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Fatigue and fracture behavior of aluminum alloys in gaseous hydrogen (PVP2023-106442)

Rakish Shrestha, Joe Ronevich, Chris San Marchi

Sandia National Laboratories (Livermore CA)

Thorsten Michler

Fraunhofer Institute for Mechanics and Materials IWM (Freiburg, Germany)

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H-Mat℠ Hydrogen Materials Compatibility Consortium

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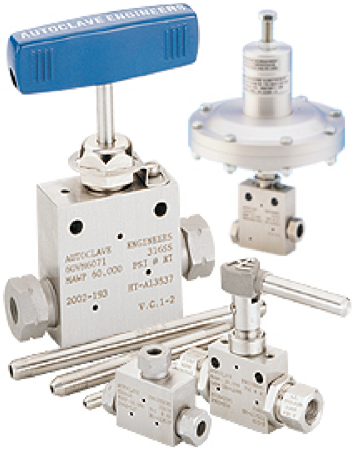
Hydrogen technologies include diverse range of operations

Hydrogen delivery

- hydrogen pipelines: carbon steels
- Challenge: cyclic pressure

Hydrogen storage

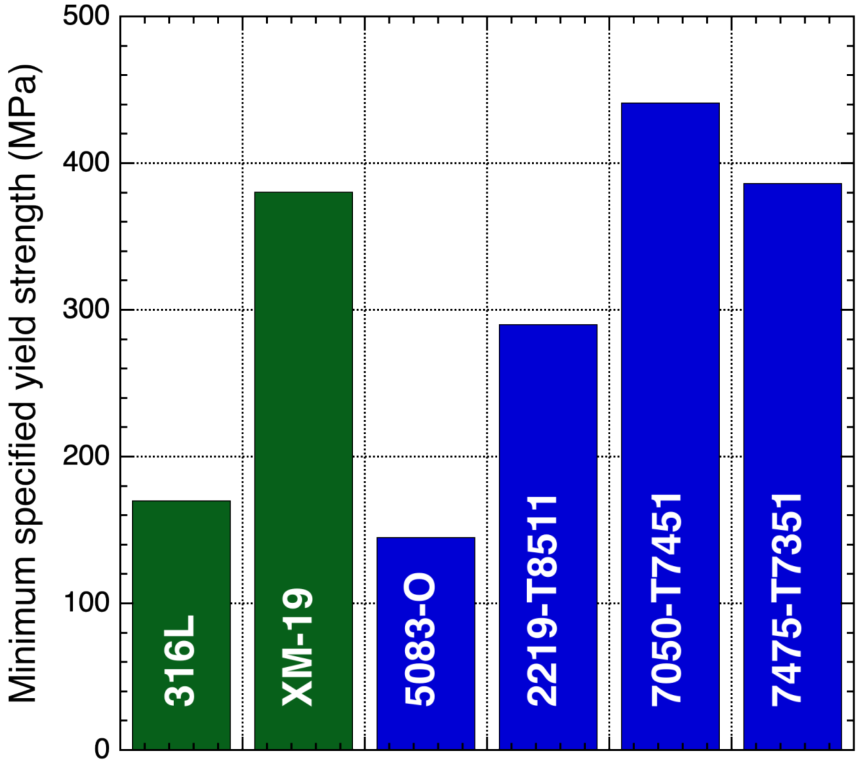
- hydrogen forklifts: Cr-Mo ferritic steels
- Challenge: filling ~6/day



Pressure manifold components

- Valves, tubing, and other devices: austenitic stainless steels
- Challenges: low temperature, lower-cost alternatives (e.g., ***aluminum*** or higher strength), alloy content, welding

Aluminum alloys can be higher strength than 316L



Solid-solution

- 5083-O: Al-Mg alloy

Precipitation-strengthened (aged)

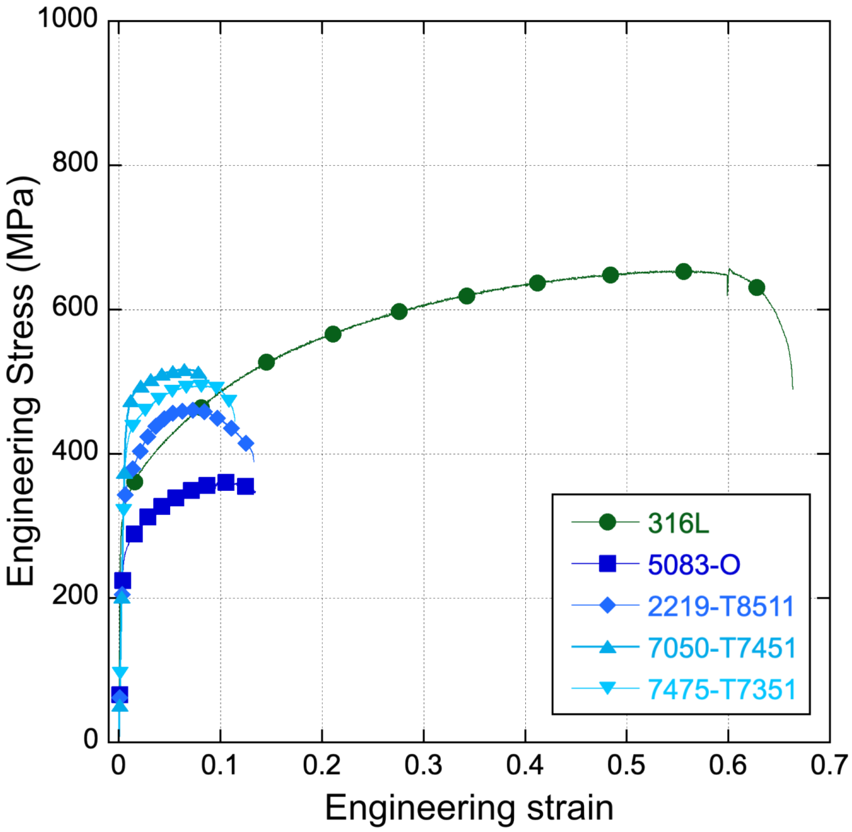
- 2219–T8511: Al-Cu alloy

Overaged

- 7050–T7451: Al-Zn-Mg-Cu alloy
- 7475–T7351: Al-Zn-Mg-Cu alloy

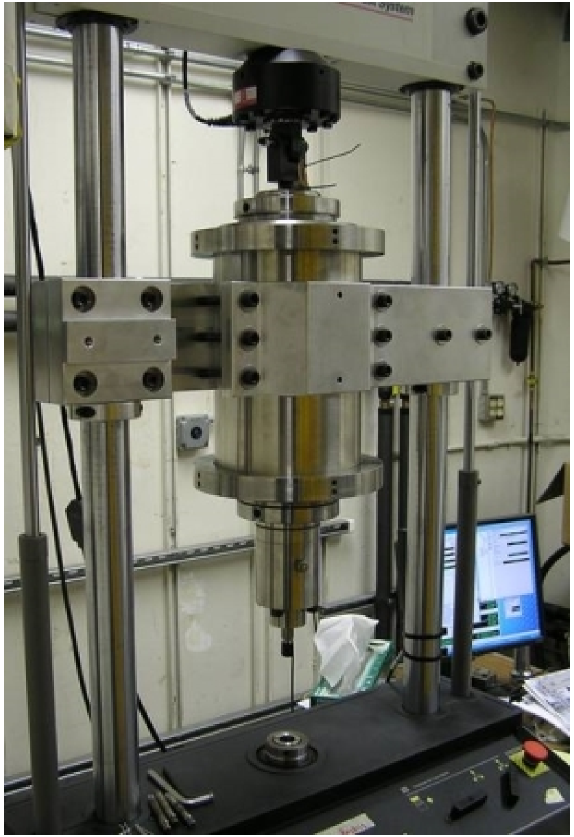
Trade-off: **Aluminum alloys display significantly lower ductility, fatigue, and fracture properties than austenitic stainless steels**

Tensile ductility of Al alloys can be less than 20% of 316L



- **Aluminum alloys are less common than steels in pressure applications due to low fatigue and fracture resistance**
- **However, aluminum is commonly used in safety critical components, such as in aerospace applications**
  - **For example, 2219 alloy was used for liquid hydrogen tanks on the space shuttle and common in other aerospace applications**
  - **7475 is an aerospace grade alloy with significantly higher fracture resistance than 7075**

Standard methods used to evaluate fatigue and fracture



Instrumentation

- **Load:** internal load cell
- **Displacement:** clip gauge on specimen
- **Crack monitoring:** Direct Current Potential Difference (DCPD)

Fatigue crack growth rate (FCGR):

ASTM E647

- **Load ratio (R):** 0.1 & 0.3
- **Frequency:** 1 Hz
- **Constant load amplitude or K-control**

Fracture resistance:

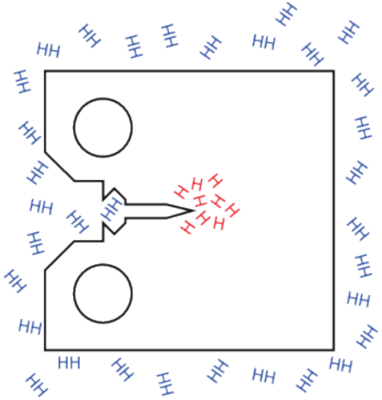
ASTM E1820 (elastic-plastic fracture)

- **Constant displacement rate:** 0.005 mm/min

Environments

- **Laboratory air**
- **99.9999% N_2:** 100 bar
- **99.9999% H_2:** 1,000 bar (GH2)

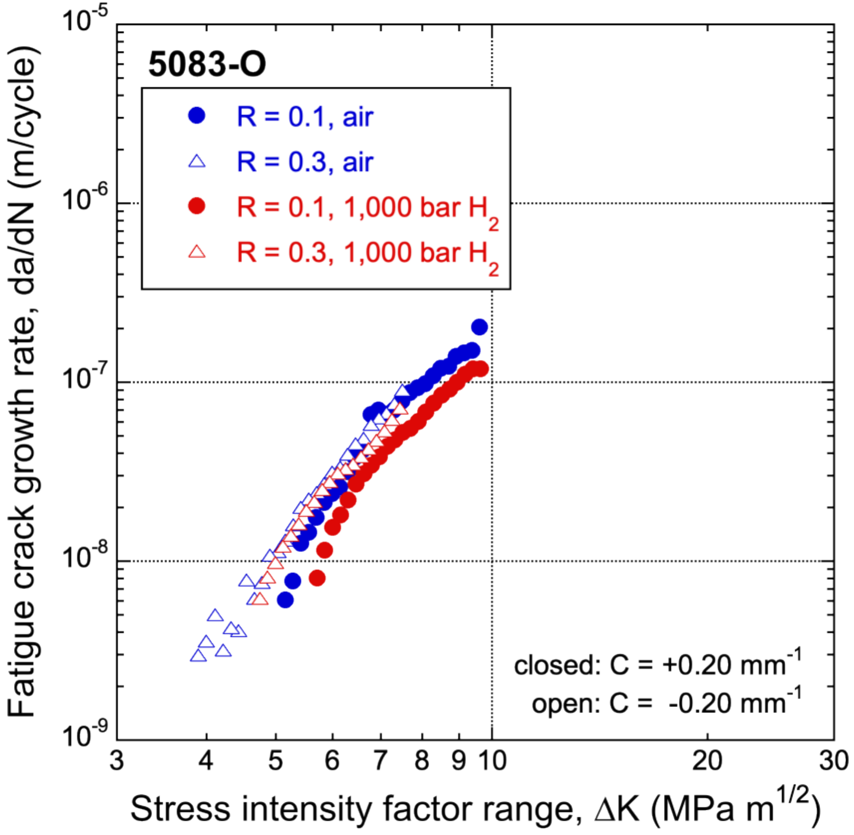
Compact tension geometry



B = 12.7mm
W = 26.4 mm

Fracture test conducted at conclusion of fatigue test

Aluminum alloy 5083-O

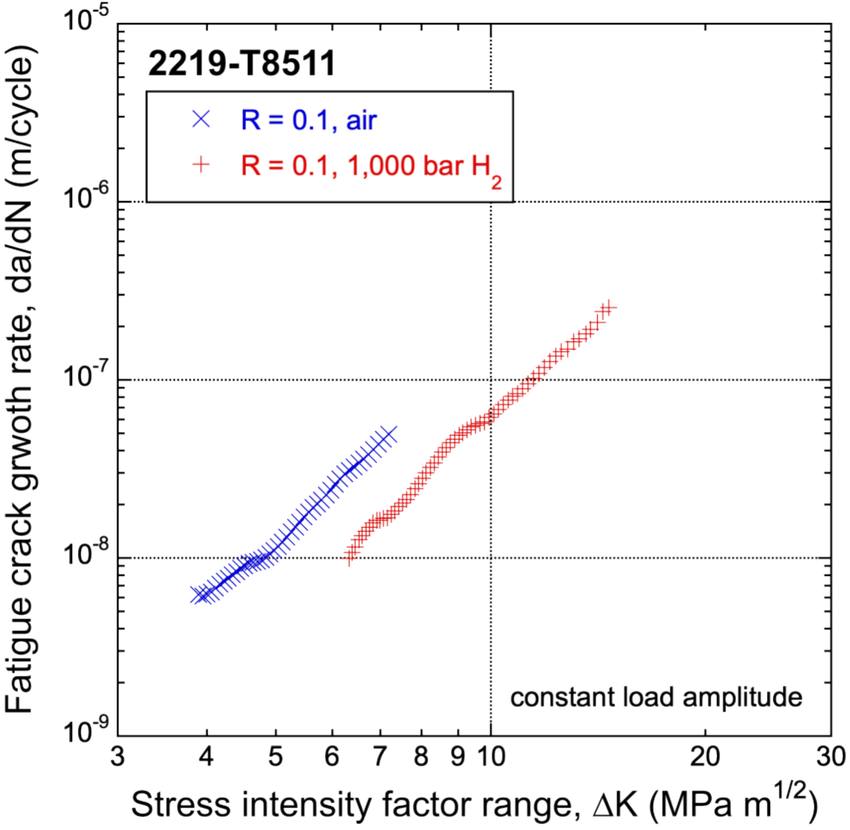


Weldable alloy common in vehicle applications with excellent environmental corrosion resistance

- **No apparent degradation of fatigue crack growth due to high-pressure (1,000 bar) gaseous hydrogen**

FCGR of 5083-O is not accelerated in high-pressure GH2

Aluminum alloy 2219-T8511

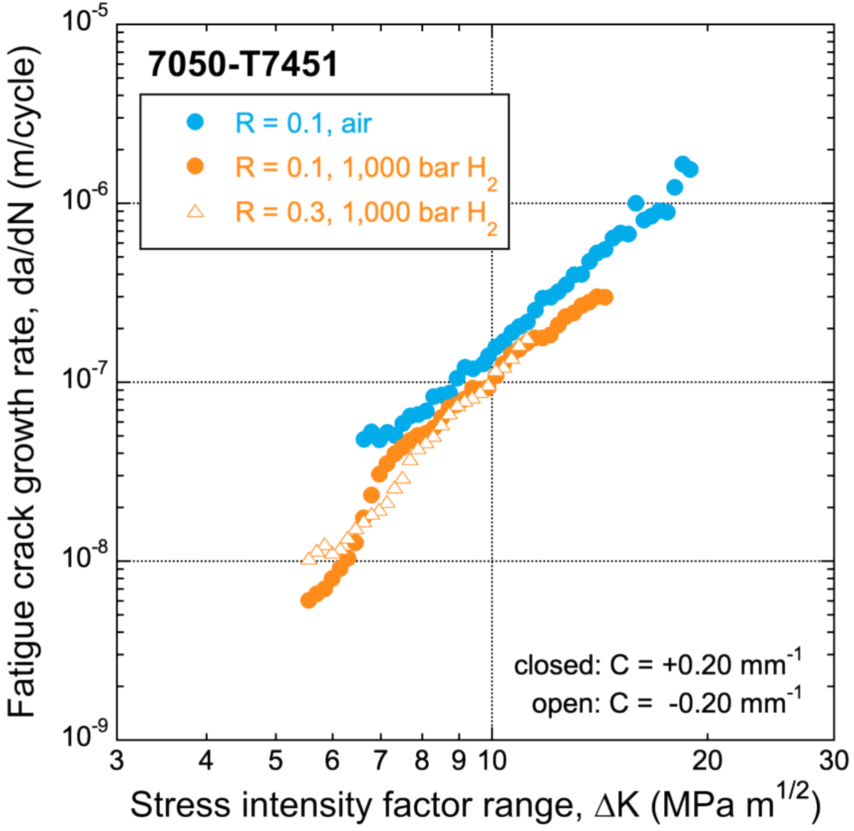


Weldable, high-strength alloy with good resistance to stress-corrosion cracking (SCC) used in aerospace applications

- **No apparent degradation of fatigue crack growth due to high-pressure (1,000 bar) gaseous hydrogen**

FCGR of 2219-T8511 is not accelerated in high-pressure GH2

Aluminum alloy 7050-T7451

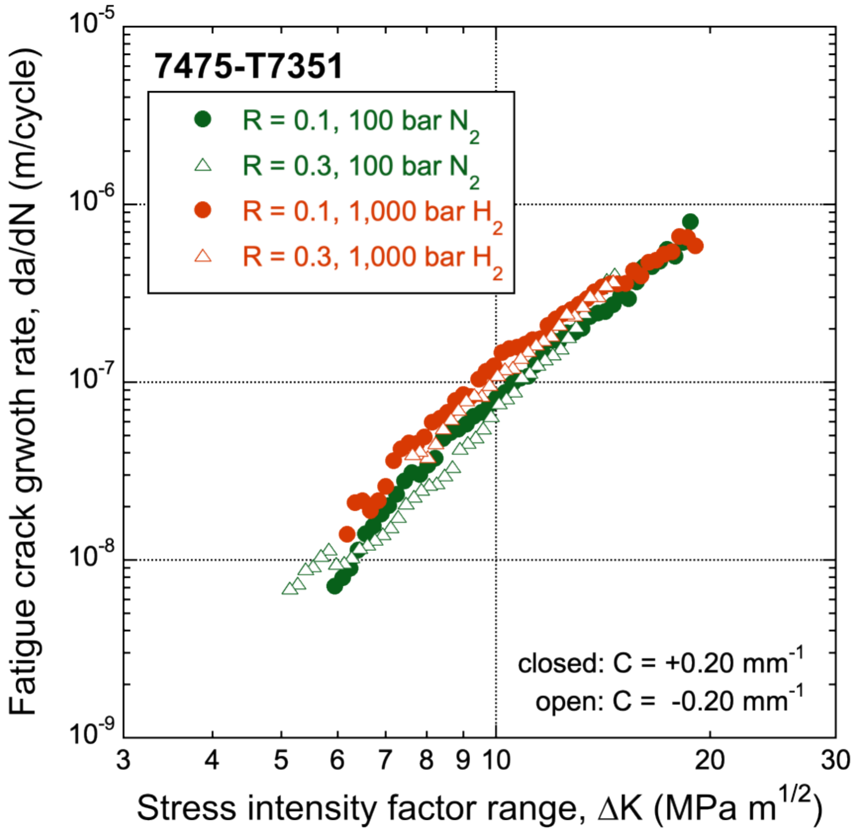


Common high-strength aluminum alloy with poor weldability and susceptibility to stress-corrosion cracking

- **Overaged condition shows no apparent degradation of fatigue crack growth due to high-pressure (1,000 bar) gaseous hydrogen**

FCGR of 7050-T7451 is not accelerated in high-pressure GH2

Aluminum alloy 7475-T7351

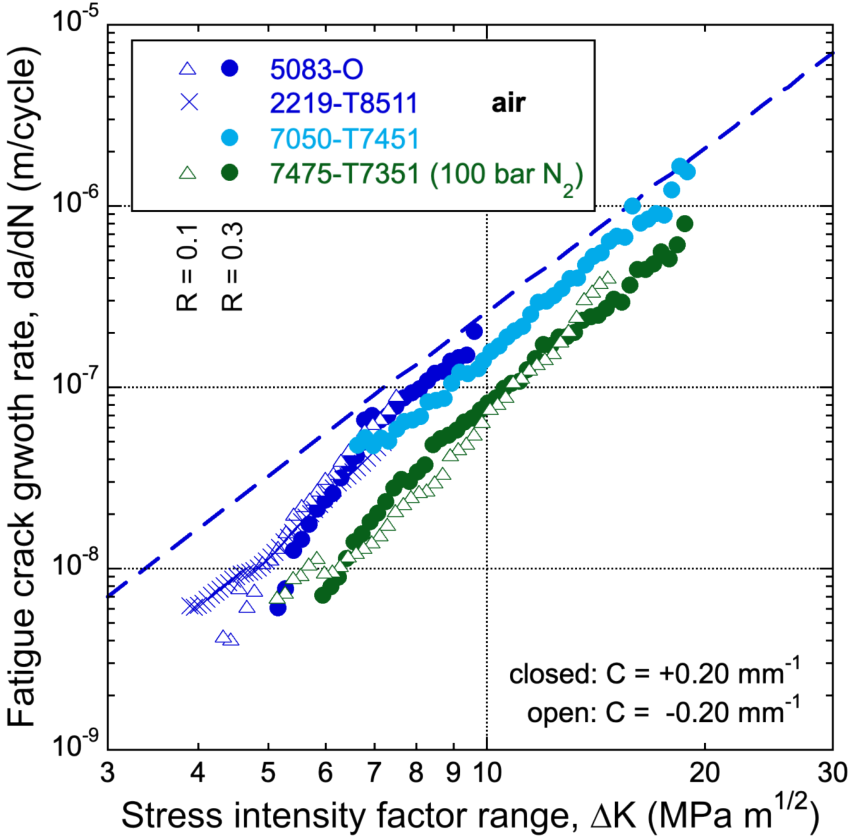


High-strength, aerospace aluminum alloy with poor weldability and susceptibility to stress-corrosion cracking

- **Fatigue crack growth appears slightly lower in dry nitrogen than in GH2**
- **Fatigue crack growth of overaged condition in high-pressure (1,000 bar) gaseous hydrogen is similar to other alloys**

FCGR of 7475-T7351 is not accelerated in high-pressure GH2

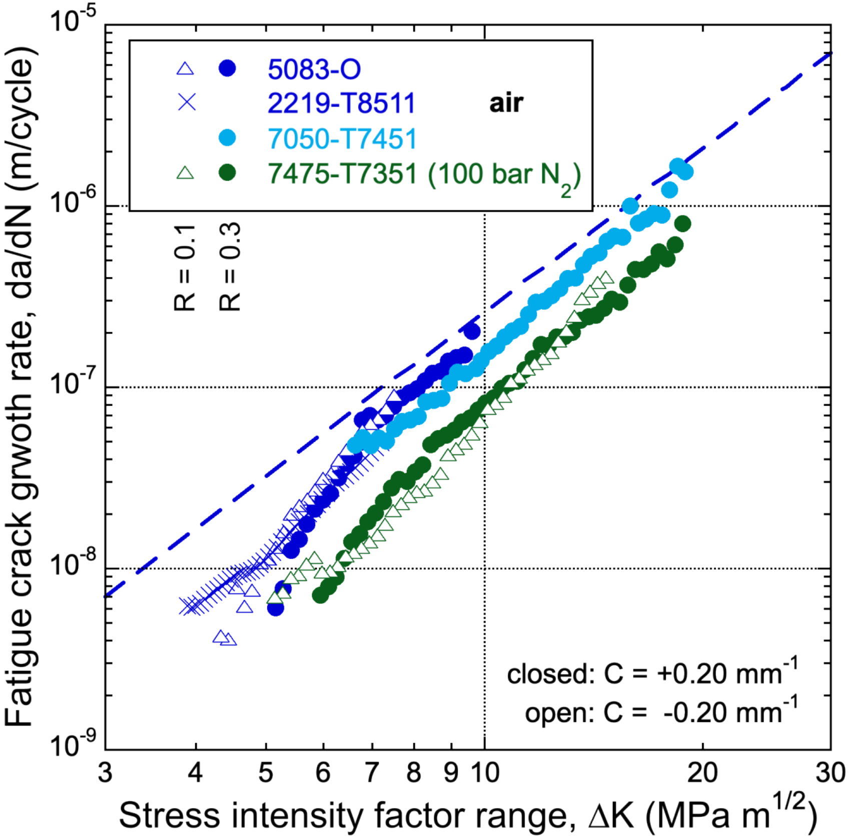
Composite data in air show consistent FCGR for all alloys

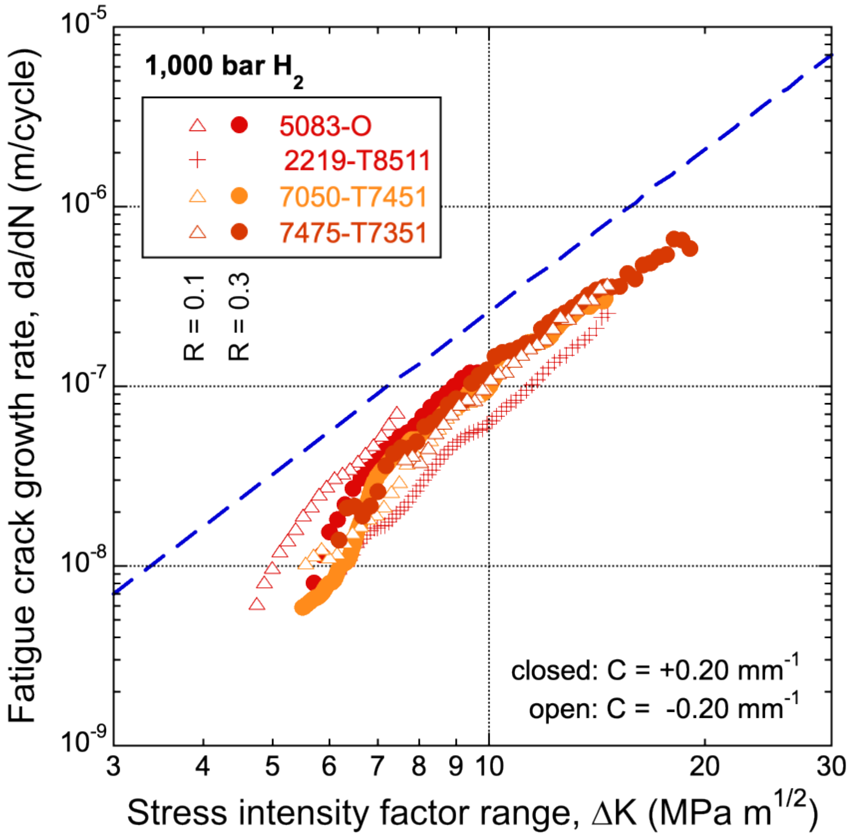


- **All tested aluminum alloys show similar fatigue crack growth in air**
- **Fatigue crack growth rates are bounded by recommended Paris Law relationship (dashed line)**
  - **from International Institute of Welding**
- **Fatigue crack growth appears lower in dry nitrogen than in air**

FCGR of aluminum alloys is sensitive to humidity

FCGR of all alloys in GH2 is slightly lower than in air

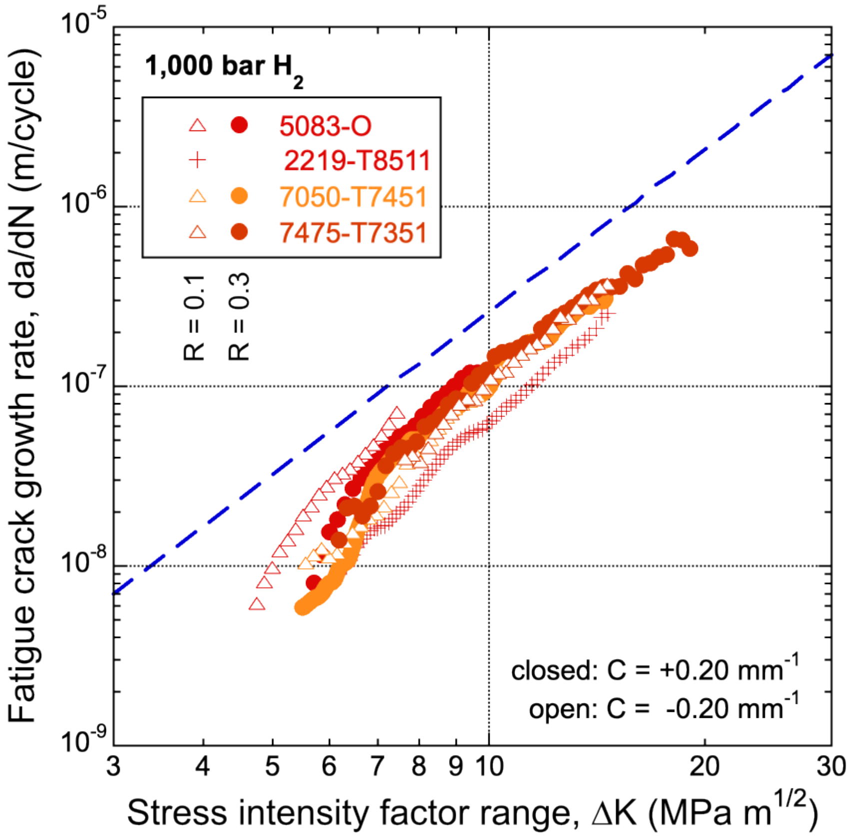




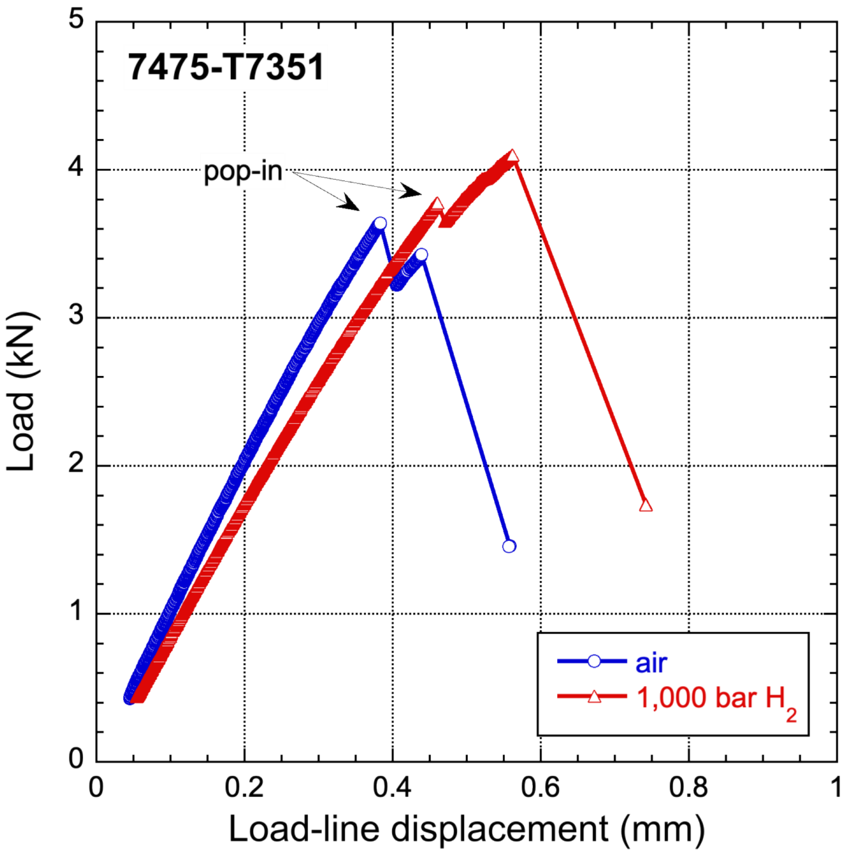
FCGR in GH2 is similar for all tested alloys

- **All tested alloys display lower fatigue crack growth rates than benchmark behavior for aluminum alloys**
- **Some scatter in the fatigue crack growth rates**
  - **Perhaps related to residual moisture content in the gaseous environment (gas quality was not evaluated for all tests)**

FCGR of high-strength aluminum alloys is not accelerated in dry, high-pressure GH2



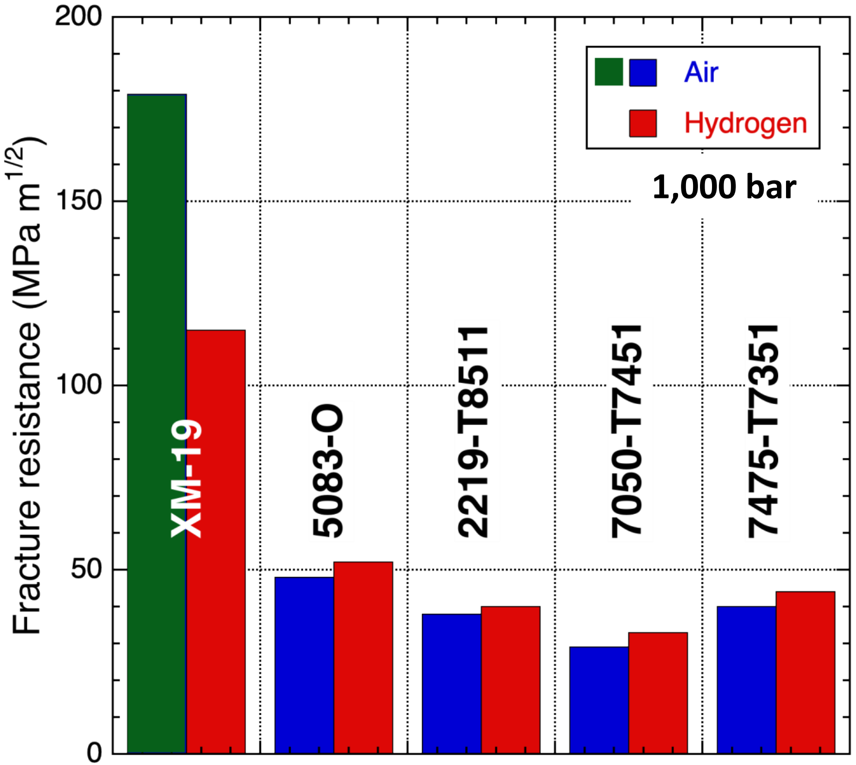
Fracture resistance is similar in GH2 and air



- **High-strength aluminum alloys show 'low' fracture resistance in air, often characterized by unstable crack growth (e.g., pop-in)**
- **In GH2, fracture resistance is generally slightly higher than in air**
  - **Improved fracture resistance can be achieved in dry gas environments, including dry GH2**

Dry hydrogen environments appear to be more 'inert' than laboratory air, even at high pressure

Fracture resistance of aluminum alloys in dry GH2 is better than in air



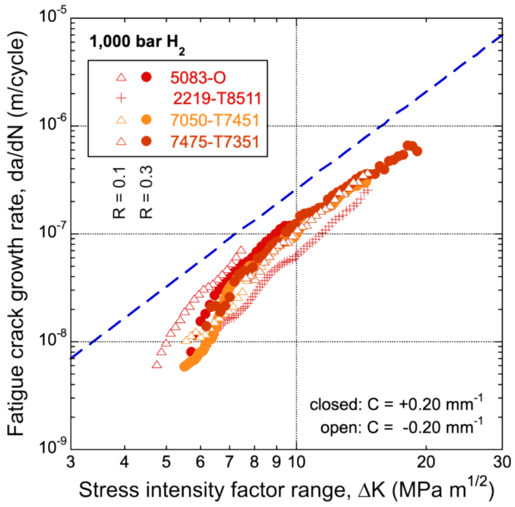
XM-19 w/ internal H from:
Metall Mater Trans **41A** (2010) 3348

- **Fracture resistance of austenitic stainless steel is reduced in hydrogen environments**
- **In contrast, fracture resistance of aluminum alloys in not degraded in dry GH2**
- **However, fracture resistance of aluminum will generally be lower than common austenitic stainless steels in GH2 environments**

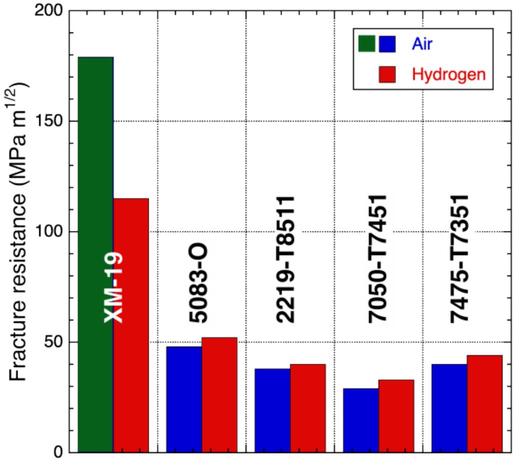
Fracture resistance of aluminum alloys is better defined in GH2 than steels, since it is unchanged (or better) relative to air

Summary

- GH2 at pressure of 1,000 bar did not degrade the fatigue crack growth behavior of the tested high-strength aluminum alloys
  - Nominally same FCGR for R = 0.1 and 0.3
- Fracture resistance also was not degraded in GH2 at pressure of 1,000 bar



Results:
- Both fatigue crack growth and fracture resistance is improved slightly in dry, high-pressure GH2 relative to tests in air
- Results likely mediated by moisture content



Thank You!

Chris San Marchi
cwsanma@sandia.gov

Joe Ronevich
jaronev@sandia.gov

H-Mat℠ Hydrogen Materials Compatibility Consortium

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