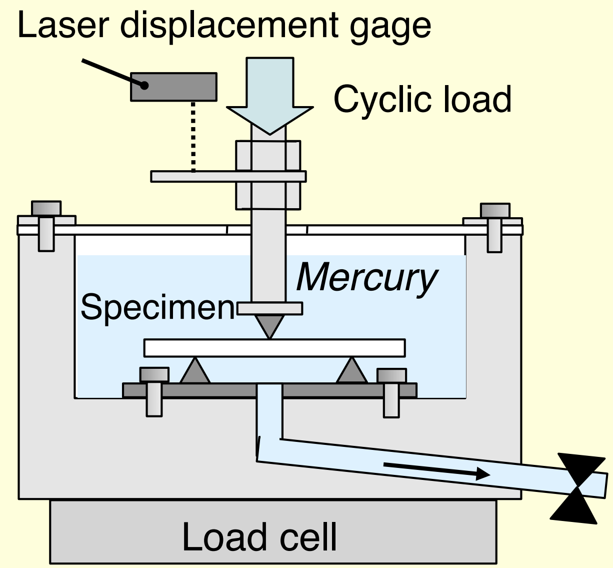


- Fatigue strength in mercury decreased depending on the time
- Displacement just before failure was slightly accelerated by mercury
- Detailed information on fatigue crack propagation was not obtained
  (the specimen was fully-immersed in mercury)

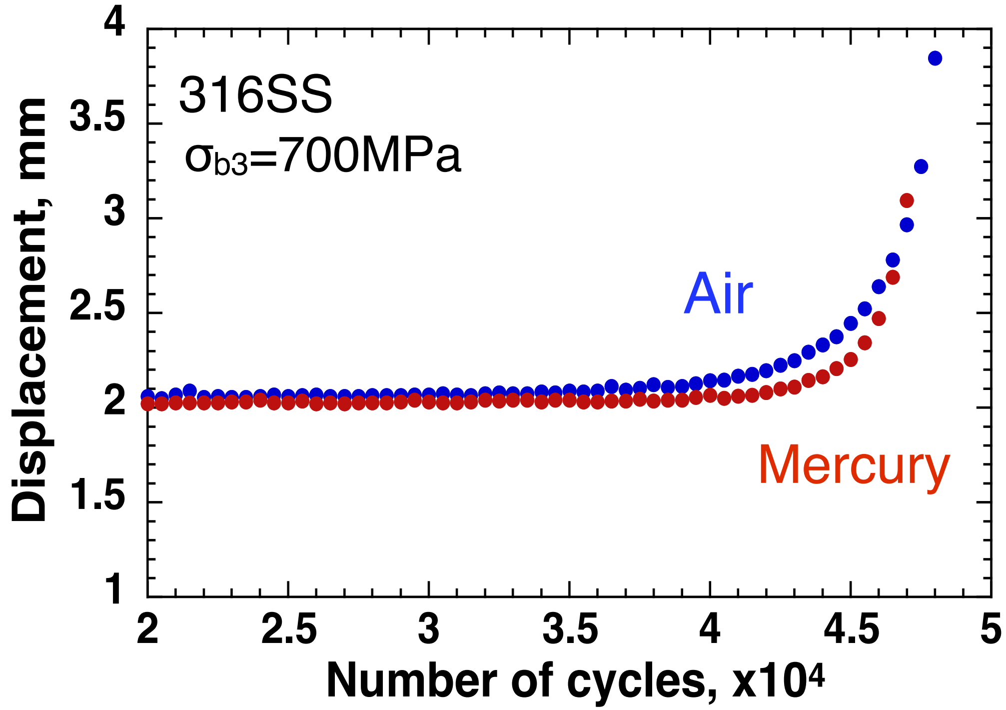
Purpose in this work

Evaluation of the effect of mercury on fatigue crack propagation

Fatigue strength in mercury



3-point bending fatigue test



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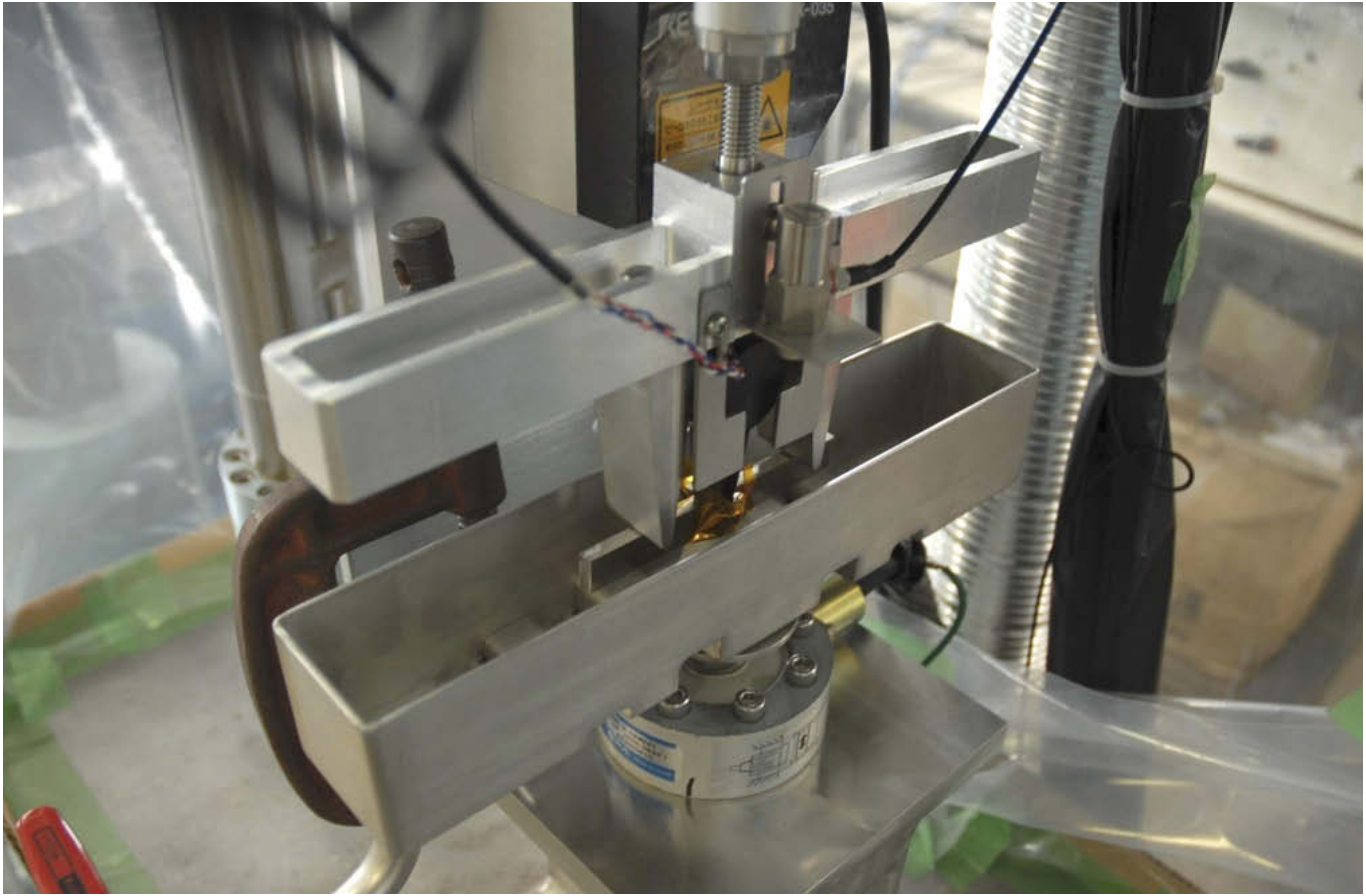
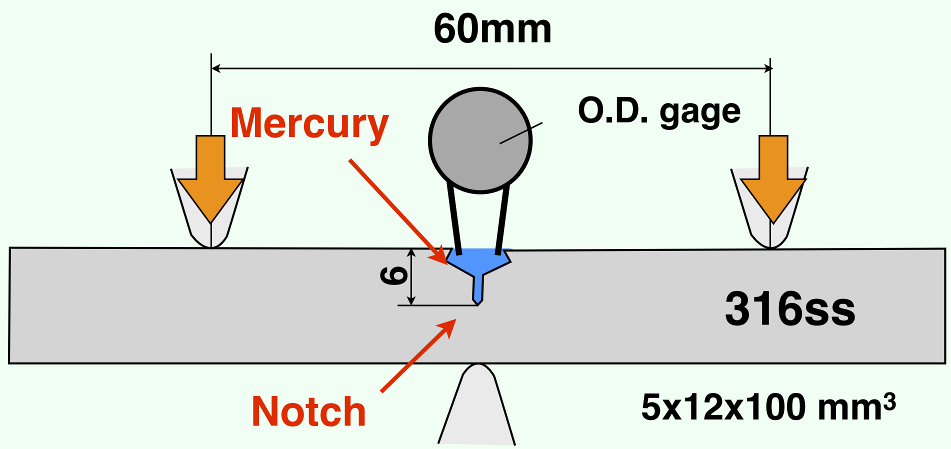
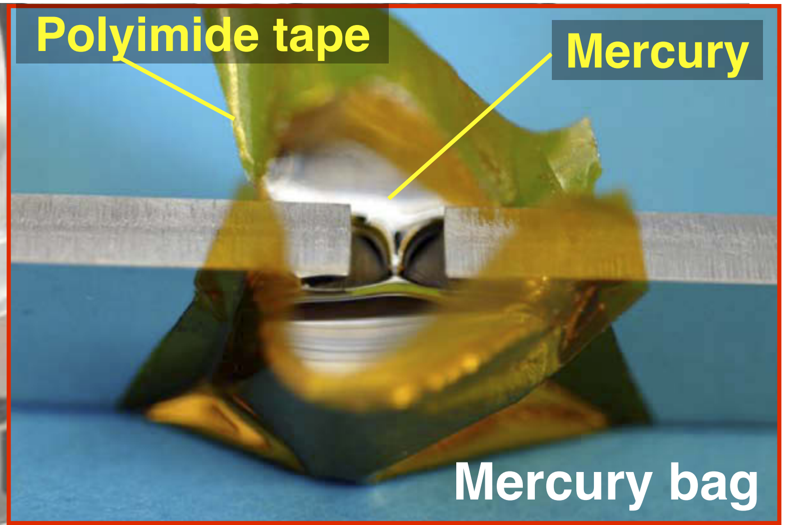
V-notch fatigue test



V-notch fatigue test



3-point bending fatigue test with V-notch



Specimen: 316ss (5x12x100mm)
Load control: Sine wave
Stress ratio: Max./Min.=0.1

Frequency: 1 Hz --Mercury effects depends on testing time
Based on the previous experiment

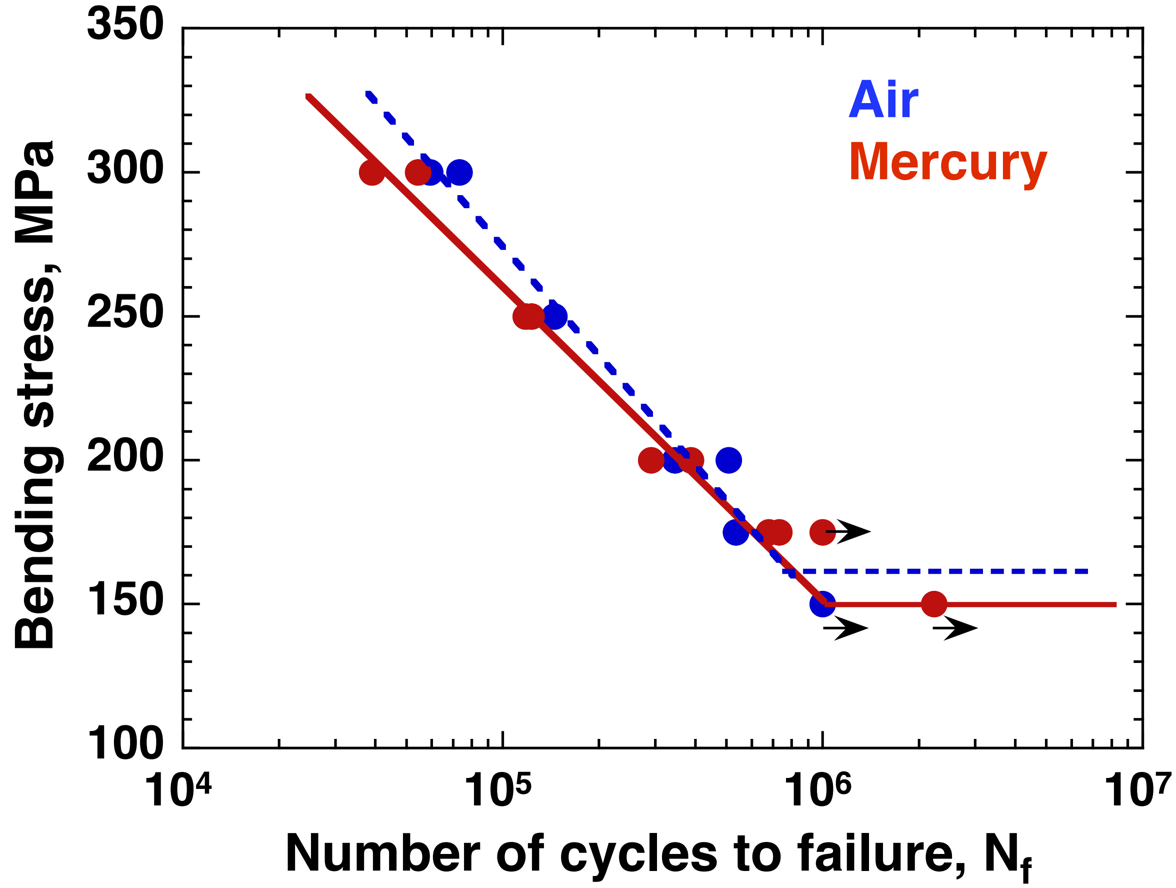
- Prepared V-notch (6mm in depth) to limit the failure point and partly immerse in mercury
- Filled mercury (2cc) in mercury bag for mercury condition
- Measured opening distance of the notch to estimate the crack length

S-N curves

Bending stress

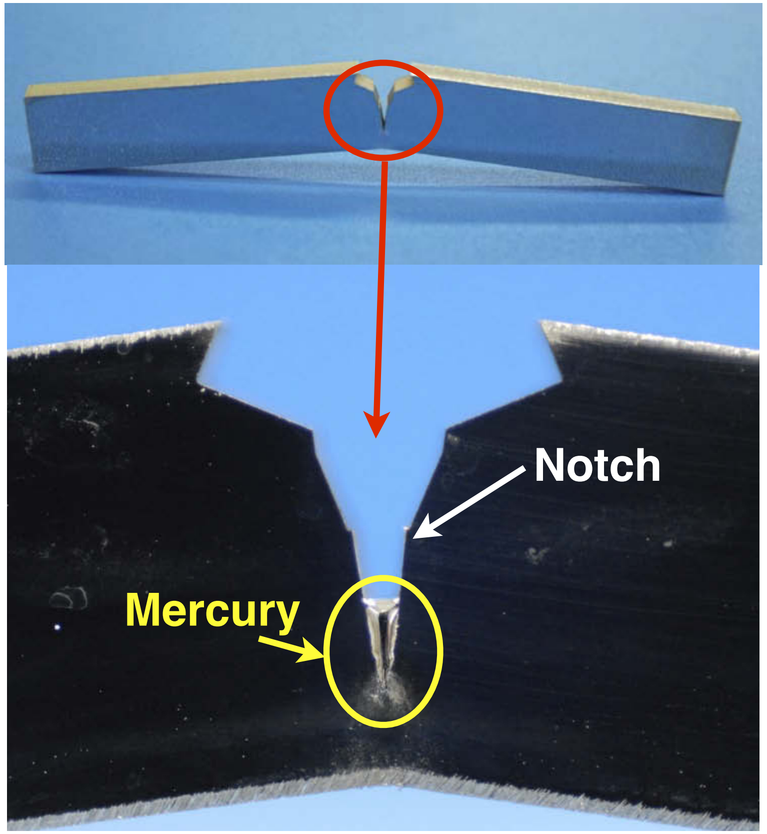
$$\sigma_{b3} = \frac{3PL}{2bd^2}$$

P: Max. load
L: Span
b,d: Width and thickness

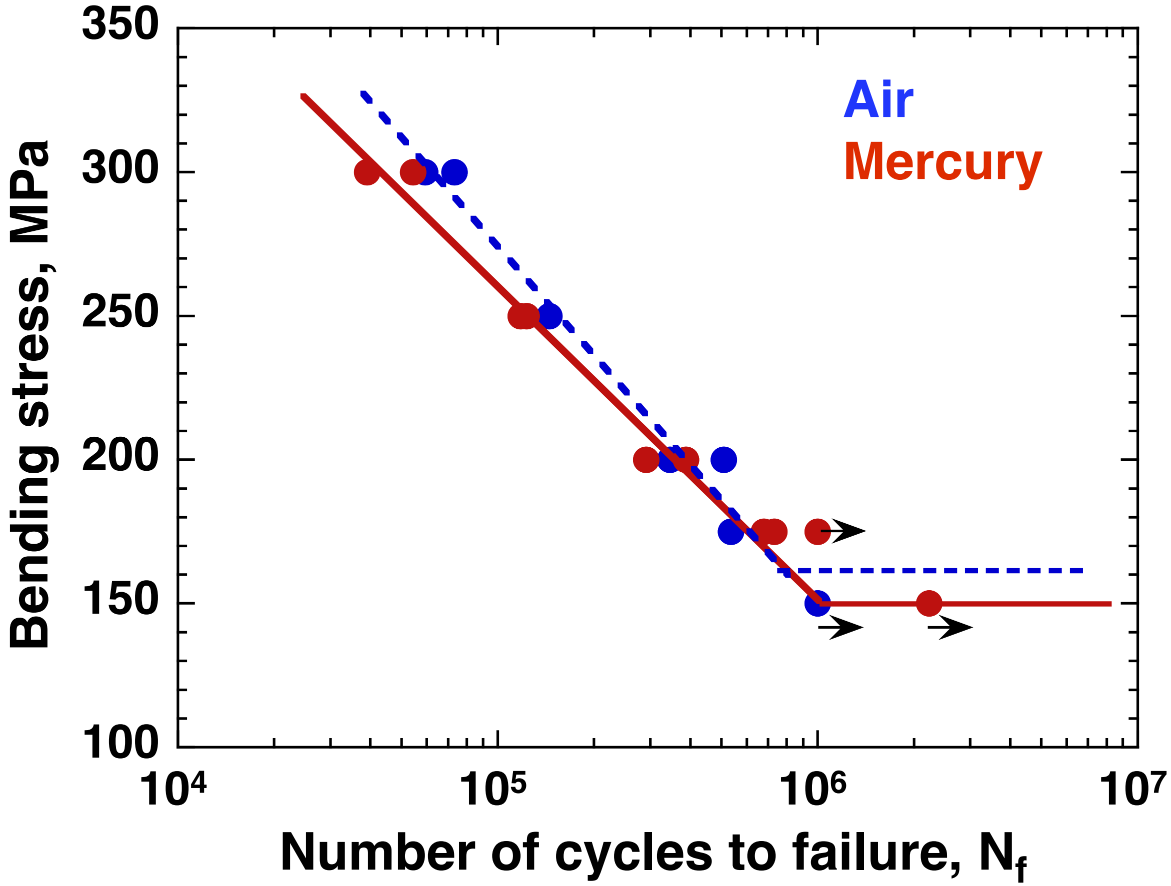


- **Crack tip completely-wet from mercury**
- **N_f in high-stress imposed area was decreased by mercury**
- **N_f in low stress imposed area was increased by mercury**

S-N curves



Crack tip after failure



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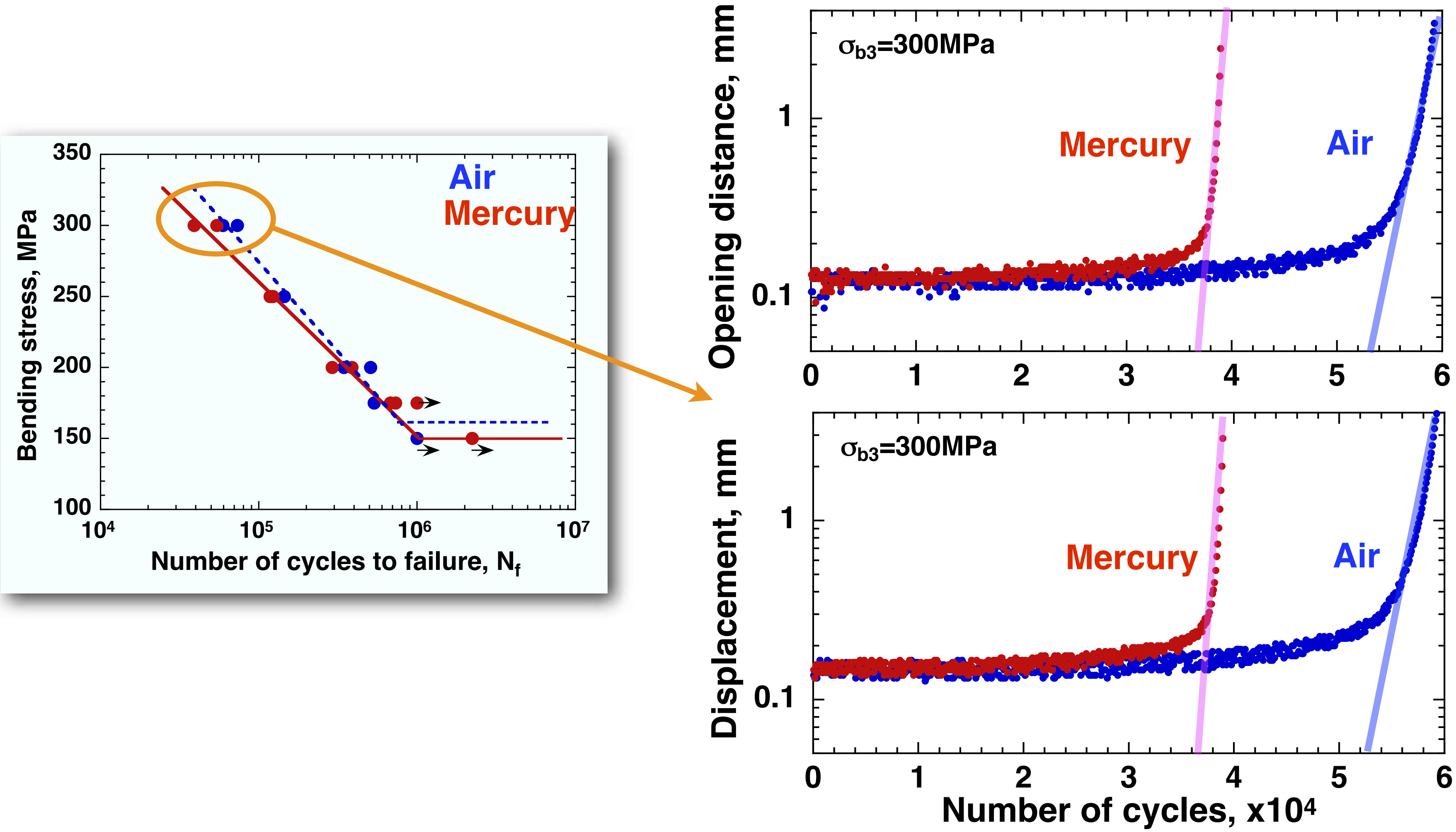
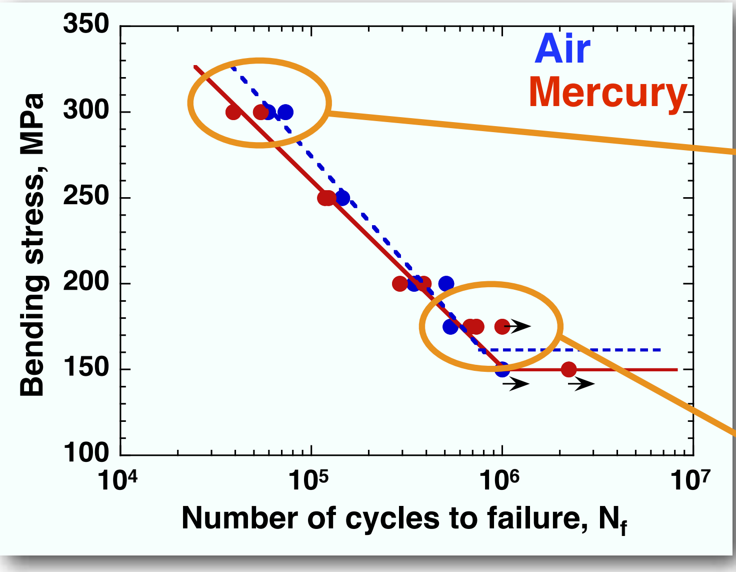
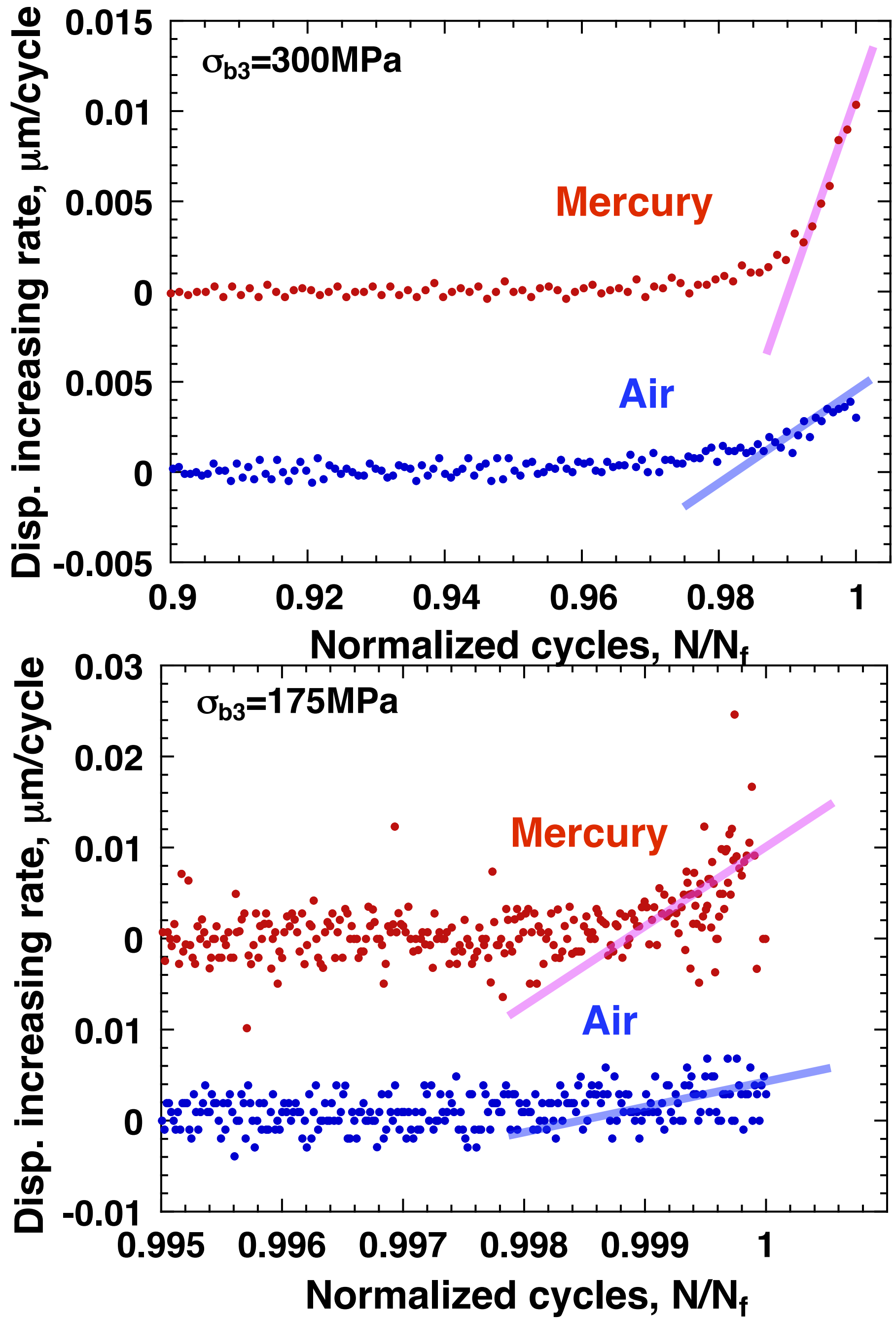
Opening distance



- Confirmed an adequate correlation between the opening distance and the crosshead displacement
- Opening distance for mercury case at just before failure was sharply increased compared with the air case.

Increasing rate of the displacement





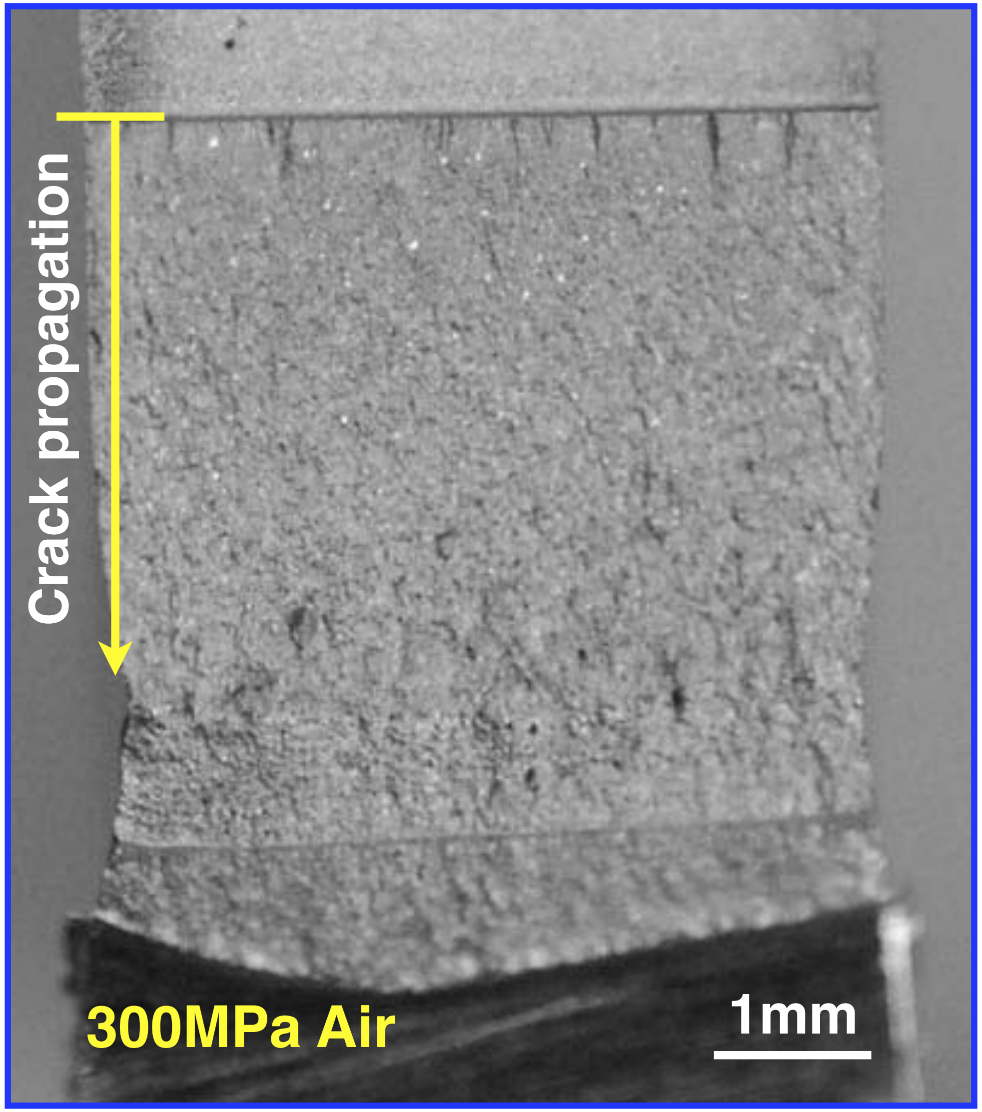
- Increasing rate of the displacement accelerates by mercury immersion regardless of the imposed stress

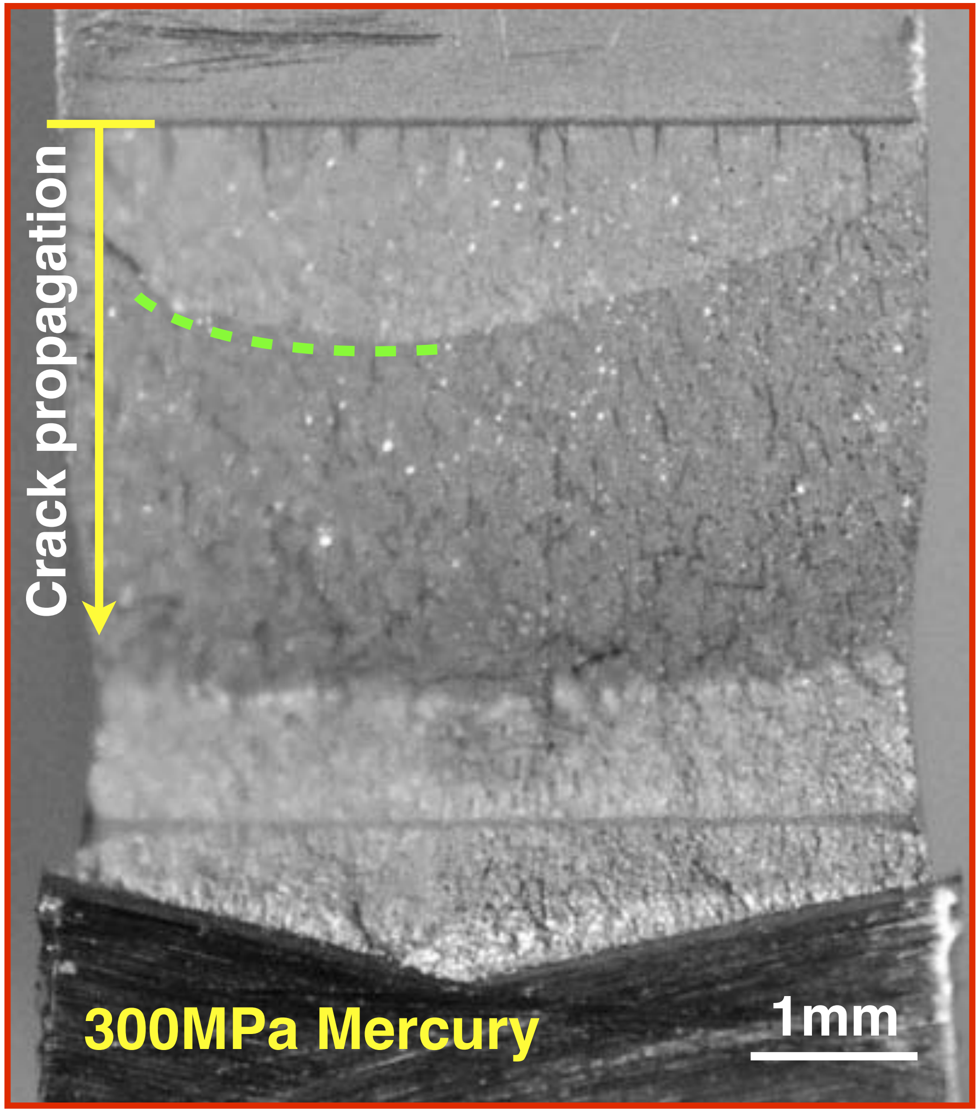
Effect of mercury on fatigue...

- ✓ Strength
- ✓ Displacement change

➡ Crack propagation

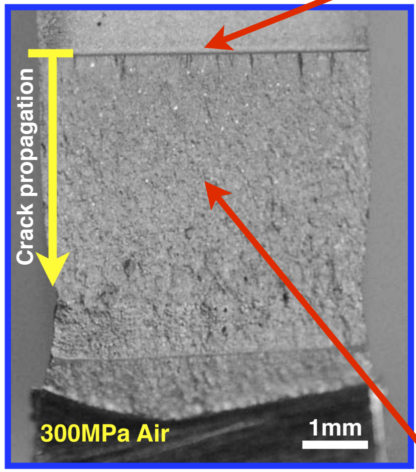
Fracture surface observation

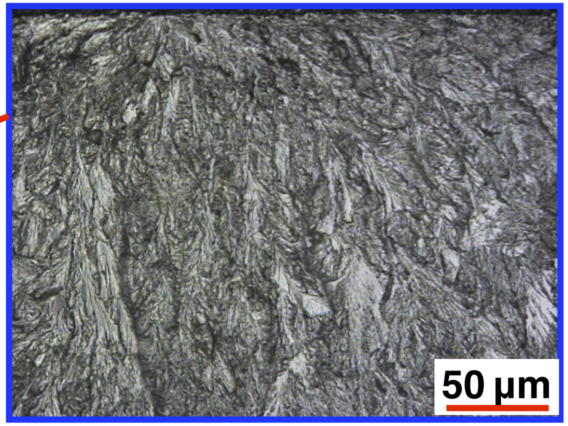


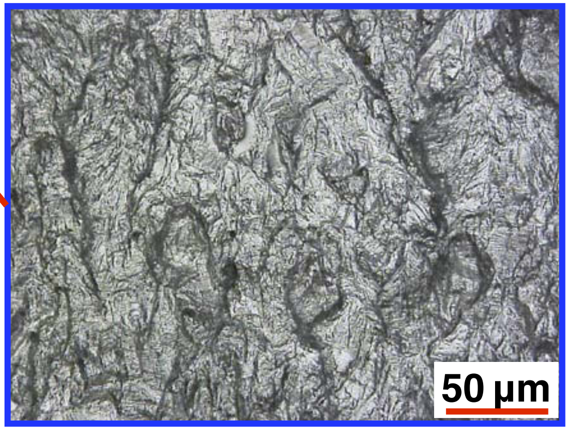


Fracture surface observation

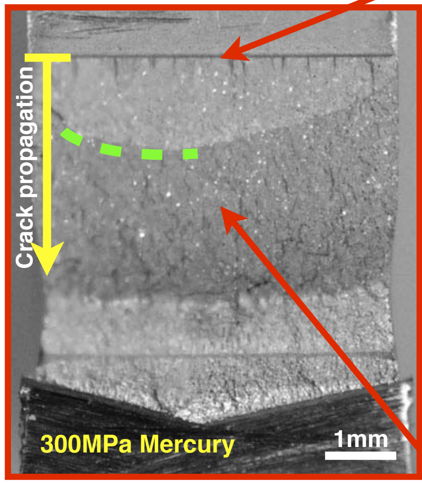
300MPa Air

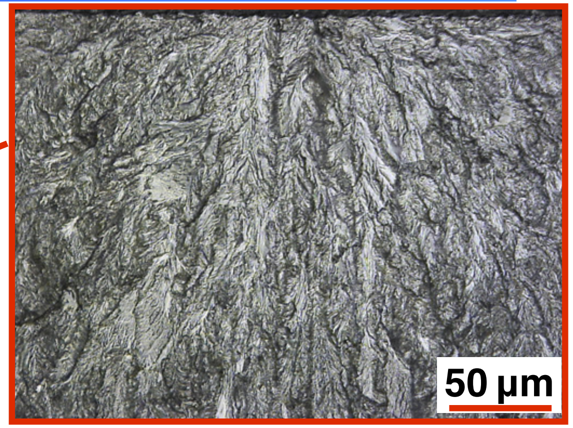




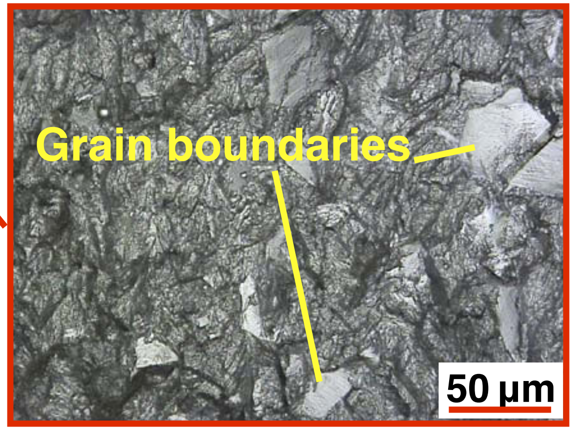


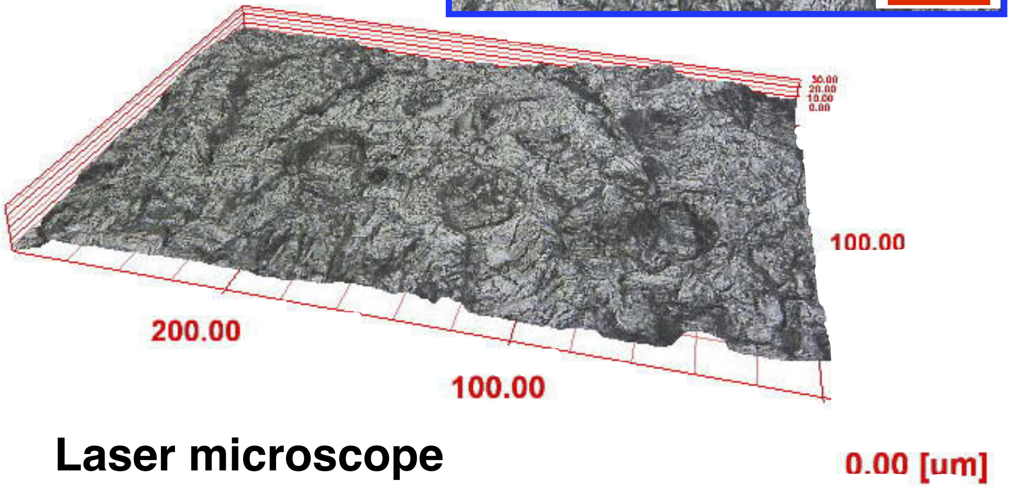
300MPa Mercury





Brittle failure



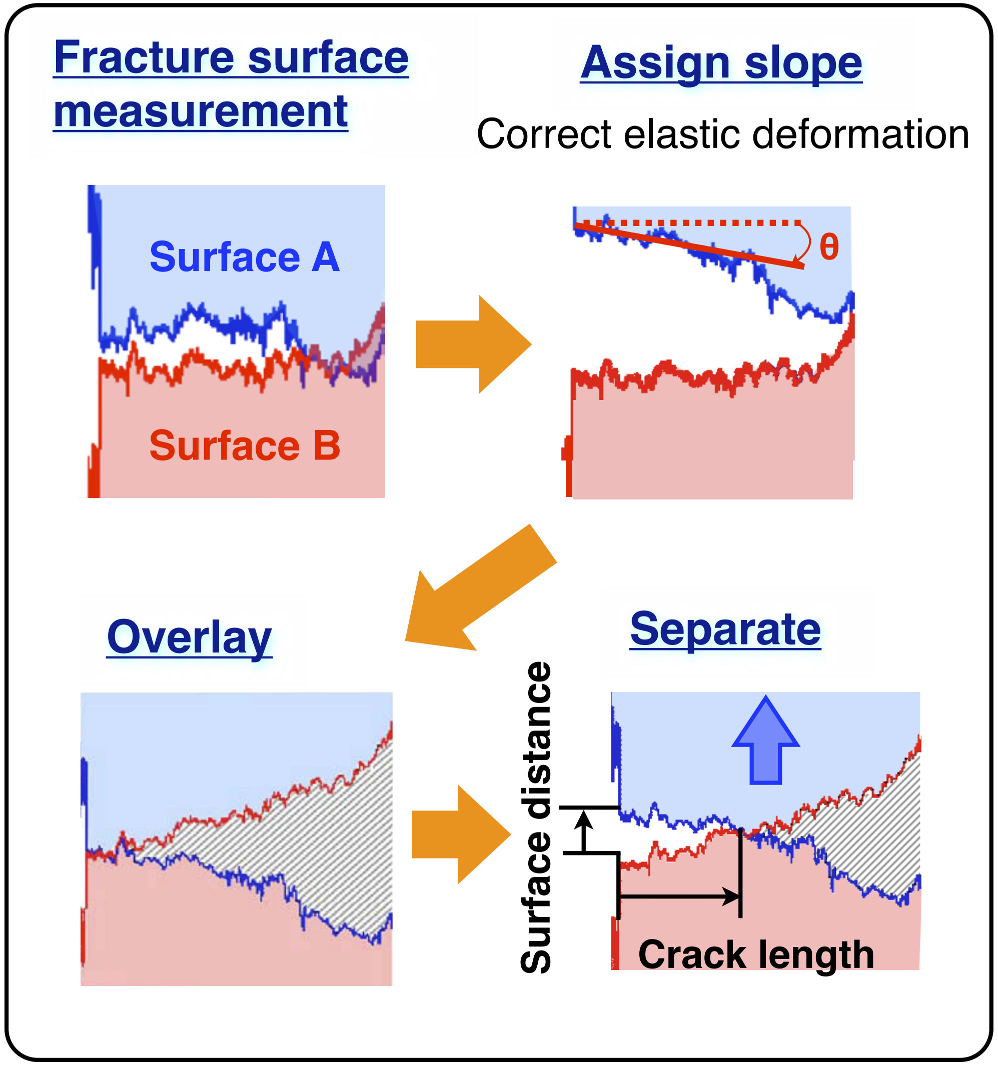


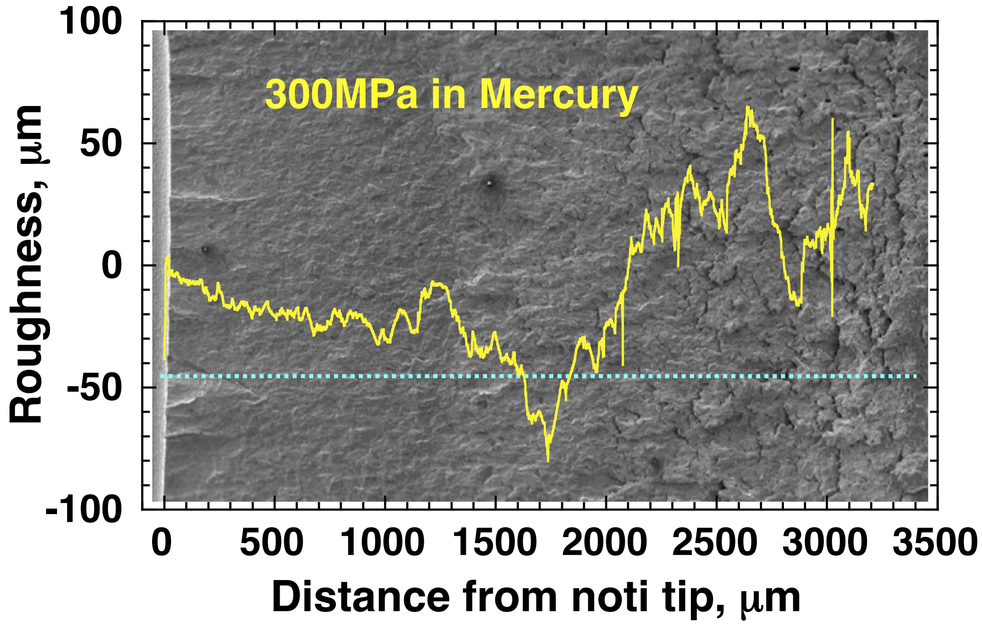
Laser microscope

FRASTA method

FRASTA: FRActure Surface Topography Analysis

- Overlay a couple of 3D image to simulate fracture process
- Estimate the crack propagation under invisible condition





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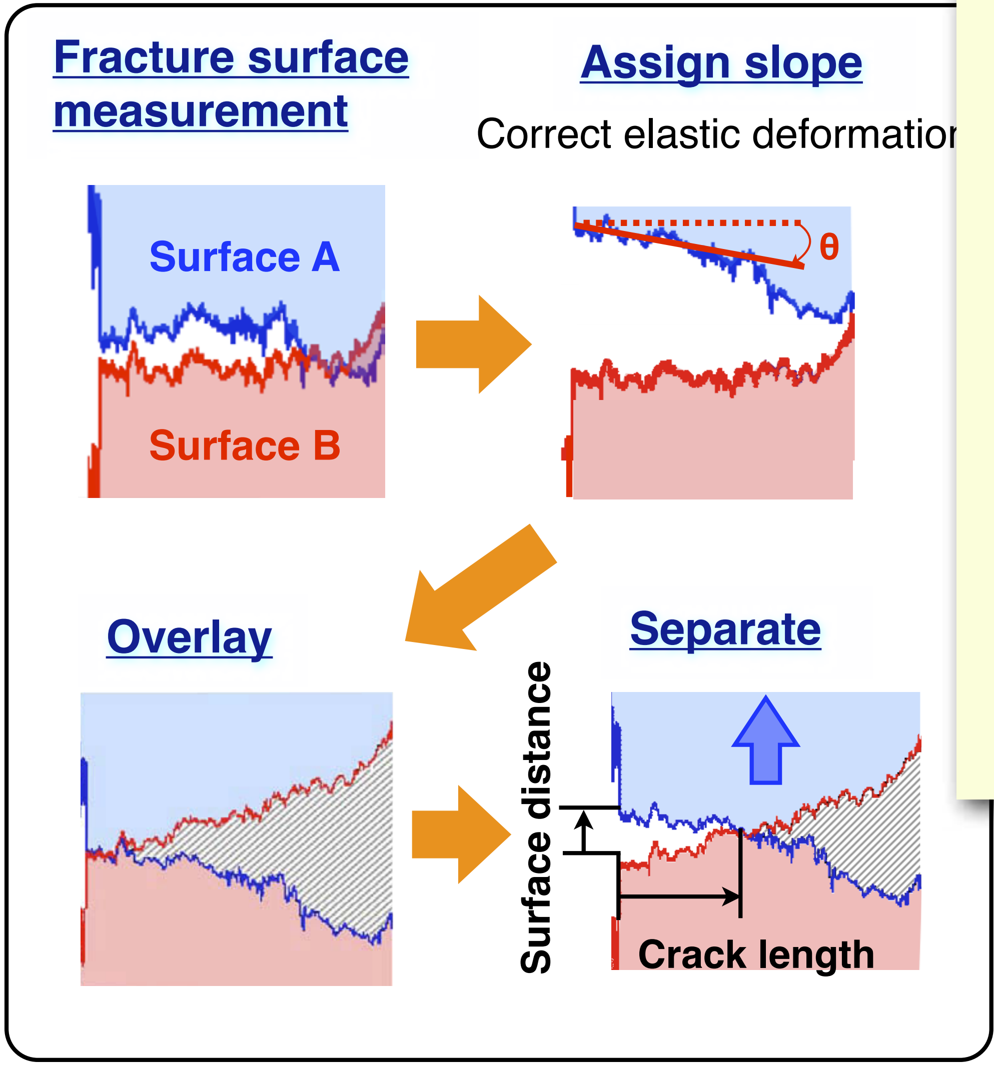
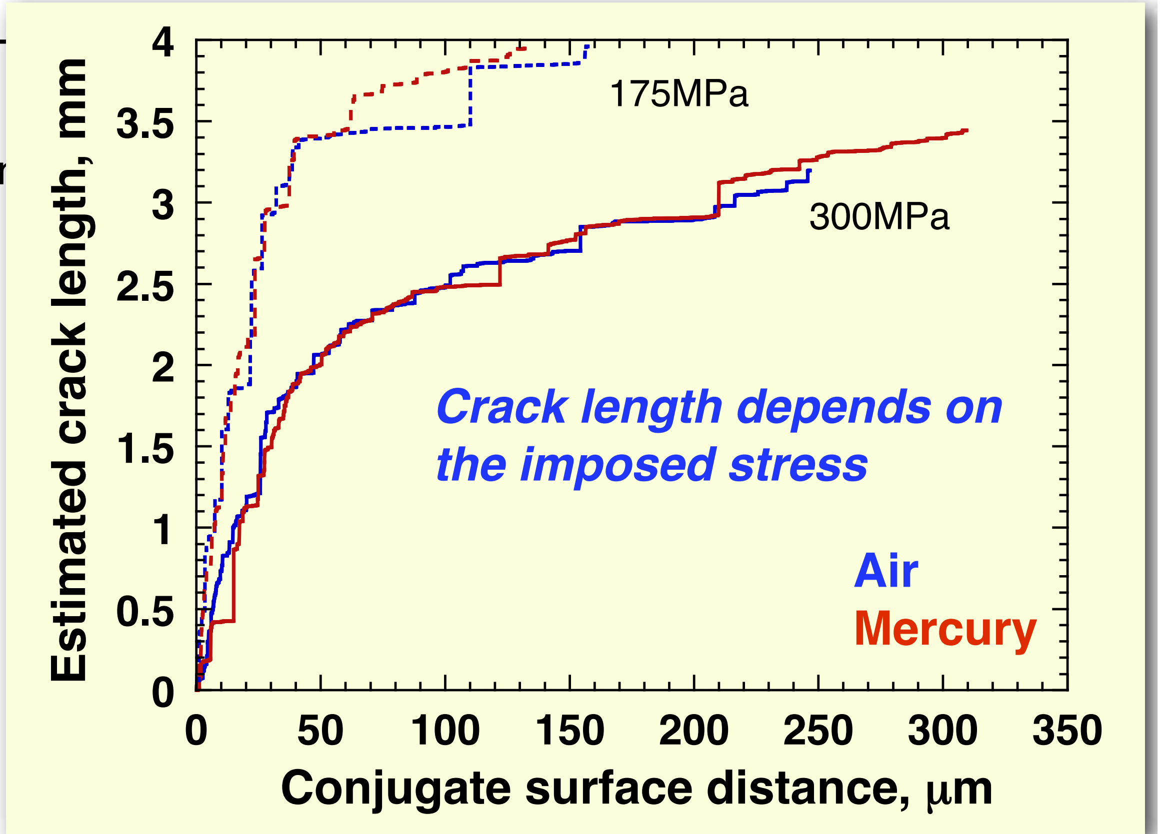
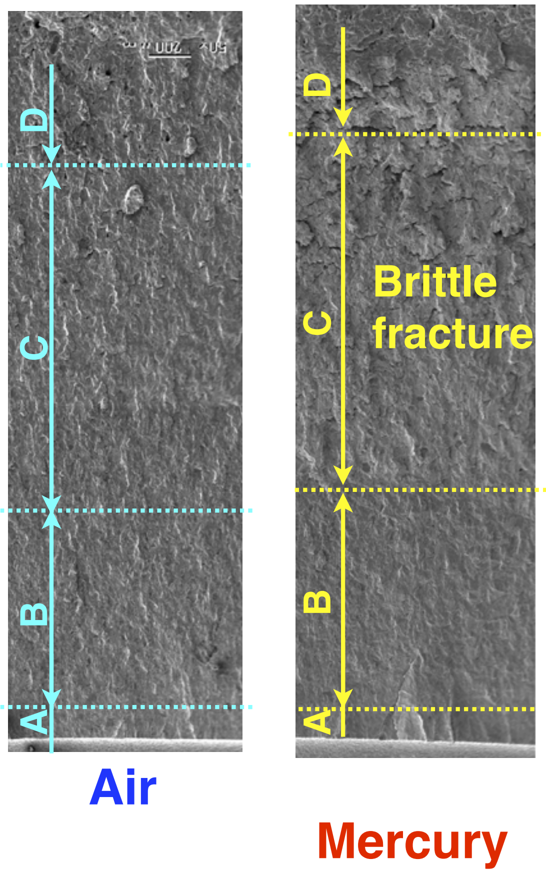


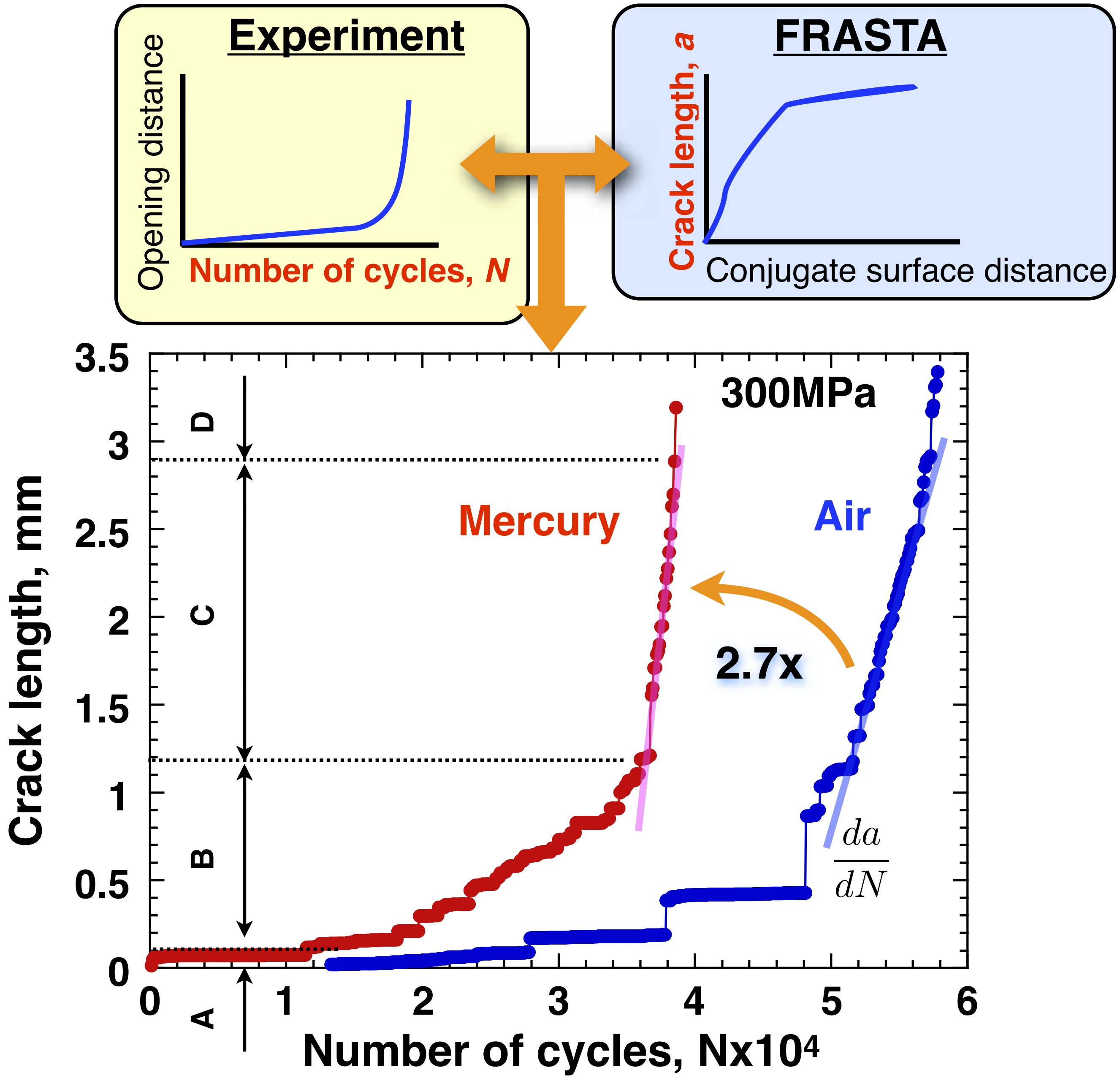


Crack propagation

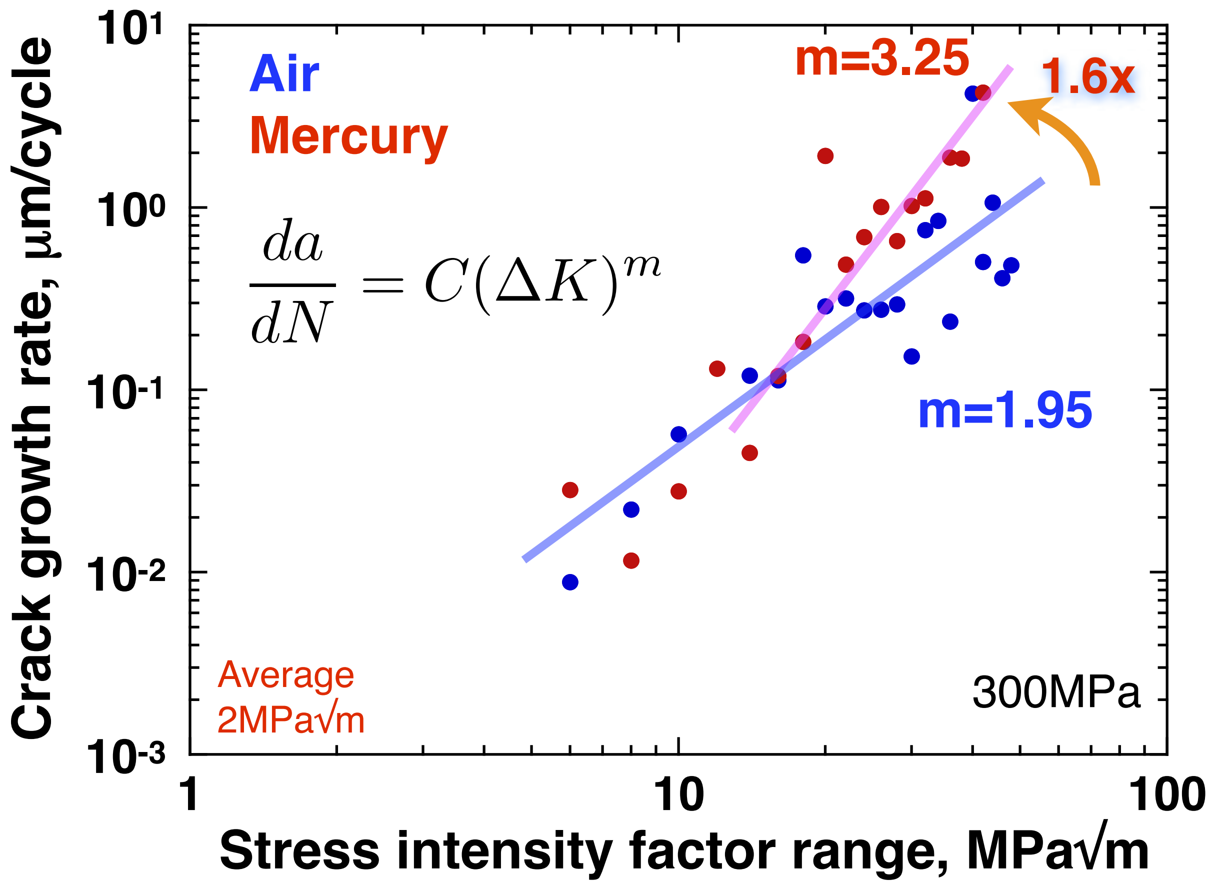
Categorize 4 region

A: Incubation
B: Gradually increase
C: Sharply increase
D: Final fracture





Stress intensity factor range



Stress intensity factor range

$$\Delta K = \Delta\sigma\sqrt{\pi a}F(\xi)$$

For 3-point bending with notch

$$F(\xi) = 1.090 - 1.735\xi + 8.20\xi^2 - 14.18\xi^3 + 14.57\xi^4$$

$$\xi = a/W$$

a: crack length
W: width(6mm)

- **Mercury effect was remarkably appeared at high-ΔK**
- **m value for mercury case was 1.6x larger than air case**
- **Crack propagation will be accelerated by mercury at high-stress imposed area and/or long crack length**

Summary

Effect of mercury immersion on fatigue crack propagation was investigated through the fatigue test with notched specimen.

- Fatigue strength was degraded by mercury immersion at high stress imposed area.
- To investigate the crack propagation in mercury, FRActure Surface Topography Analysis with opening distance measurement was performed
- At the brittle failure region, crack propagation rate in mercury was 2.7x larger than that of in air.
- We suggested that the fatigue crack propagation accelerates by mercury immersion in the high-stress intensity factor range.