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Fatigue crack growth of structural metals for hydrogen service

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Motivation

- ***Austenitic stainless steels*** and ***aluminum alloys*** are commonly used in gaseous hydrogen systems
- Fatigue data in hydrogen environments is limited for these classes of materials
- Nevertheless, some of these materials are "approved" for hydrogen
  - Type 316/316L austenitic stainless steels
  - 6061-T6 aluminum

Engineering and science community need:

- Basic engineering data (structural properties) in gaseous hydrogen
- Foundational tests to elucidate physical processes of hydrogen embrittlement at the microstructural level to inform materials design and selection

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Fatigue crack growth measurements of high-strength alloys

- ***Austenitic stainless steels***
  - Type 316 and 316L
  - Strain-hardened to yield strength ~700 MPa or higher
  - Thermally-precharged with hydrogen to simulate long-term exposure, tested in air (*internal hydrogen*)

- ***Aluminum alloys***
  - 7475-T7351 (over-aged for corrosion resistance)
  - Precipitation-strengthened (yield ~ 400 MPa)
  - Tested in high-pressure gaseous hydrogen (*external hydrogen*)

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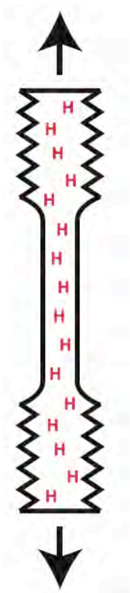
Internal and external hydrogen environments have important differences



Internal hydrogen

Testing in air
after thermal precharging
in gaseous hydrogen

Exposure to
gaseous H_2
at <u>100-300 °C</u>

10-30 days

Austenitic stainless steel
- Uniform hydrogen content near 1 atomic % (138MPa H_2 at 300˚C)

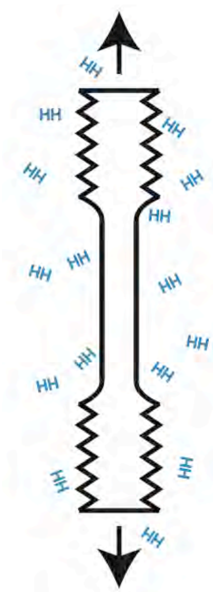
Aluminum
- limited to precharging at low temperature (≤ 150˚C)

External hydrogen

Testing in gaseous hydrogen

Exposure to
gaseous H_2
at <u>20 °C</u>

1-10 hours



- Non-uniform hydrogen content and distribution (not controlled)
- Diffusion distances are short at 20˚C
- Significant infrastructure requirements

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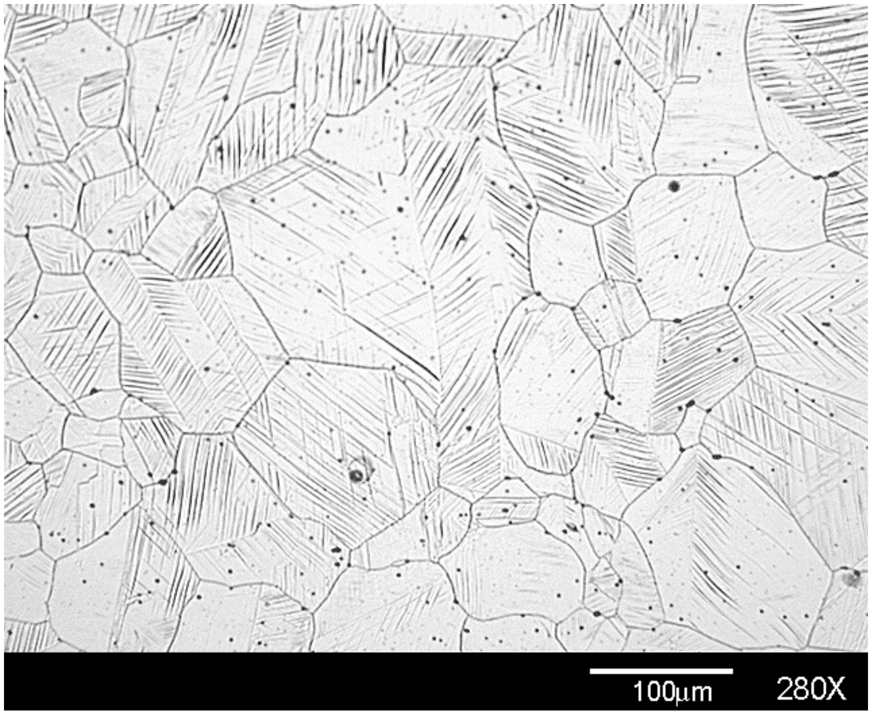
Fatigue crack growth was measured for two *strain-hardened* austenitic stainless steels

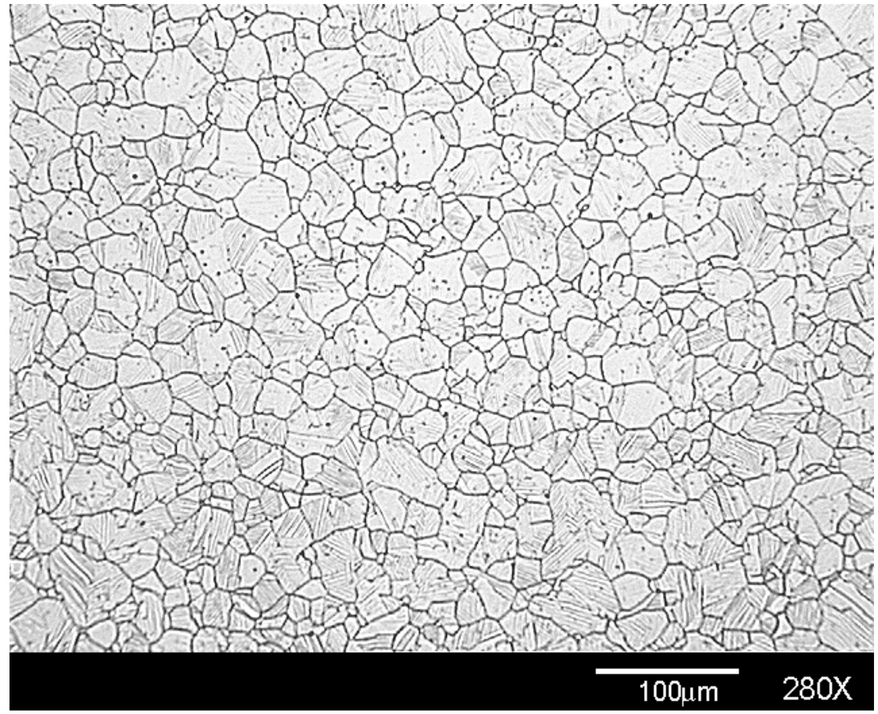
Heat D: type 316



Yield strength = 693 MPa

Ni = 12.1 wt%
C = 0.043 wt%

Heat E: type 316L



Yield strength = 790 MPa

Ni = 13.2 wt%
C = 0.022 wt%

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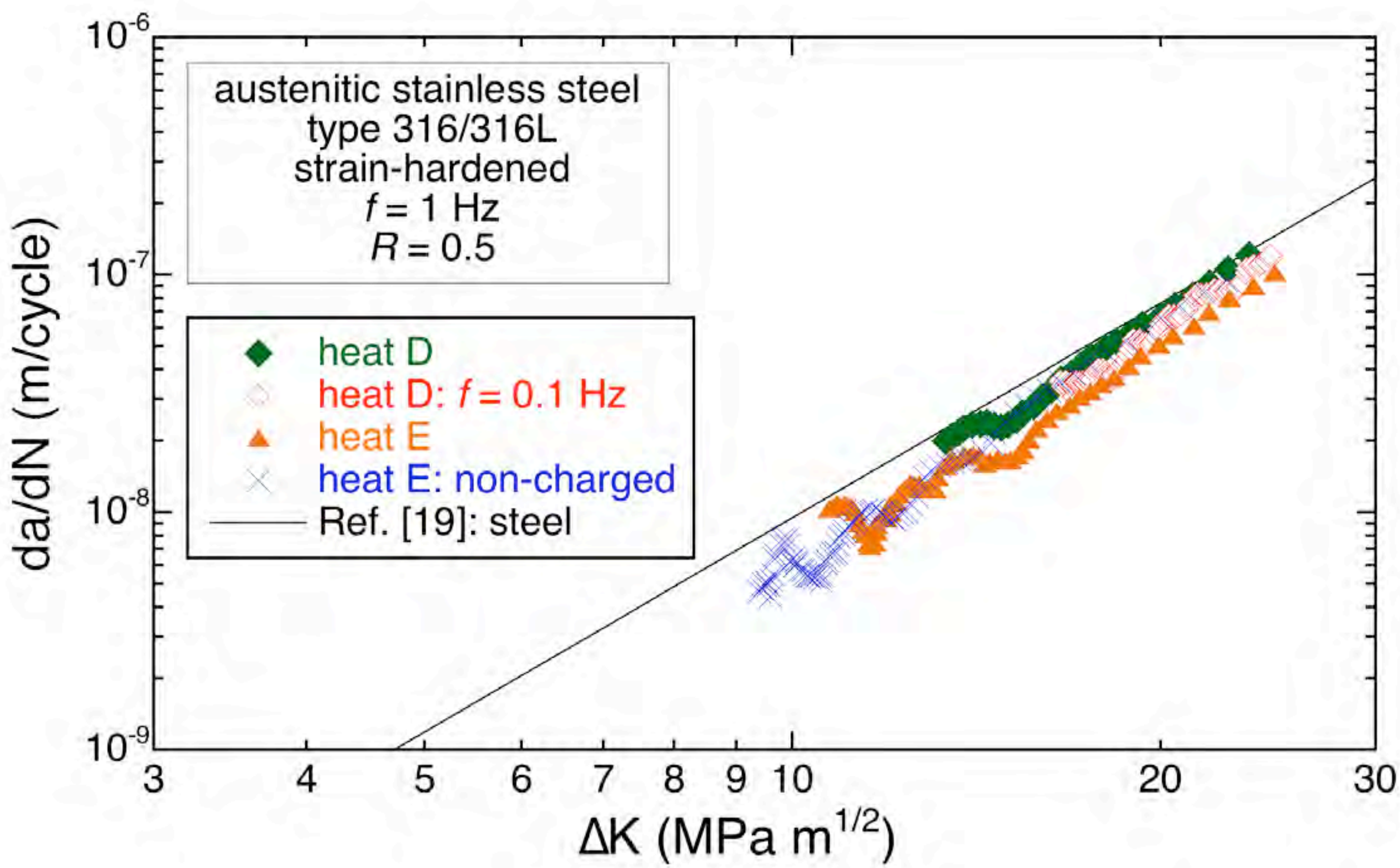
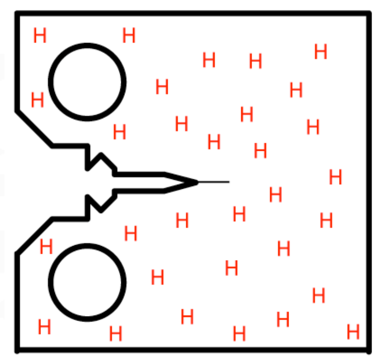
Fatigue crack growth of type 316/316L austenitic stainless steel

Fatigue crack growth is essentially unaffected by high-concentration of internal hydrogen (140 wt ppm hydrogen)





Except where noted H-precharged:
T = 300˚C
P = 138 MPa

Ref [19]: Fatigue design of welded joints and components, International Institute of Welding, 1996.

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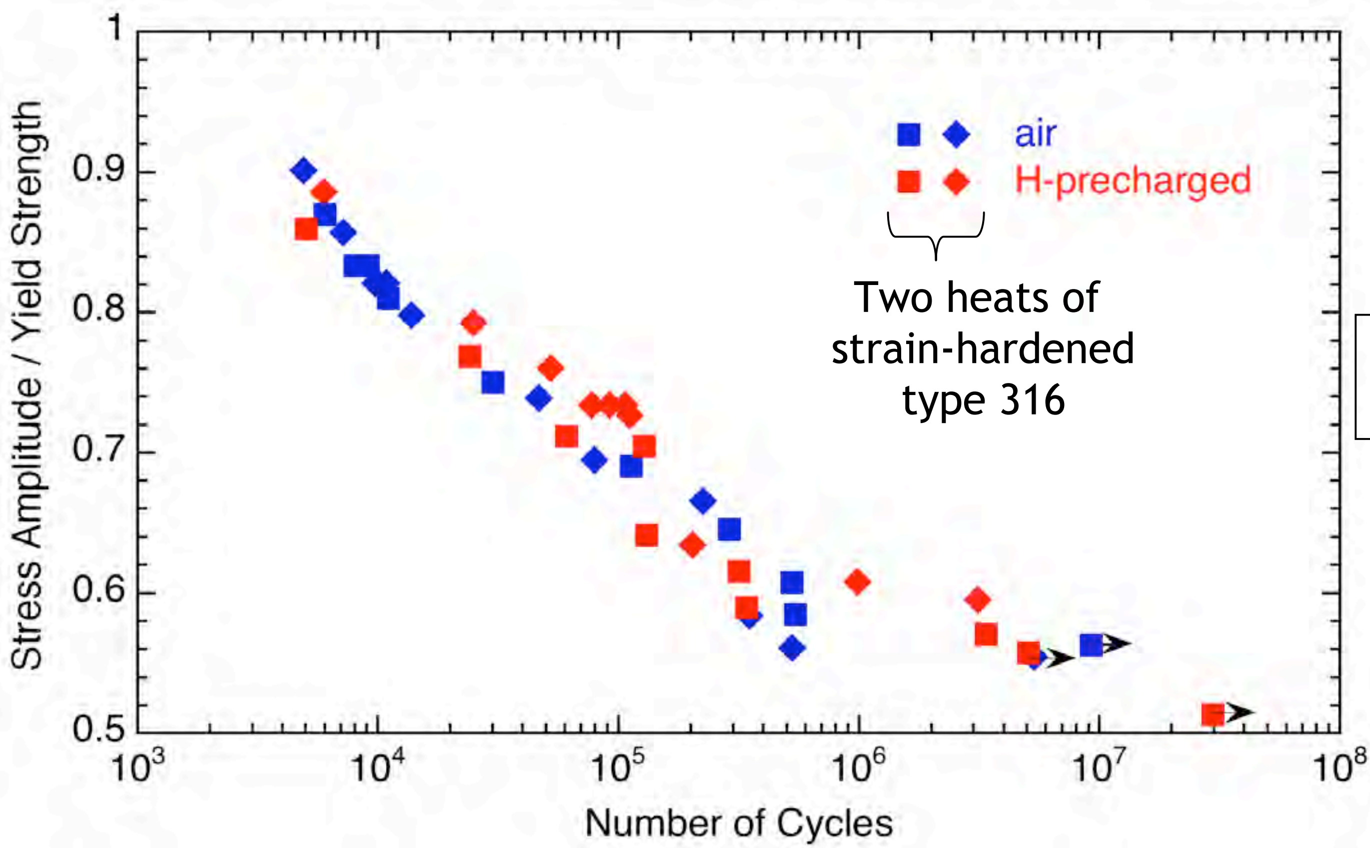
Fatigue life tests also show no significant effect of hydrogen

When the increase in yield strength due to hydrogen is considered, high concentration of internal hydrogen does not affect fatigue life of type 316 austenitic stainless steels



Rotating beam fatigue

Internal hydrogen content ~140 wt ppm

Ref: Skipper et al. International Hydrogen Conference, 2008, Moran WY.

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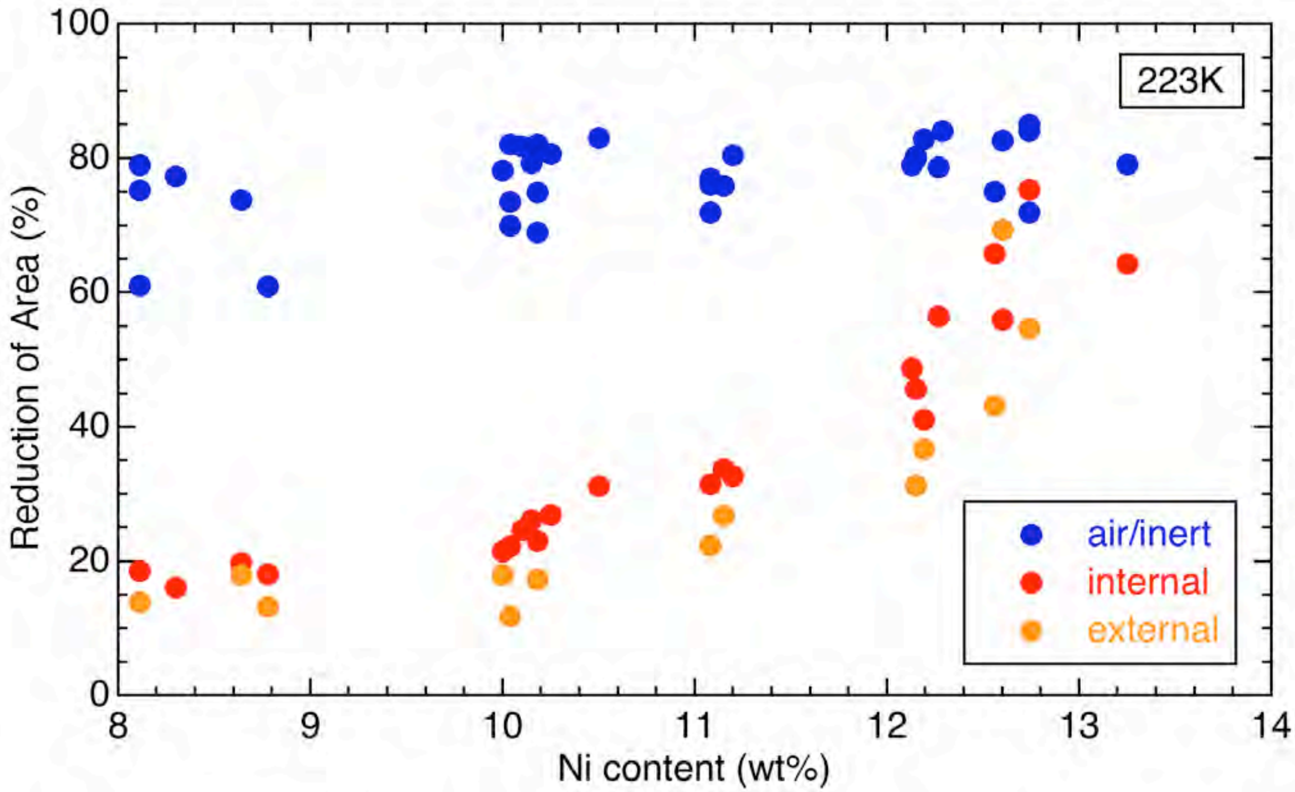
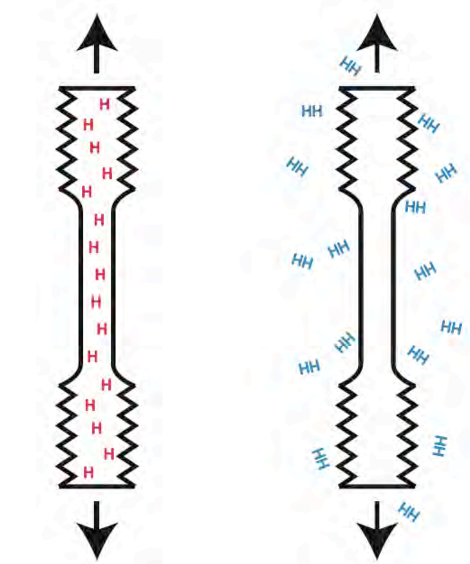
Effects of hydrogen, however, are observed in tension for type 304 and type 316 alloys

Tensile ductility is reduced for austenitic stainless steels exposed to hydrogen

- Both internal and external hydrogen show similar trends
- Nickel content and temperature are important parameters





Ref: San Marchi et al. Int J Hydrogen Energy 35 (2010) 9736.

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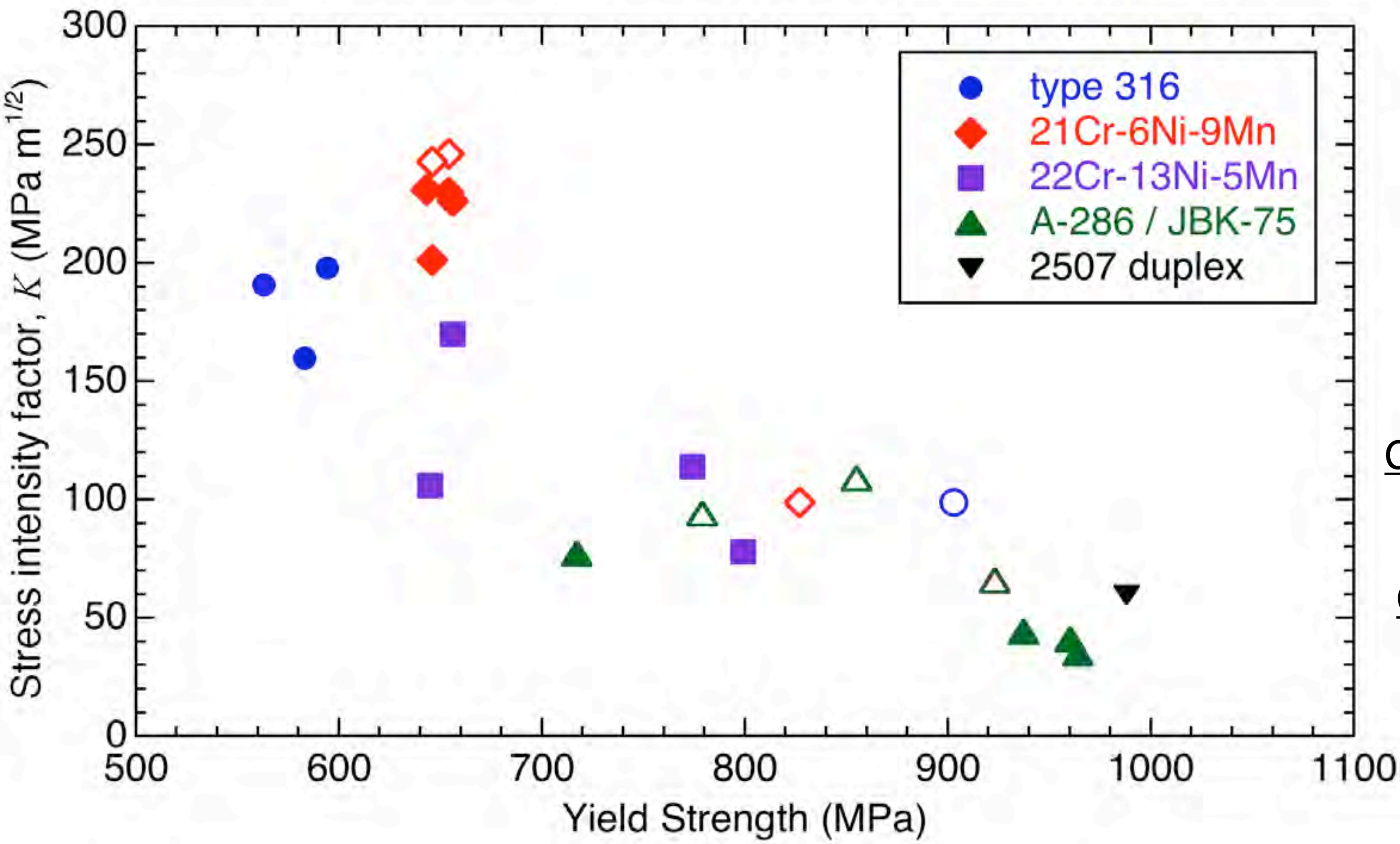
Fracture resistance of austenitic stainless steels is also affected by hydrogen

Fracture toughness is typically >300 MPa $m^{1/2}$ for austenitic stainless steels with yield strength <700 MPa



Closed symbols: H-precharged

Open symbols: Tests in H_2

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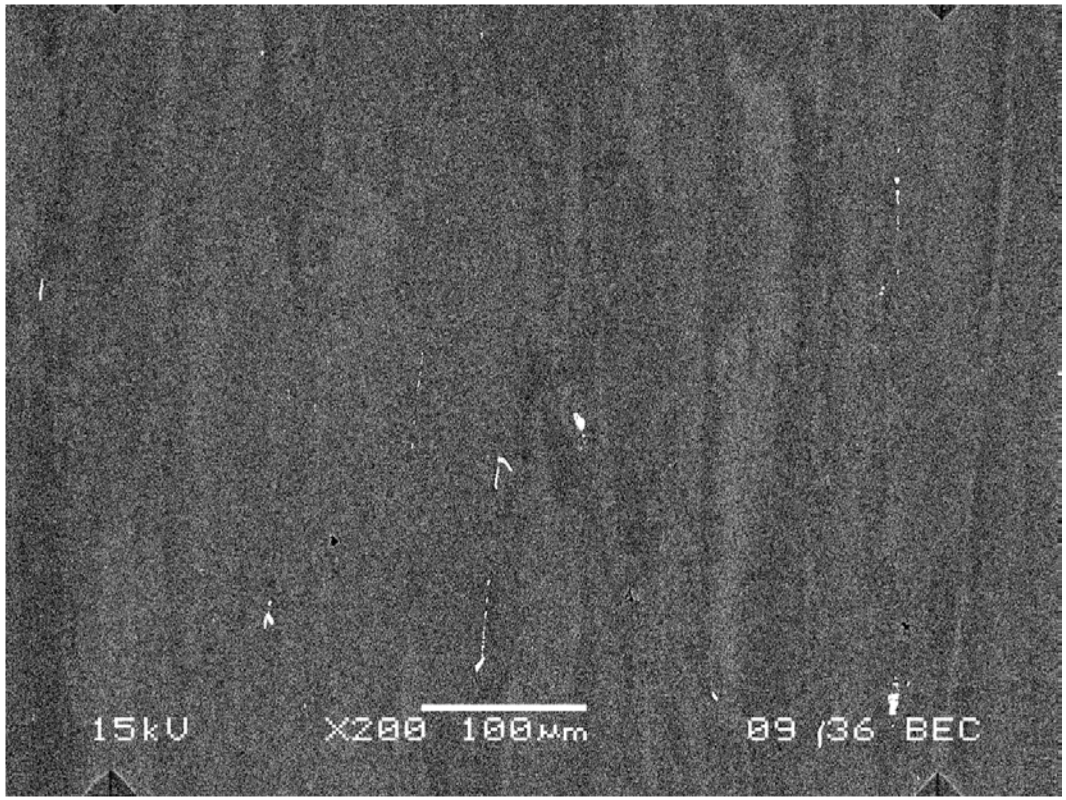
High-strength aluminum alloy

7475-T7351



Yield strength = 407 MPa

Al - 5.8Zn - 2.2Mg - 1.4Cu

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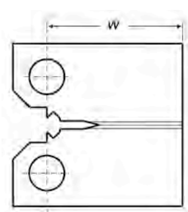
Fracture mechanics tests were conducted in gaseous hydrogen at pressure of 103 MPa

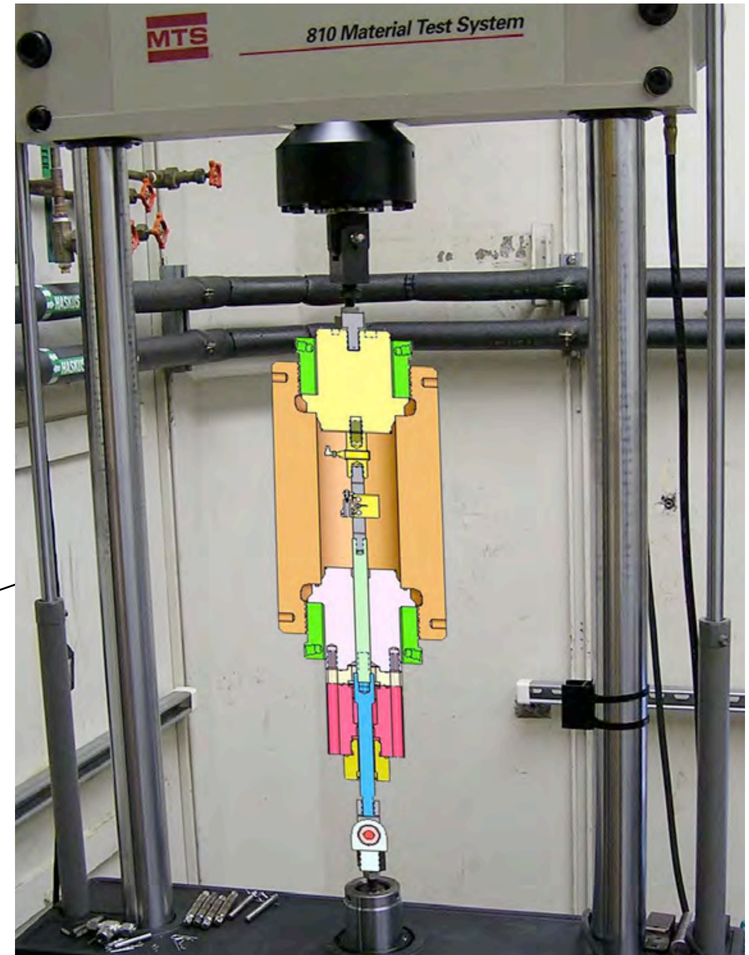
- Fatigue crack growth: da/dN
  - ASTM E647, constant load amplitude
- Fracture resistance: K_{IH}
  - ASTM E1820, elastic-plastic analysis using J-R curve determination

Fracture/fatigue specimens



W = 26.4 mm
B = 12.7 mm

Plate:
3" thick



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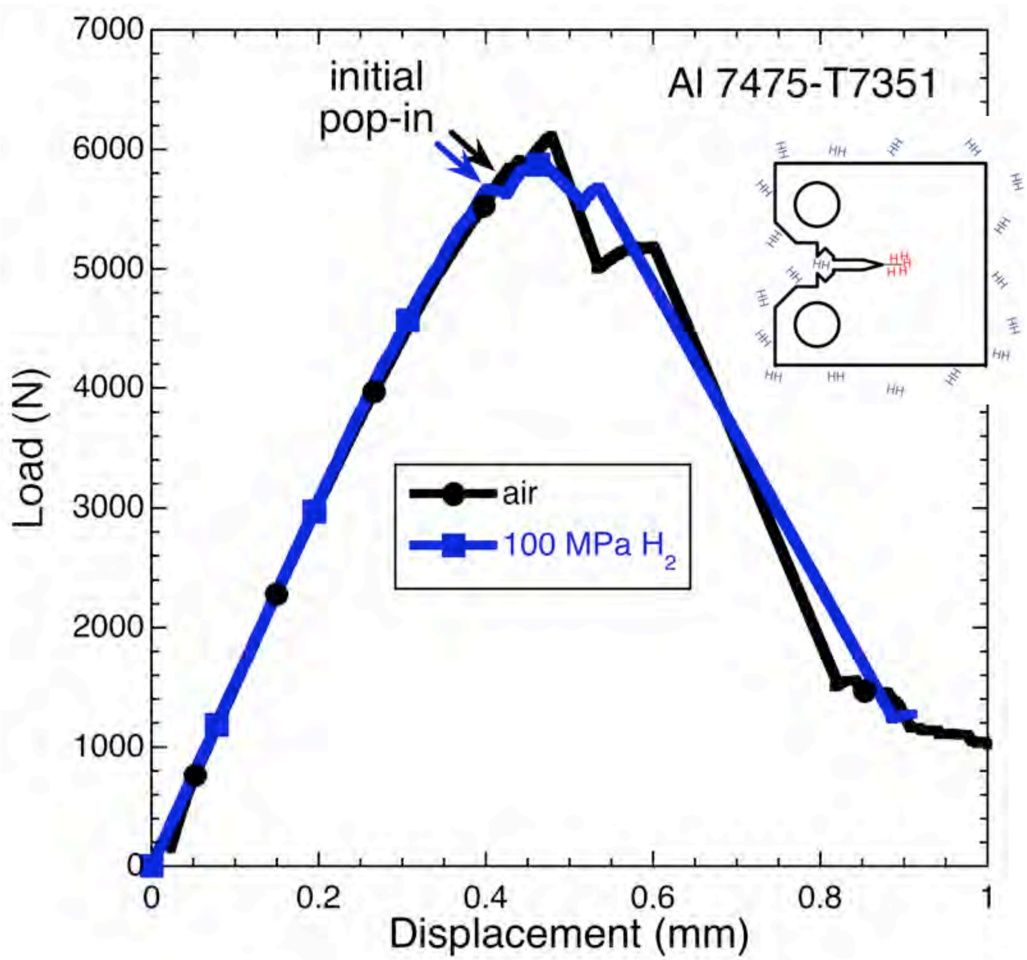
Fracture resistance of high-strength aluminum is not affected hydrogen



- SL/ST orientation
- Manufacturer reported toughness: 40 MPa $m^{1/2}$ (SL)
- Measured in laboratory air:
  44 MPa $m^{1/2}$
- Measured in gaseous hydrogen at pressure of 103 MPa:
  45 MPa $m^{1/2}$
  (average of 4 replicates)

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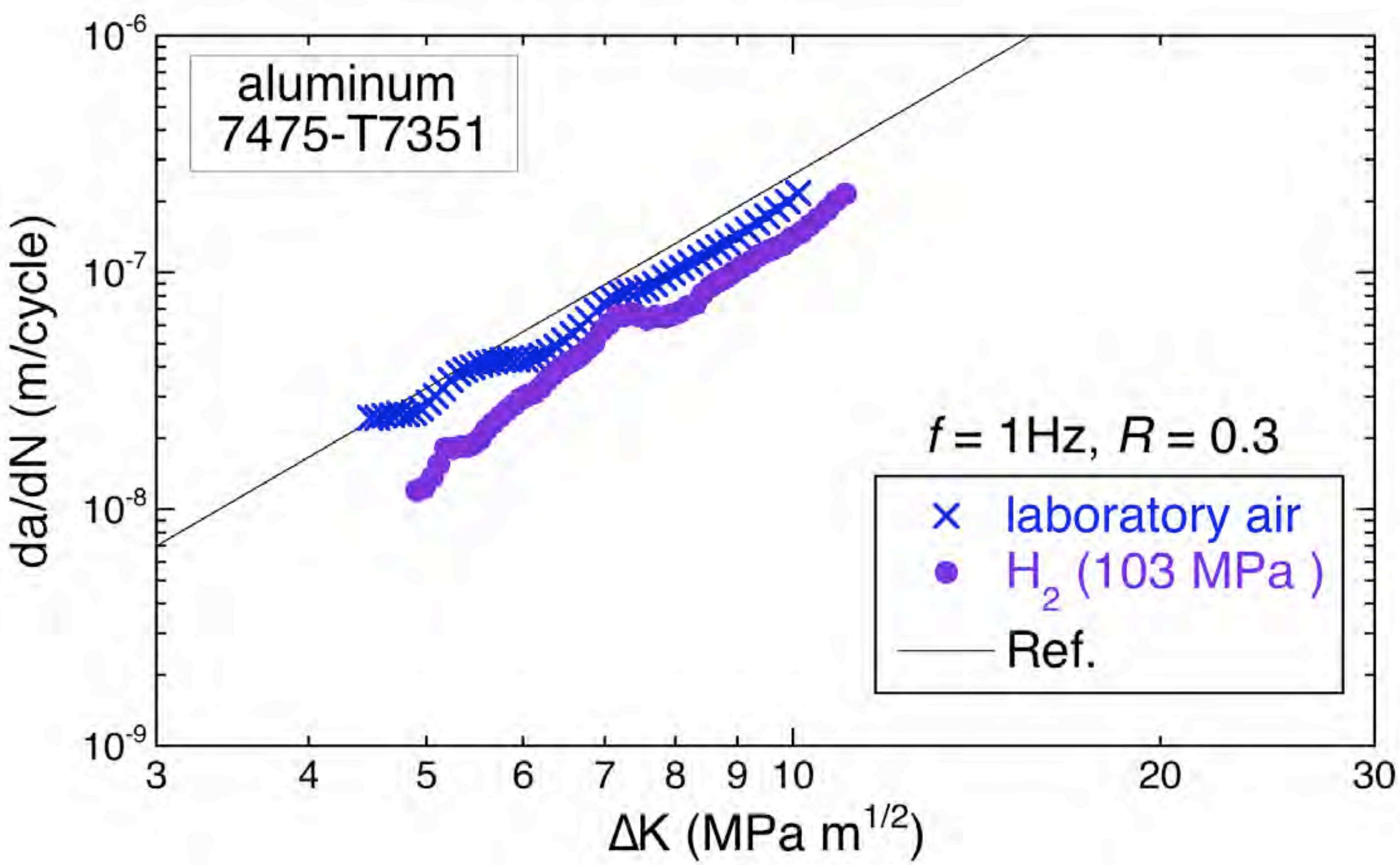
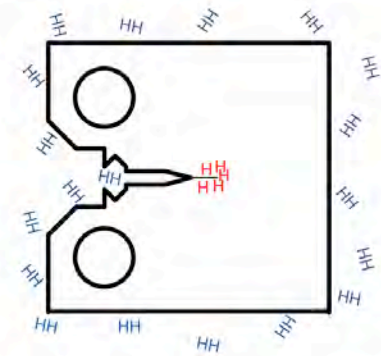
Fatigue crack growth in 7475-T7351 is unaffected by gaseous hydrogen

Fatigue crack growth rates in both air and gaseous hydrogen are consistent with conservative design values





Ref.: Fatigue design of welded joints and components, International Institute of Welding, 1996.

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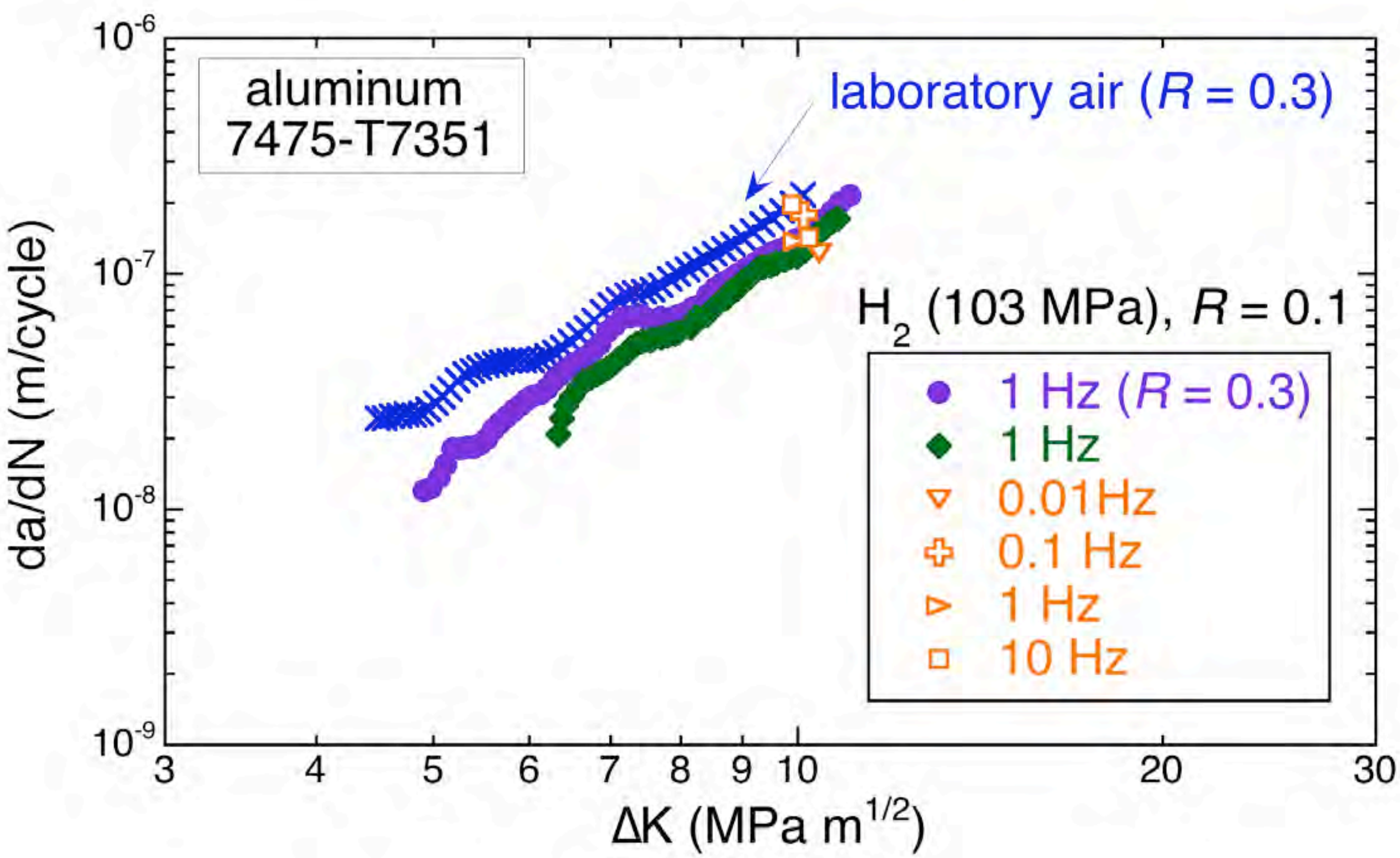
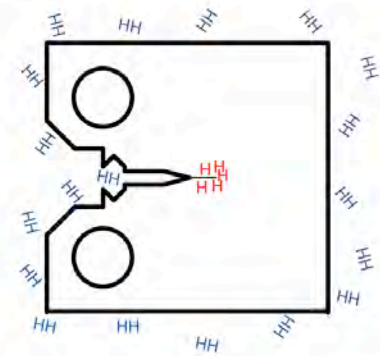
Fatigue crack growth in 7475-T7351 is unaffected by gaseous hydrogen

Preliminary measurements suggest that the effects of hydrogen on aluminum are not dependent on frequency or R





Ref.: Fatigue design of welded joints and components, International Institute of Welding, 1996.

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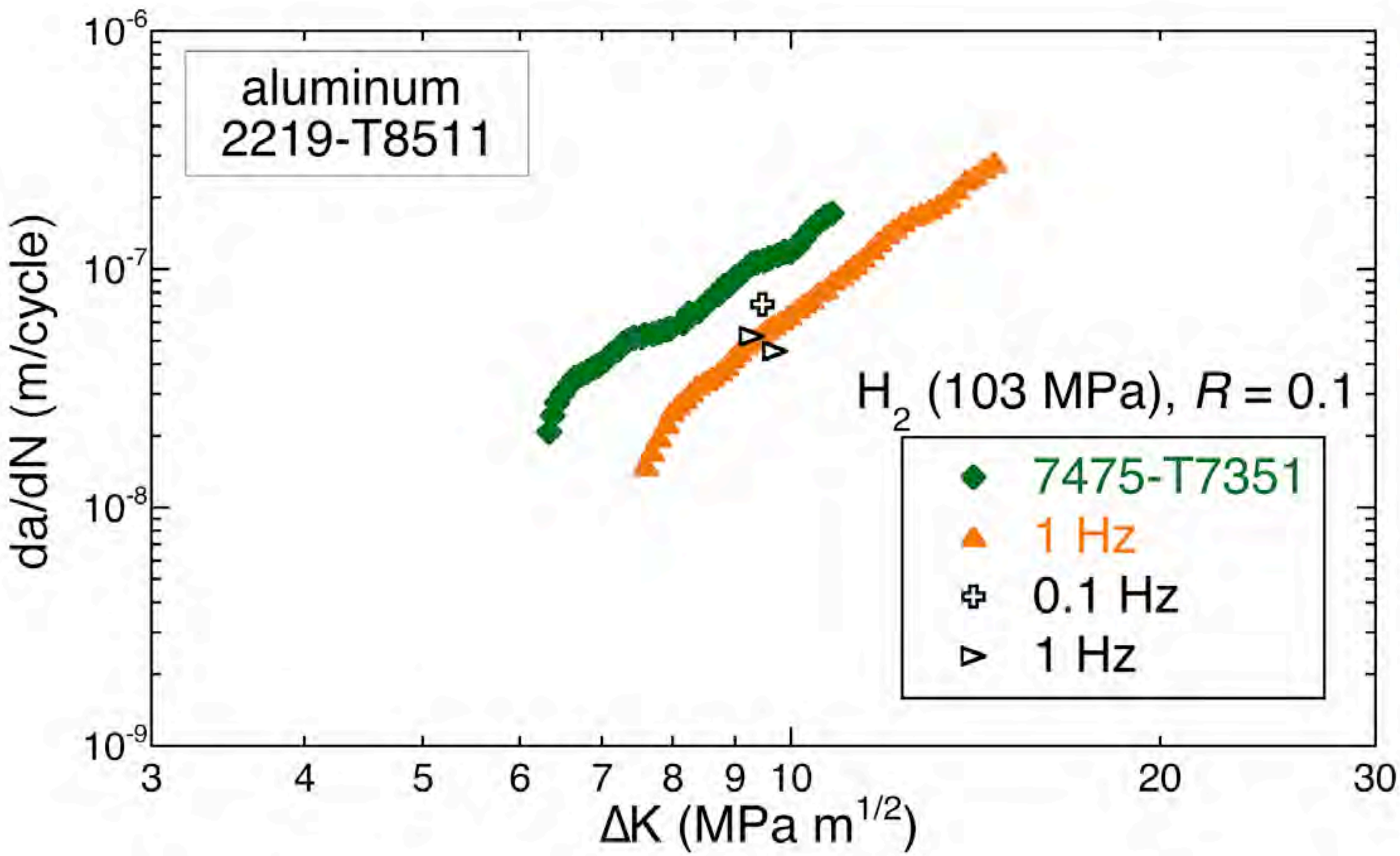
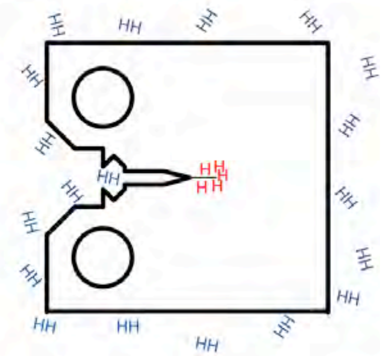
Fatigue crack growth in 2219-T8511 shows similar trends as 7475

Preliminary measurements suggest fatigue crack growth rates are lower for 2219 compared to 7475



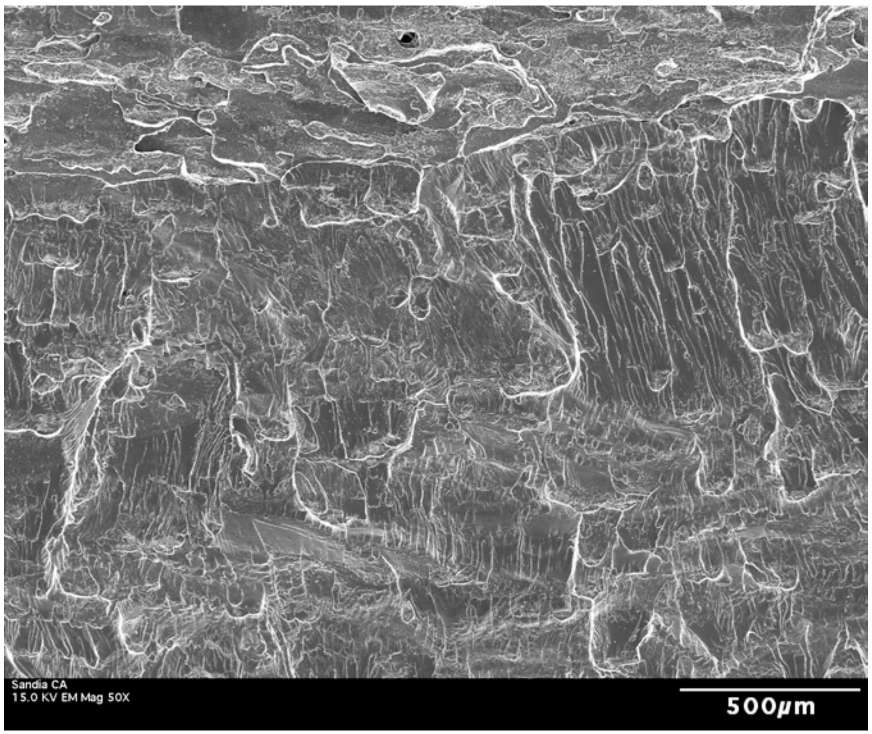


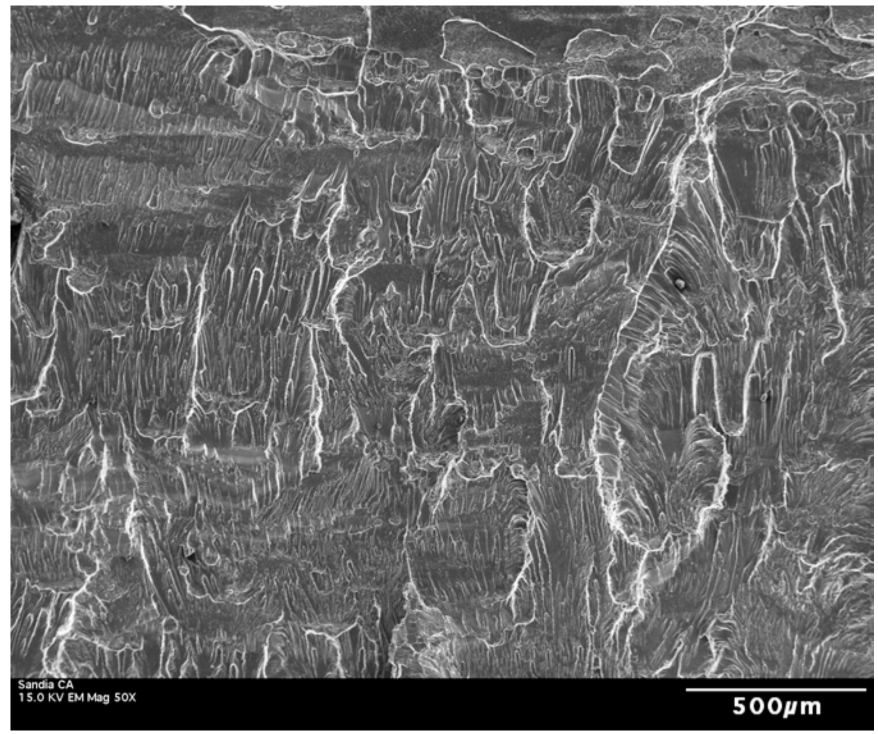
Ref.: Fatigue design of welded joints and components, International Institute of Welding, 1996.

Fatigue fracture surface in hydrogen are similar to surfaces in air

Laboratory air

Gaseous hydrogen
P = 103 MPa





K_{max} ~ 14 MPa $m^{1/2}$

Aluminum 7475-T7351

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Summary

Strain-hardened austenitic stainless steels

- Fatigue crack growth of type 316/316L alloys is unaffected by hydrogen precharging
- Tensile ductility and fracture resistance, however, are reduced by both internal and external hydrogen

High-strength aluminum alloys

- 7475-T7351 shows no effects of exposure to high-pressure gaseous hydrogen during fracture and fatigue testing
- Elastic-plastic fracture mechanics testing results in fracture toughness of ~44 MPa $m^{1/2}$
- Fatigue crack growth is less than conservative relationships given in the literature

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