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Metrics, trends and capabilities for evaluating hydrogen effects in metals

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H-Mat Kick-off Meeting

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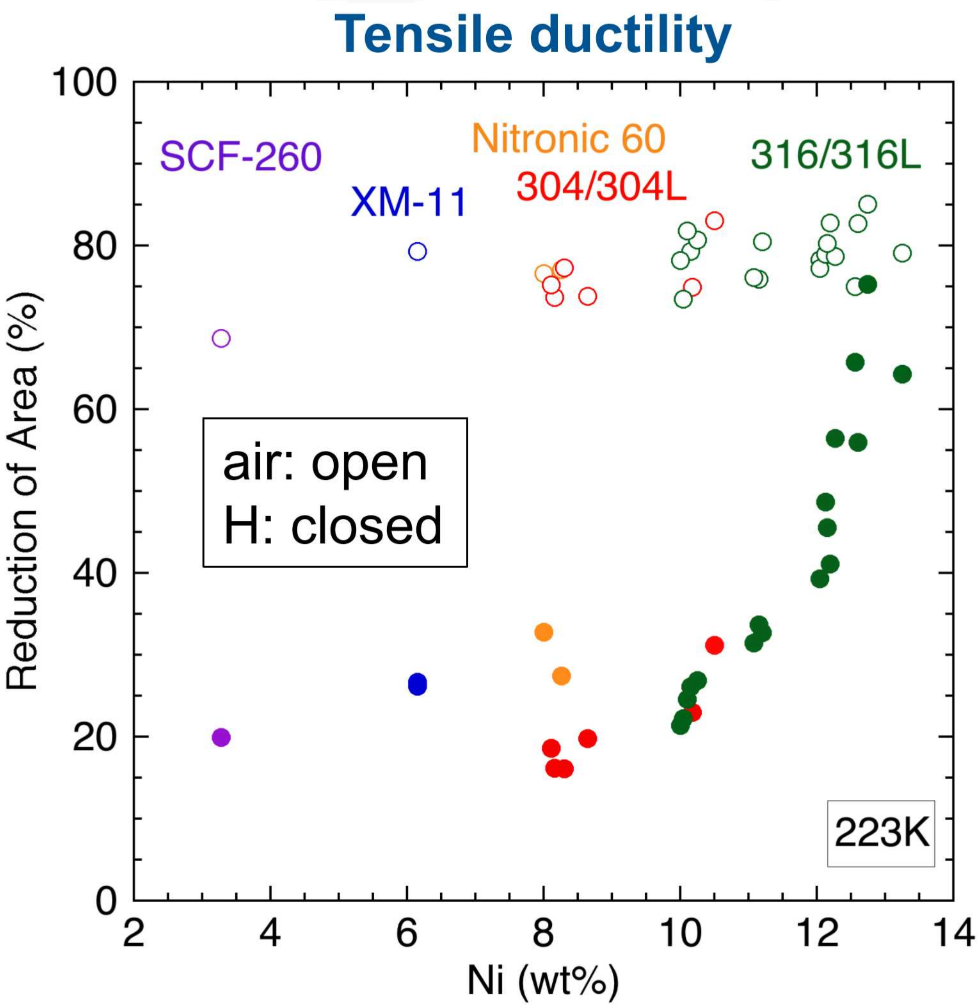
Outline

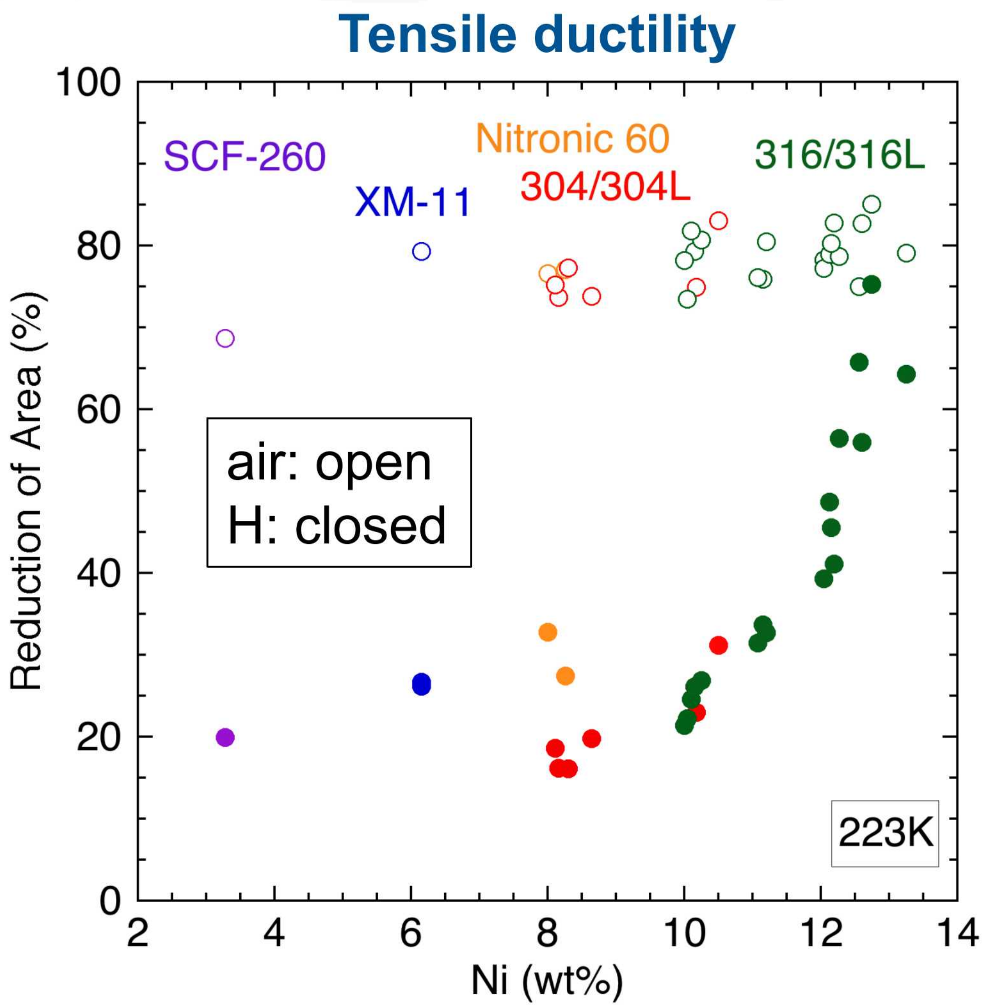
- Metrics and Targets
  - Why do we need them?
  - What does ‘better than’ mean?
  - What is a meaningful metric/target?
- Demonstrate importance of quantitative metrics with data trends
- Describe high-pressure capabilities at Sandia

Extensive database exists for tensile behavior of γ-stainless steels in hydrogen environments



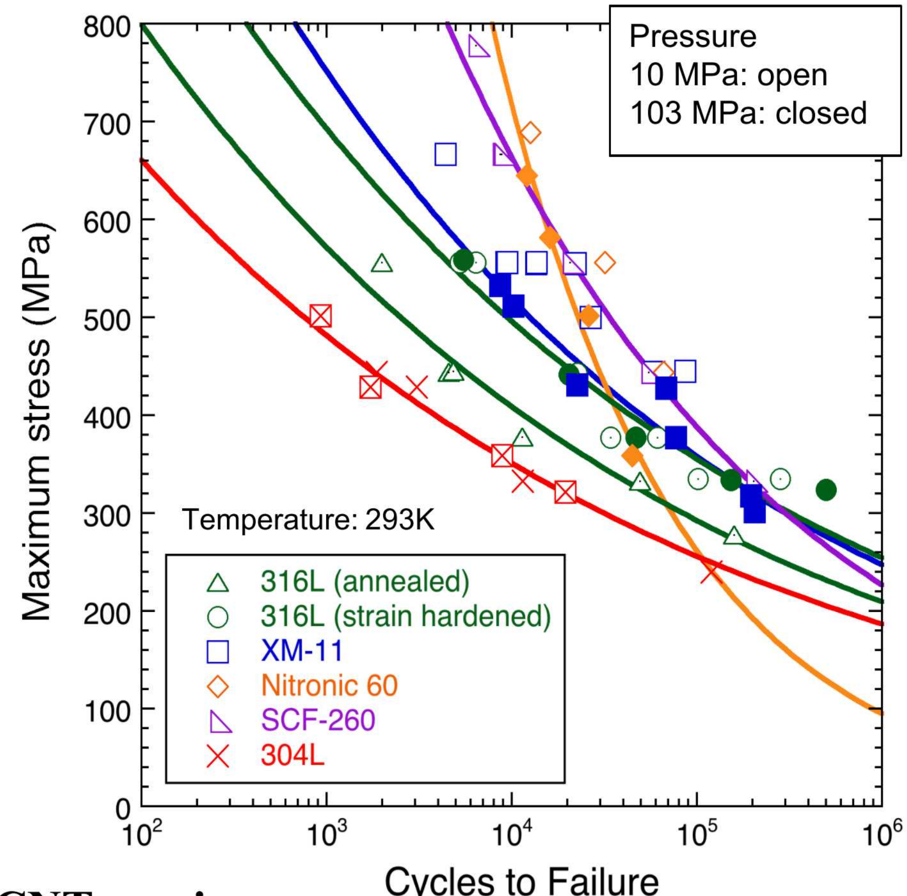
- **Strength properties are generally not affected by hydrogen**
- **Nickel correlates with ductility in hydrogen as well as any other indicator**
- **Austenite stability is not as good an indicator when nitrogen-strengthened alloys are considered**

Is tensile ductility a meaningful metric for evaluating hydrogen effects?



- **RA can be useful screening and comparative measure**
  - **eg, verification of the materials pedigree**
- **RA is not a useful design parameter**
  - **RA for high-strength aluminum can be <20%**
- **Therefore, RA is not a sufficient general metric for materials selection**

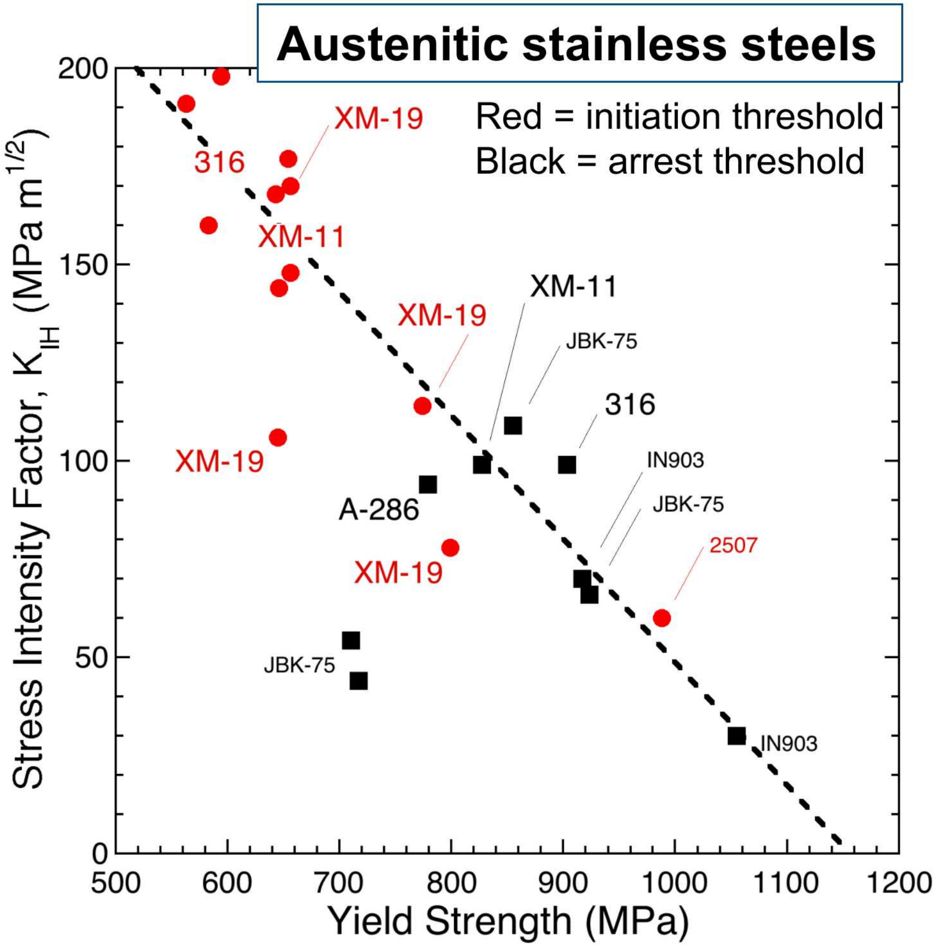
Fatigue life data shows less dramatic effects from hydrogen than tensile data



CNT specimens
***R* = 0.1, *f* = 1Hz**

- **Fatigue life data are used in design and can be a meaningful metric**
- ***For example*: automotive uses performance metric for materials selection in hydrogen systems:**
  - **10^5 cycles to failure at 1/3 tensile strength**
- **Other metrics can be just as meaningful**

Typical austenitic stainless steel maintain high fracture threshold in hydrogen environments



- **Fracture threshold in gaseous hydrogen is reduced by >50% for all steels on this plot**
- **General trend of lower fracture threshold with higher strength**
- **More highly alloyed and/or complex alloys can have lower fracture threshold**

Diverse range of austenitic stainless steels show exceptional properties in hydrogen

material	Yield (MPa)	Tensile (MPa)	Tension RA (%)	Fracture K_{JH} (MPa m$^{1/2}$)	Fatigue S_{fH}† (MPa)
316L	280	562	57	–	295
CW 316L	573 563	731 735	60 66	316L – 190	355 –
304L	497 452	721 674	25 49	304L – 220	255 –
XM-11	539 643	881 816	42 51	XM-11 – 225	355 –
Nitronic 60	880 499	1018 857	36 53	– –	260 –
SCF-260	1083	1175	50	–	390

† defined as the stress for with notched fatigue life ~10^5 cycles in H_2 (100 MPa, R = 0.1, f = 1Hz)

Strength and composition can be relevant metrics

material	Yield (MPa)	Tensile (MPa)	Cr	Ni	Mn	N	Typical allowable stress (MPa)
316L	280	562	17.5	12	1.2	0.04	115
CW 316L	573	731	17.5	12	1.2	0.04	218
304L	497	721	18.3	8.2	1.8	0.56	195
XM-11	539	881	20.4	6.2	9.6	0.26	207
Nitronic 60	880	1018	16.6	8.3	8.0	0.16	218
SCF-260	1083	1175	19.1	3.3	17.4	0.64	333

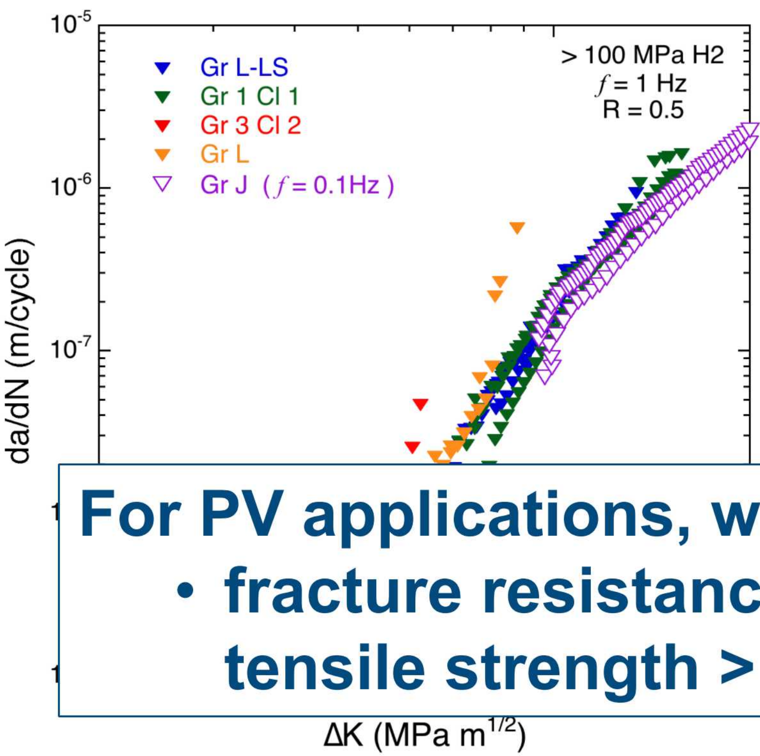
Wide range of strength

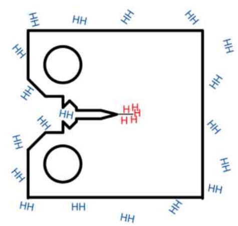
Wide range of Ni/Mn content

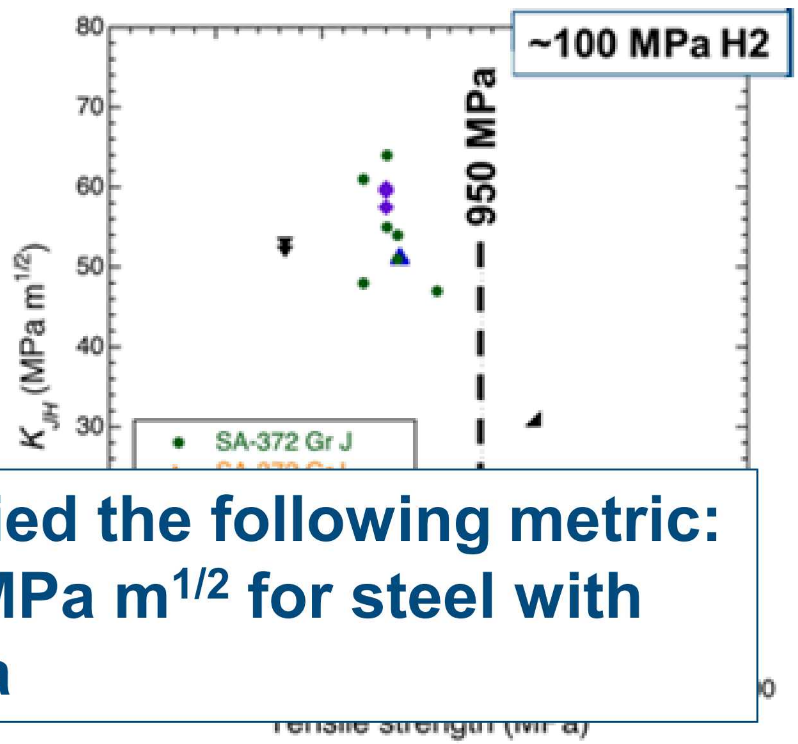
- **Strength reflects allowable stresses and wall thickness**
- **Composition is related to cost (but not only factor)**

Fatigue and fracture of ferritic steels

- **Fatigue crack growth is similar for typical pressure vessel and linepipe steels (deviations relate to fracture toughness)**
- **Fracture resistance is consistent and acceptable for low strength – fracture resistance of steels with tensile strength > 900-950 MPa is unacceptable for PVs (~20 MPa $m^{1/2}$)**





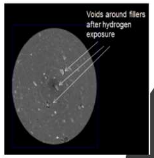


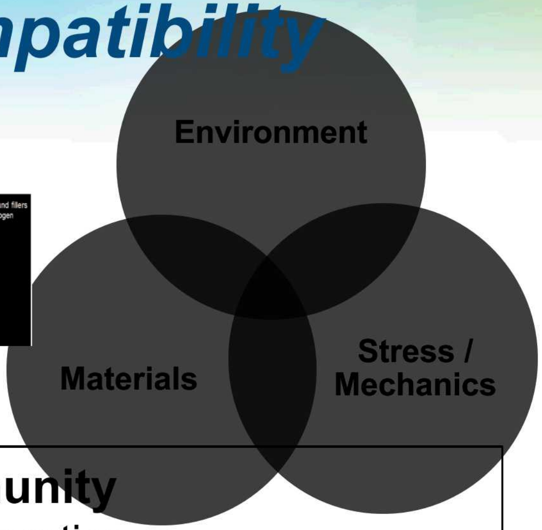
For PV applications, we identified the following metric:
- **fracture resistance of 50 MPa $m^{1/2}$ for steel with tensile strength > 950 MPa**

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

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



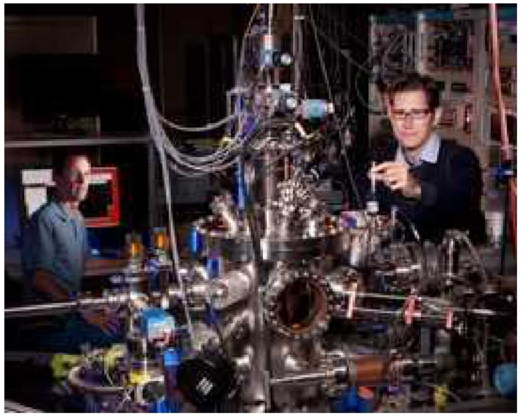


Active materials science community

- 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

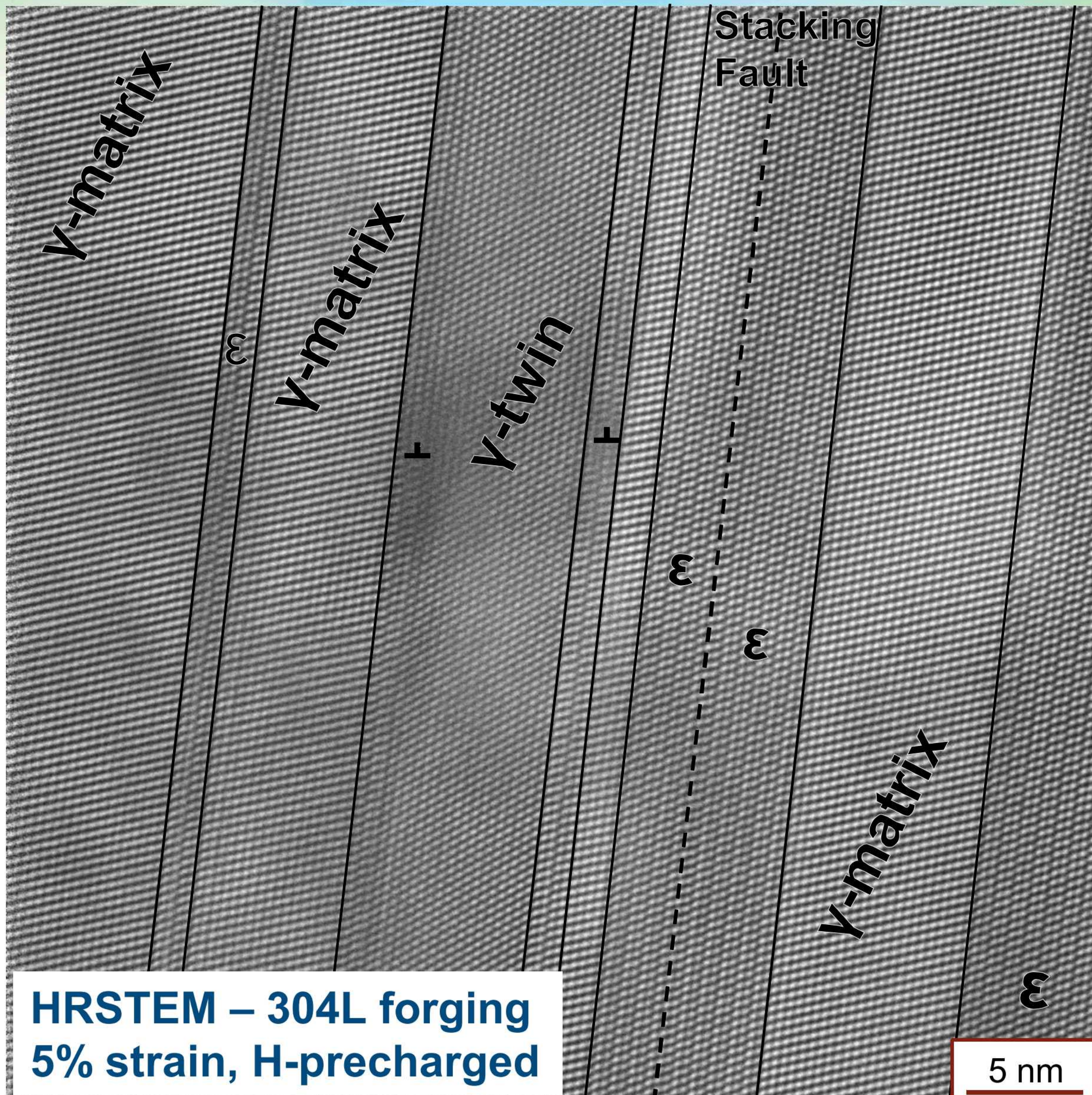


Hydrogen-Surface Interactions Laboratory

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

Example of characterization at the nanometer length scale

- HR-STEM shows some interface dislocations ($\frac{1}{6}\langle 112\rangle$ and $\frac{1}{3}\langle 111\rangle$) with no dislocations observable within twins, matrix, or ε-martensite
- Martensite is more common here than twinning (typical for 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



Julian Sabisch &
Doug Medlin (SNL/CA)

H-precharging is used to simulate hydrogen service environment for some materials systems

- Exposure to gaseous H_2 until saturated with hydrogen
  - ~10 days for 4 mm round bar
  - Pressure: 138 MPa
  - Temperature: 300˚C
  - For stainless: hydrogen content ~140 wt ppm (0.8% H/M)

- Testing in air after H-precharging

- Mechanical testing in H-precharged condition is similar to *in situ* testing in high-pressure gaseous hydrogen for tension, fatigue and fracture
  - *Must consider the H-solute hardening: strength increase of 10-20%*

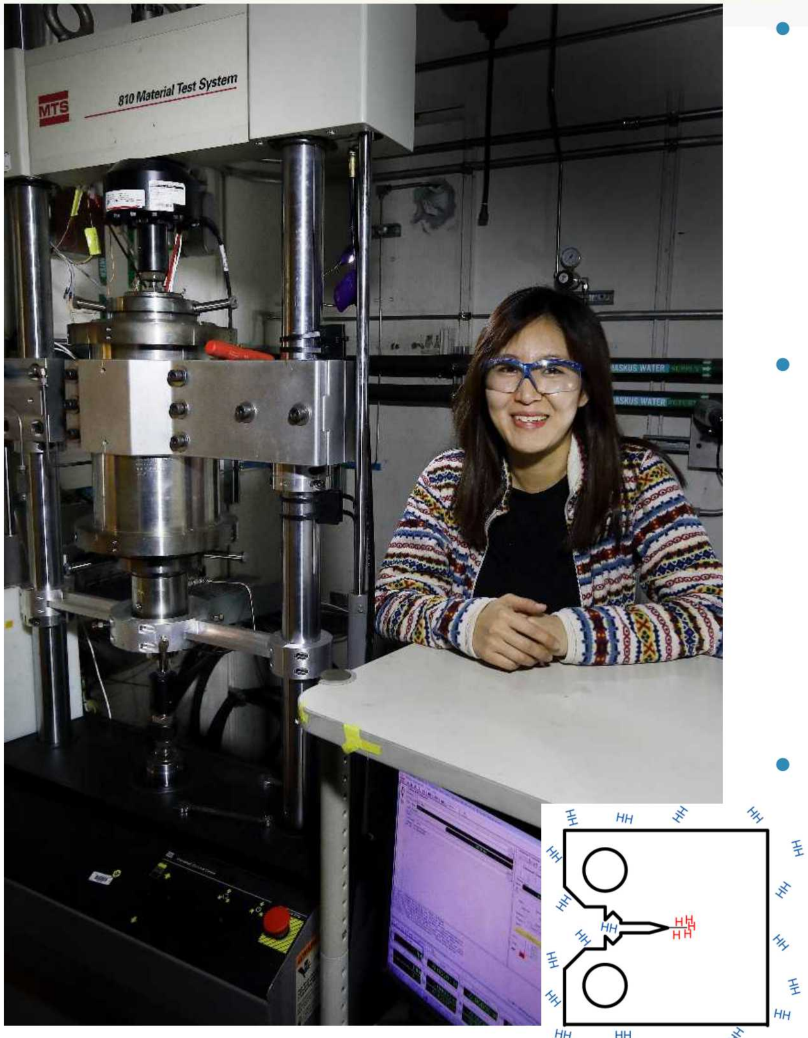
General trends in hydrogen transport

- Ferritic steels
  - Diffusivity: 10^{-8} m^2/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} m^2/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

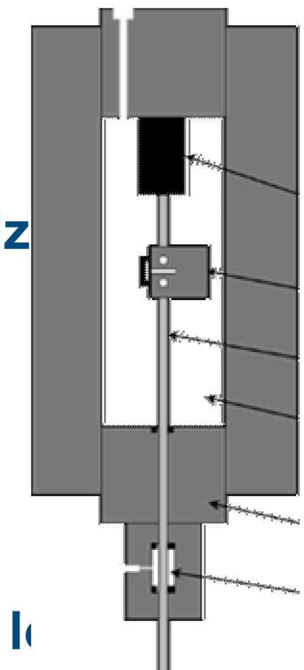
Solubility (ideal gas)

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

Fatigue and fracture measurements in high-pressure gaseous hydrogen

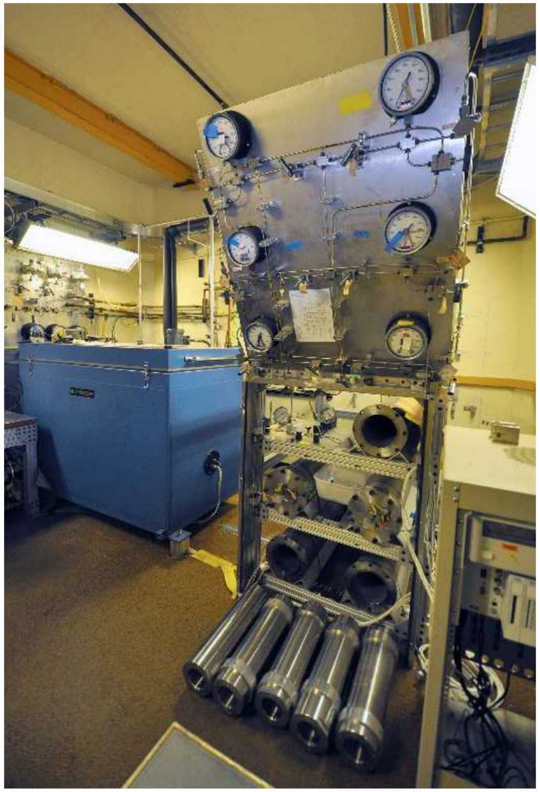


- Instrumentation
  - Internal load cell (w/ feedback)
  - Displacement measured on sample using LVDT or clip gauge
  - DCPD measurements possible
- Mechanical loading
  - Cyclic / monotonic
  - Load-ratio = 0.1 to 0.8
  - Frequency = 0.002 to 10 Hz
  - Loads: 1–15 kN
  - ASTM E1820, E647, etc
- Environment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

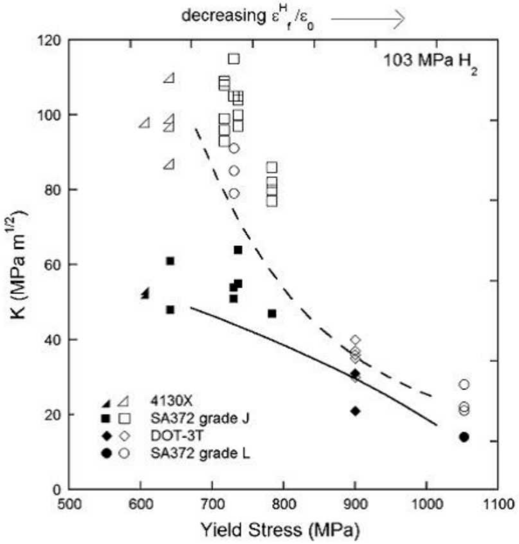


Constant displacement fracture tests in gaseous hydrogen environments

- **Constant displacement fracture testing (ASTM E1681)**
  - **exposed to high pressure hydrogen to evaluate fracture thresholds**



- **Relatively easy to load and leave specimens**
- **Test methods often require 1000s of hours**
- **Linear elastic method**
- **Requires large specimens for ductile metals**



Summary

- It is important to think critically about quantitative measures of success
  - What are we trying to achieve?
    (cost, strength, fatigue behavior, fracture resistance, and/or other)
  - On what length scale?
  - What are the requirements of the application, standards and codes? (is better the enemy of good enough…)
- National laboratories have 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