SAND2020-4233PE

Sandia's Capabilities and Relevant Research

H2@Scale Kickoff

Colorado School of Mines

April 14, 2020

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Sandia National Laboratories

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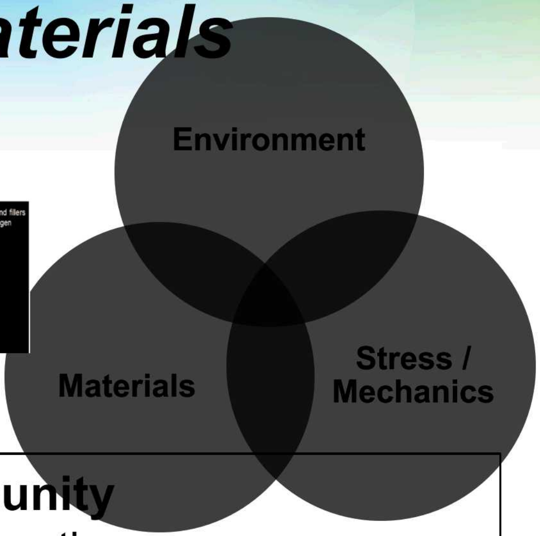
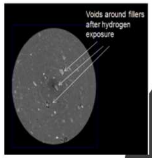
Sandia maintains unique capabilities to support research on *Hydrogen Effects on Materials*



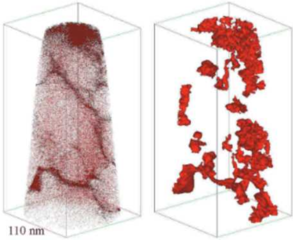
Hydrogen Effects on Materials Laboratory

- In situ mechanical testing
  (P >100 MPa and 230K < T < 400K)
- Long-term, high-pressure H2 exposure
- Pressure cycling at controlled temperature



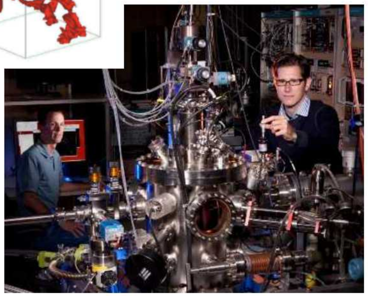
Active materials science community

- Computational materials science expertise
- Full-suite of state-of-the-art materials characterization tools
- Joining laboratory (austenitic steels, non-ferrous materials)



Hydrogen Transport and Trapping Laboratory

- Diffusion and permeation
- Thermal desorption spectroscopy
- Local-electrode atom probe tomography



Hydrogen-Surface Interactions Laboratory

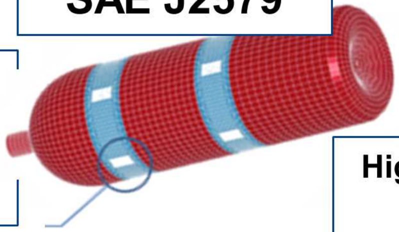
- Low-energy ion spectroscopy
- Ambient pressure x-ray photoelectron spectroscopy
- Kelvin probe atomic force microscopy

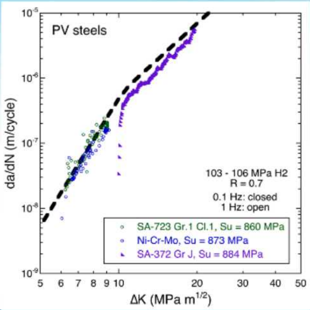
Evaluation of *Materials Compatibility with H_2* enables materials innovation

ASME article KD-10 input on test methodology

First qualification data for high-pressure ASME vessels

Full-scale tank testing CSA HPIT1 SAE J2579



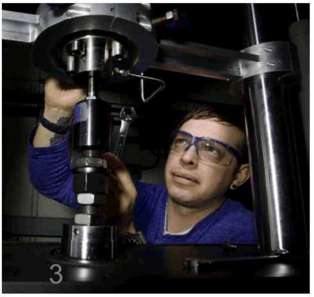


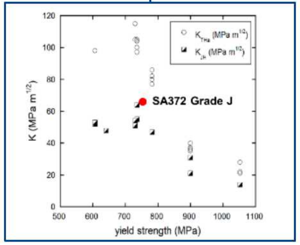
Platform for pressure cycling of polymers in GH2 (up to 400 C)

High-hardenability pressure vessel steel results presented to ASME KD-10 for acceptance of curve fits based on data

2006 | 2008 | 2010 | 2012 | 2014 | 2016 | 2018

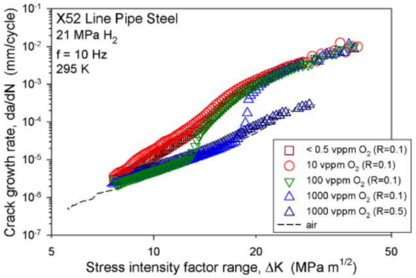
Platform for matls testing in GH2 at high pressure





Critical assessment of statically loaded cracks

Modeled H_2 embrittlement mitigation through O_2 gas impurities



Platform for high-pressure GH2 over temperature range (-40˚C to +85˚C)

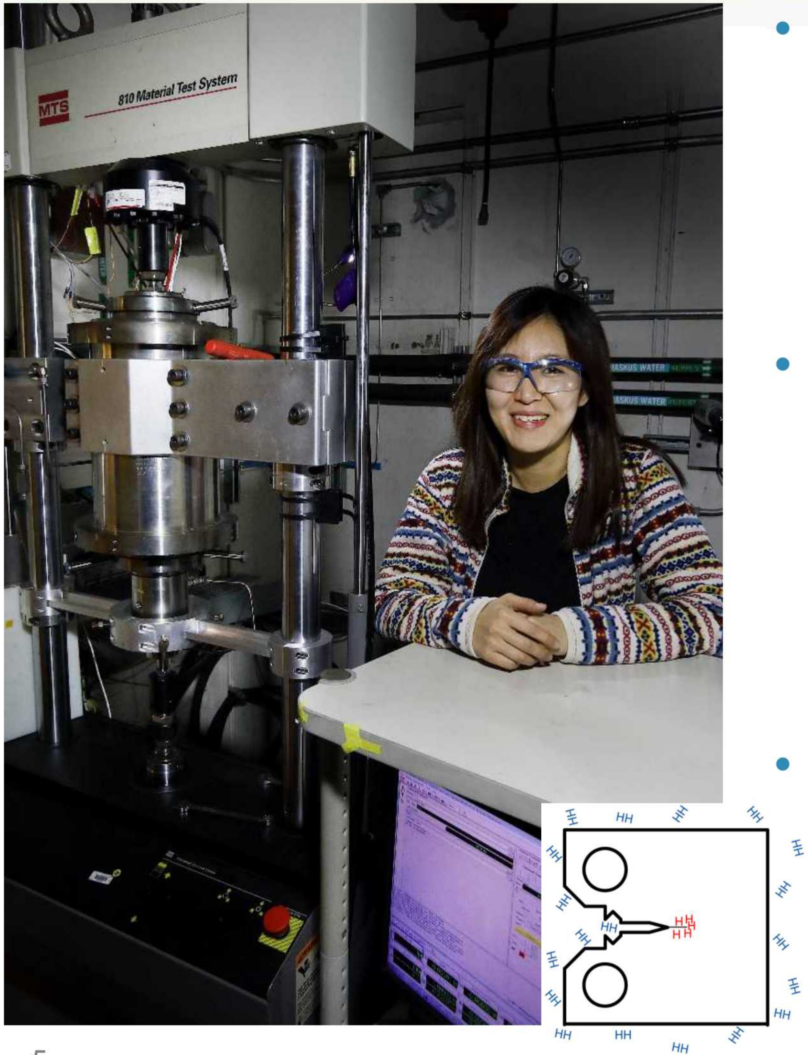
General trends in hydrogen transport

- **Ferritic steels**
  - **Diffusivity: 10^{-8} m²/s**
  - **Solubility: 10^{-8} H/M MPa$^{-1/2}$**
    - **Lattice concentration (P=100 MPa): 0.3 ppm H/M**
    - **Trapping concentration: 100x greater than lattice concentration**
  - ***Not amenable to gas-phase precharging***
- **Austenitic stainless steels**
  - **Diffusivity: 10^{-15} m²/s**
  - **Solubility: 10^{-4} H/M MPa$^{-1/2}$**
    - **Lattice concentration (P=100 MPa): 0.2% H/M**
    - **Trapping concentration: <<1x lattice concentration**
  - ***Gas-phase precharging is a well-developed technology***
    - **Specimens can be shipped anywhere on dry ice and stored for extended time (months) at low temperature (-50˚C)**
    - **Precharging time weeks to months depending on specimen size**

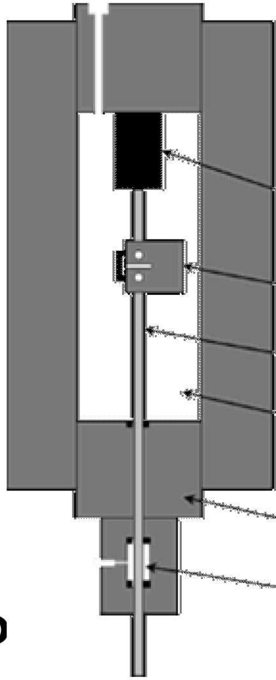
Solubility (ideal gas)

$$K = \frac{c_L}{\sqrt{P}}$$

Fatigue and fracture measurements in high-pressure gaseous hydrogen



- Instrumentation
  - Internal load cell (w/ feedback)
  - Displacement measured on sample using LVDT or clip gauge
  - DCPD measurements possible
- Mechanical loading
  - Cyclic / monotonic
  - Load-ratio = 0.1 to 0.8
  - Frequency = 0.002 to 10 Hz
  - Loads: 1–15 kN
  - ASTM E1820, E647, etc
- Environment
  - Gaseous environment
  - Pressure ≤ 120 MPa
  - Room temperature (some lo temperature capability)

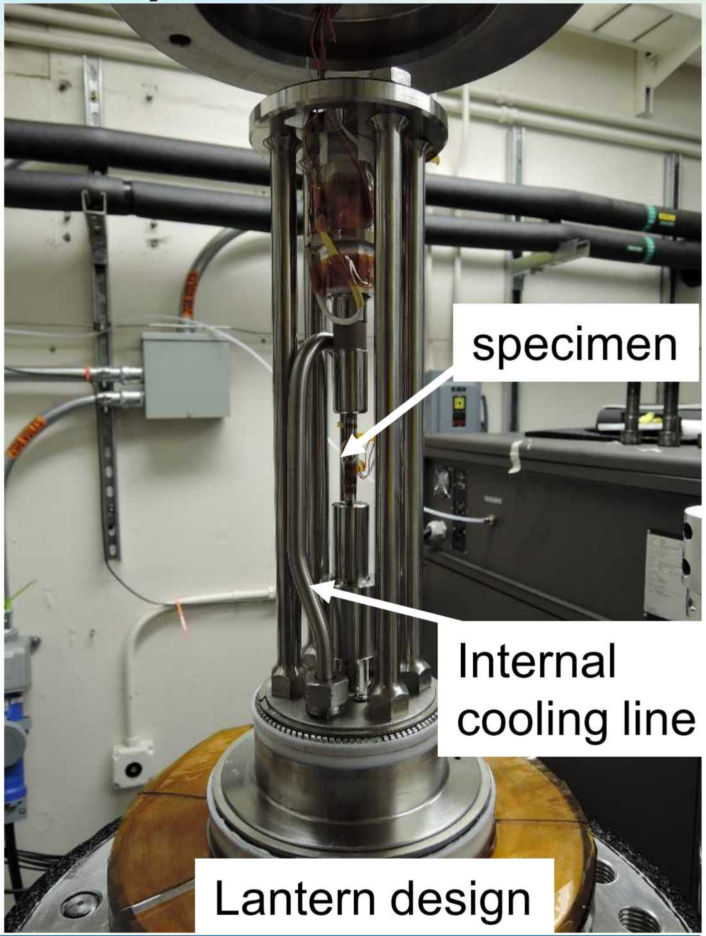


Dynamic testing in high pressure hydrogen at sub-ambient temperatures (Cell 2)

Temperature
-50C to 150C

Pressure
Up to 106 MPa

Mechanical Test
Quasi-static
or
Cyclic loading

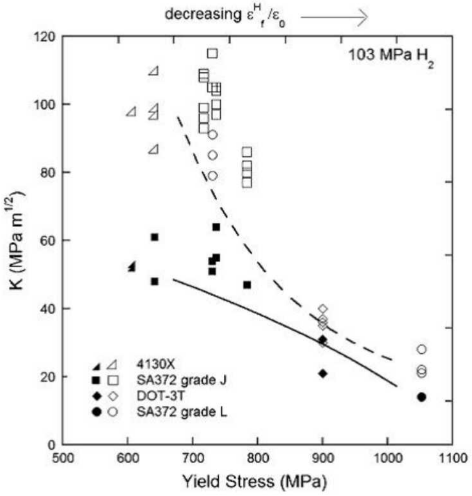


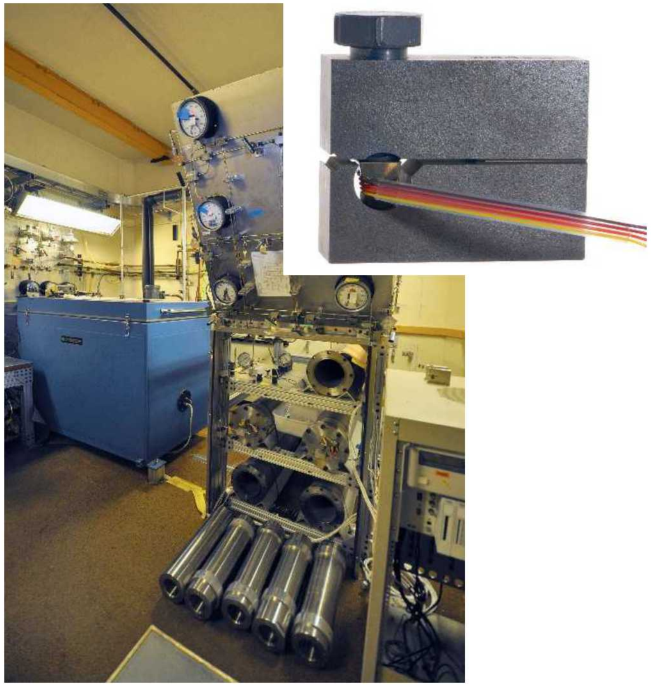
Hydrogen refueling stations pre-chill gas and components experience temperatures from -40C to +85C

High temperature hydrogen pre-charging or statically loaded tests in hydrogen environment (Cell 5)

- Thermally pre-charge test specimens up to 138 MPa H_2 at 300C
- For austenitic stainless steel, results in approximately 1 at% hydrogen
  - 140 wppm in 300 series

- Statically loaded specimens (ASTM E1681) exposed to high pressure hydrogen to evaluate fracture thresholds





Hydrogen-materials exemplar projects

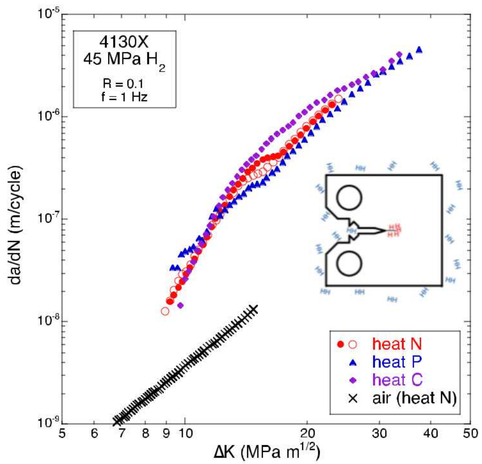
1) Evaluated pressure vessels for H_2 fuel cell fork lift trucks

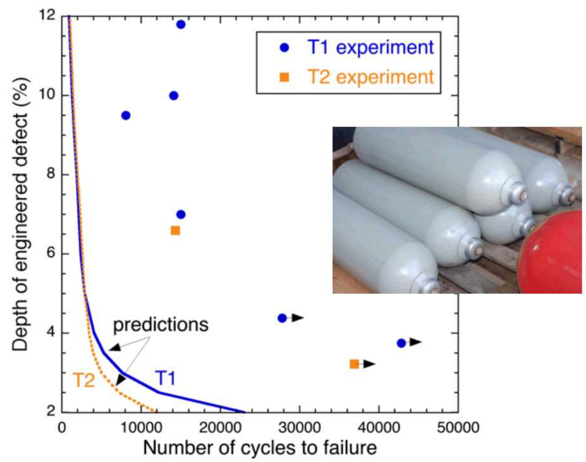
2) Residual stress effects on high strength pipeline steel welds

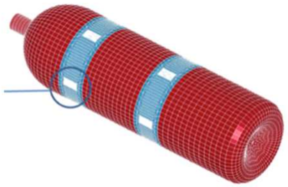
3) Microscopy characterization at different length scales – 304L austenitic stainless steel

1) Full-scale testing of pressure vessels enabled deployment of safe, low-cost fuel cell forklift fuel systems

Materials testing and evaluation → *Component testing* → *Lifetime prediction and SCS development*





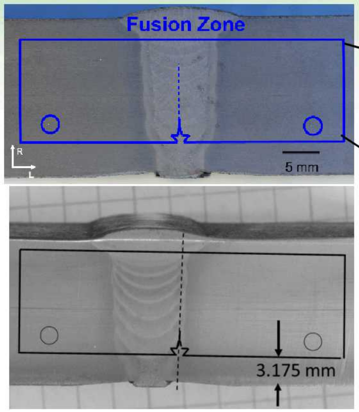


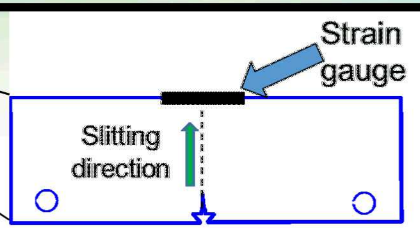
- **Quantified uncertainties in the cycle life of hydrogen storage tanks for the lift-truck application**
- Enhanced safety and market growth enabled through standards development (CSA HPIT1)
- Today, there are >23,000 clean and efficient fuel cell forklifts in service (and growing!)

Enabled H_2 fueled forklifts through combined full-scale & laboratory materials testing

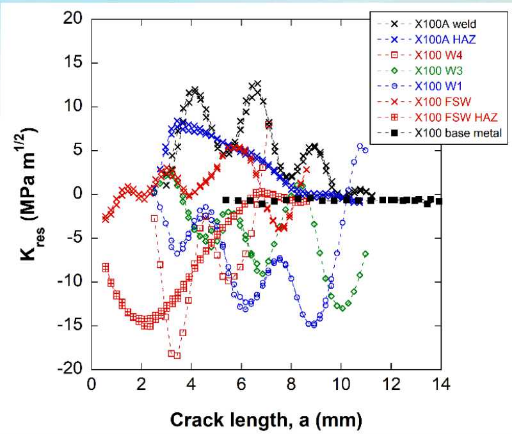
Sandia National Laboratories · Oak Ridge National Laboratory · NIST · Alabama · H_2FC Hydrogen and Fuel Cells Program

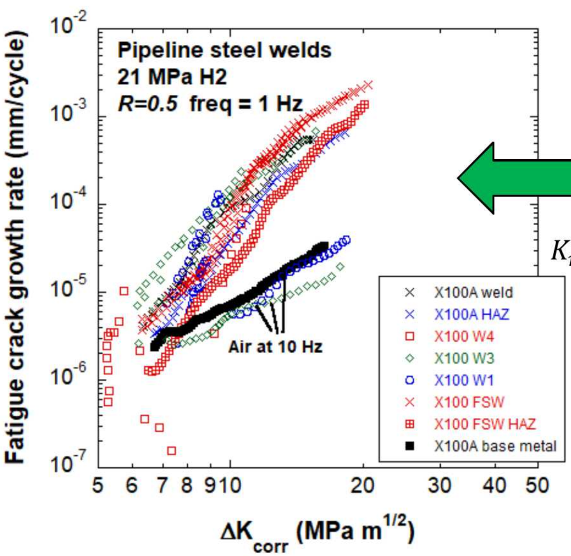
2) Fundamental understanding of hydrogen-assisted fatigue behavior of pipeline welds through measurements & correction for residual stress





Slitting method used to measure K_{res} as function of crack length (*Collaboration with Prof. Mike Hill at U.C. Davis)



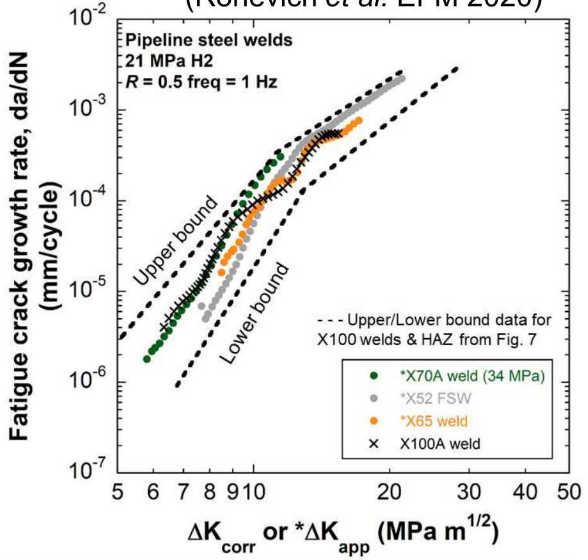


Corrected data normalizes FCGR curves to single R-ratio = 0.5 providing better utility and fidelity

$$K_{norm}(a) = (\Delta K(a))^{1-n} * (K_{max-app}(a) + K_{res}(a))^n$$

$$\Delta K_{corr} = K_{norm} * (1 - \bar{R})^n$$

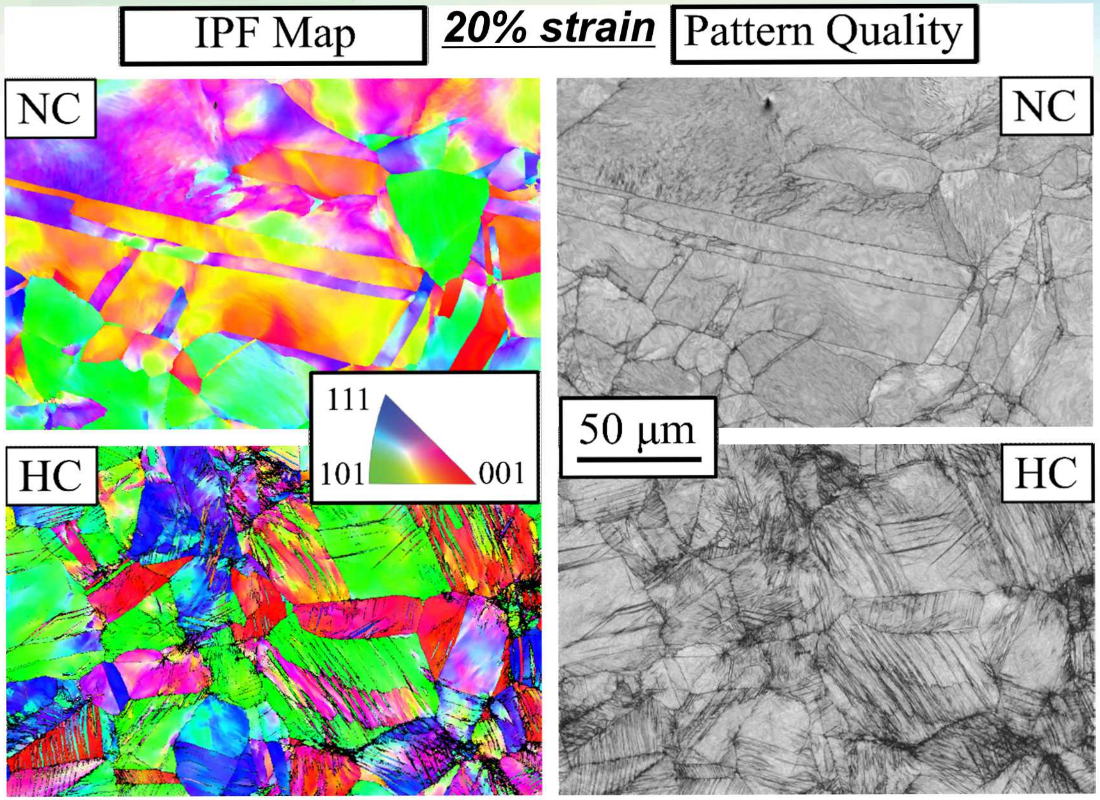
(Ronevich *et al.* EFM 2020)

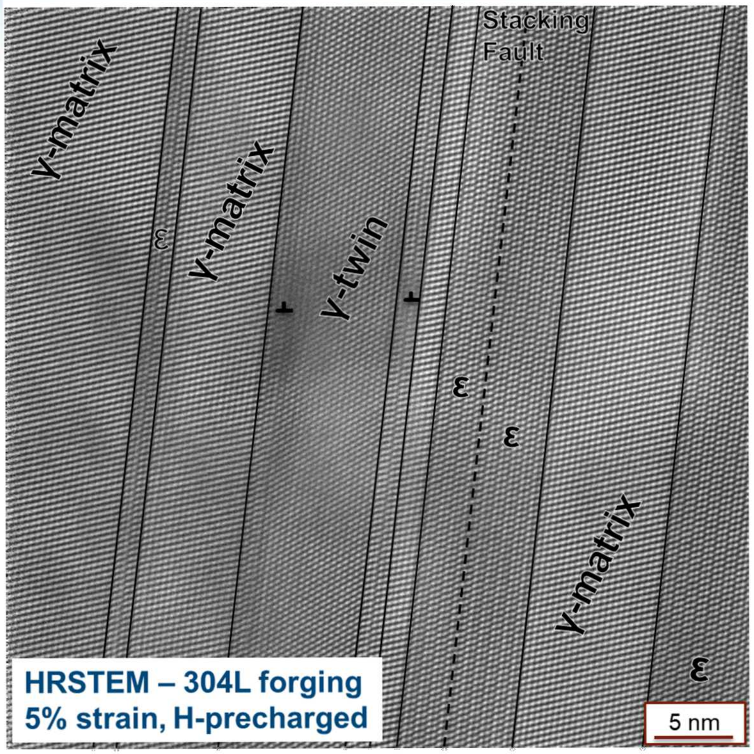


FCGR of high strength welds were comparable to lower strength welds, when residual stress is considered

3) Characterization at different length scales – 304L

Julian Sabisch, Doug Medlin, Josh Sugar (SNL/CA)





- 304L deformed 5% and 20% without (NC) and with H-precharging (HC)
- Martensite is more common than twinning in H-precharged samples
- Twins and ε-martensite are generally very thin (less than ~20 {111} planes) while spanning through most of the grain. With twins appearing as faulted ε-martensite

Summary

- **Sandia National Laboratories has numerous H-related capabilities**
  - **Thermal (gas-phase) H-precharging**
  - **Fatigue and fracture in high-pressure gaseous hydrogen**
  - **Hydrogen transport (TDS, diffusion/permeation)**
  - **Static loading/displacement testing**
- **Should not overlook other capabilities and expertise, such as**
  - **Expert materials science characterization**
  - **Computational materials science**

Acknowledgements

FCTO for funding much of this research

Hydrogen Effects on Materials Laboratory Team
- Chris San Marchi, Joe Ronevich, Jeff Campbell, Brendan Davis, James McNair, Brian Kagay

Microscopy
- Josh Sugar, Doug Medlin, Julian Sabisch

Modeling
- Jay Foulk, Coleman Alleman, Xiaowang Zhou, Norm Bartelt, Chris Nowak

Surface Science
- Farid El Gabaly, Rob Kolasinski, Konrad Thurmer

Trapping and Transport Lab
- Rick Karnesky

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