SAND2019-11725C

Assessing hydrogen-assisted fatigue crack initiation and propagation in austenitic stainless steels

Chris San Marchi[1]

Paul Gibbs[2], Kevin Nibur[3], Guy Bergel[1], Jay Foulk[1]

[1] Sandia National Laboratories, Livermore CA

[2] now at Los Alamos National Laboratory, Los Alamos NM

[3] Hy-Performance Materials Testing, LLC, Bend OR

Sandia National Laboratories is a multimission laboratory managed and operated by National Technology and Engineering Solutions of Sandia, LLC., a wholly owned subsidiary of Honeywell International, Inc., for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-NA-0003525.

Motivation

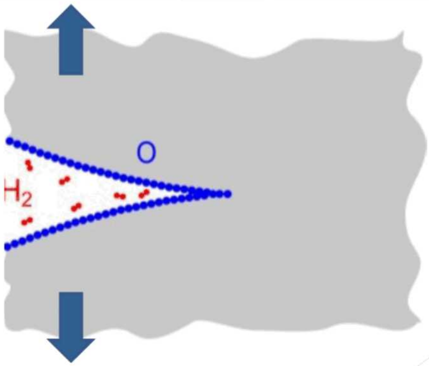
Identify low-cost, light-weight alternatives to annealed type 316L austenitic stainless steels for vehicle applications

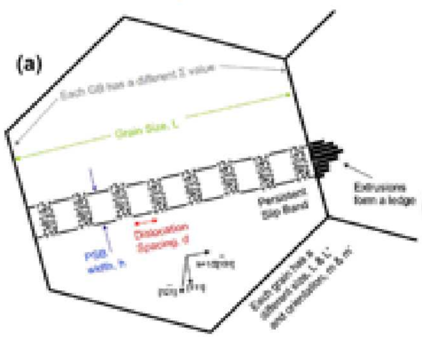
- ***Reduced nickel*** **content is prime candidate for *cost reduction***
- ***High-strength*** **is prime candidate for *weight reduction***
  - ***Less material*** **also reduces cost**

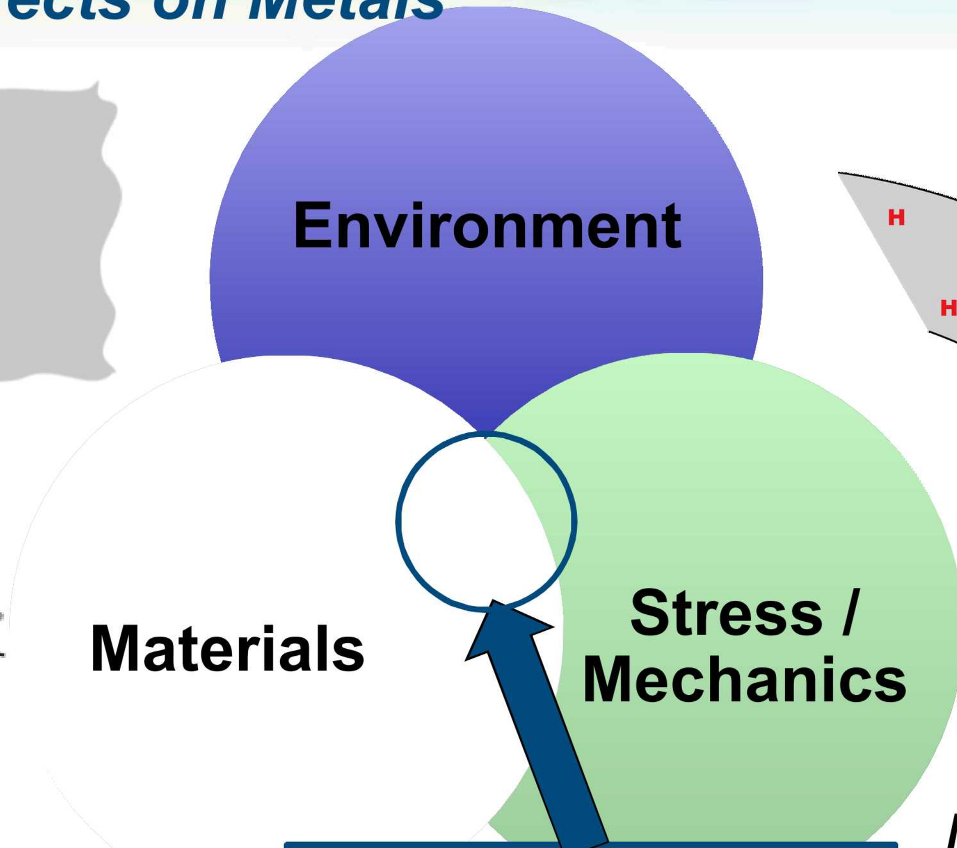
Testing development challenges:

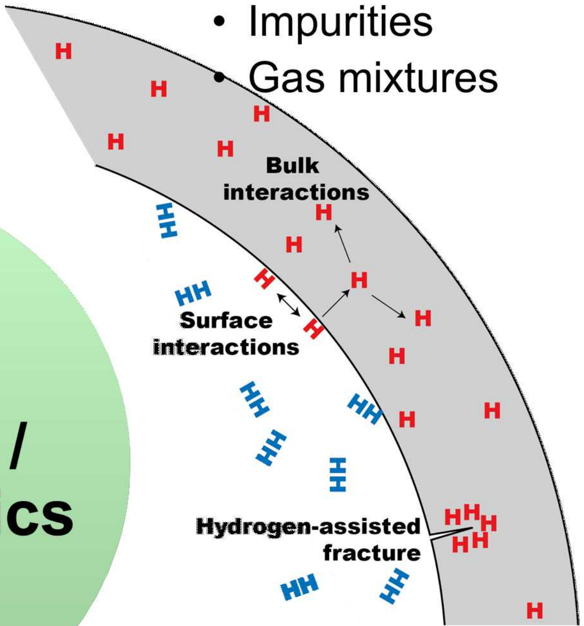
- **Relevant method that can be effectively adopted for testing in high-pressure gaseous hydrogen**
- **General method for evaluating as-manufactured materials and welded configurations**
- **Method to quantify crack initiation (and growth)**

Consider the intersection of *environmental*, *mechanics* and *materials* variables to understand *Hydrogen Effects on Metals*









Environment

- Low temperature
- High pressure
- Impurities
- Gas mixtures

Materials

- High-strength
- Hydrogen-enhanced plasticity
- Boundary cracking
- Surface passivation

Hydrogen effects occur in ***materials*** *under the influence of* ***stress*** *in hydrogen* ***environments***

Mechanics

- Autofrettage
- Short crack behavior
- Fatigue crack initiation
- Fracture resistance

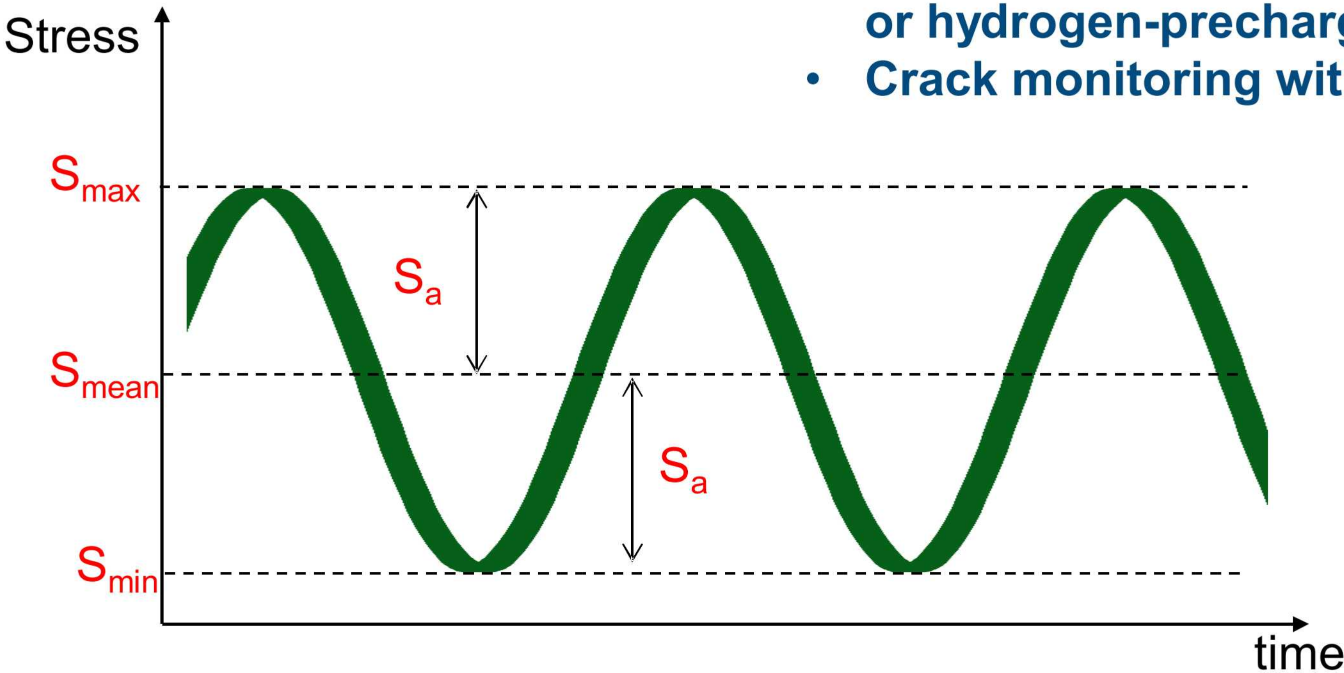
Mechanics: fatigue life testing adapted to environment and engineering configurations

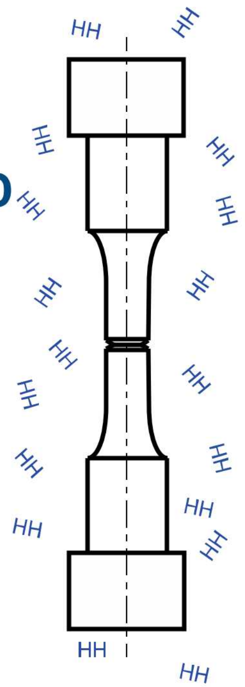
Conventional fatigue life testing

- "smooth" specimens
- Fully reversed loading (R = -1)
- Strain-based for low cycle

Hydrogen fatigue life testing

- "notched" specimens: $K_t \sim 3.9$
- Tension-tension loading (R = 0.1)
- Constant stress amplitude
- *In situ* in gaseous hydrogen or hydrogen-precharged
- Crack monitoring with DCPD





$R = S_{min} / S_{max}$

$S_{max} = 2S_a/(1-R)$

Environment: evaluate influence of pressure and temperature on fatigue life

- Effect of hydrogen pressure
  - 10 MPa
  - 103 MPa
- Effect of temperature
  - Room temperature: 293 K
  - Low temperature: 223 K (-50˚C)
- Surrogate hydrogen environment: internal H
  - Thermal precharging: 138 MPa H_2 at 300˚C for 10+ days
    - Uniformly saturated
    - ~140 wt ppm H for 300-series alloys
    - ~220 wt ppm H for nitrogen-strengthened alloys

Materials: consider a diverse range of austenitic stainless steels, both composition and strength

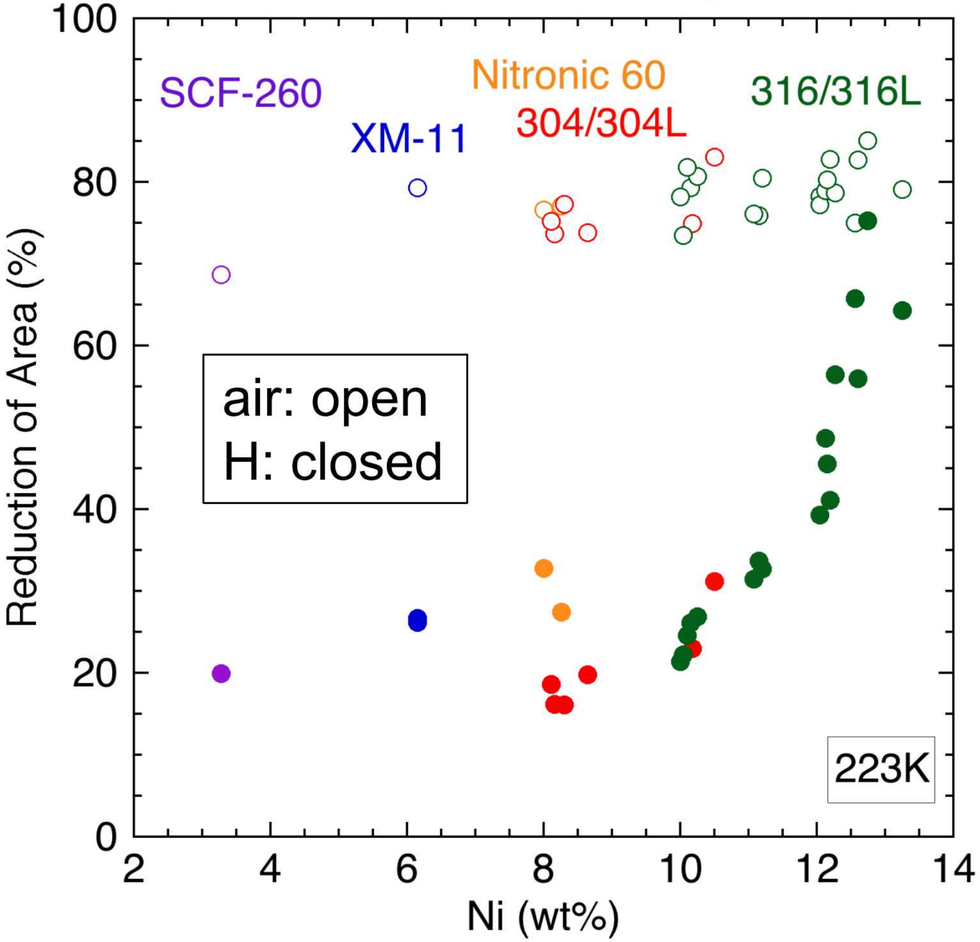
material	Yield strength (MPa)	Tensile strength (MPa)	Cr	Ni	Mn	N
316L	280	562	17.5	12	1.2	0.04
CW 316L	573	731	17.5	12	1.2	0.04
304L	497	721	18.3	8.2	1.8	0.06
XM-11	539	881	20.4	6.2	9.6	0.26
Nitronic 60	880	1018	16.6	8.3	8.0	0.16
SCF-260	1083	1175	19.1	3.3	17.4	0.64

Wide range of strength

Wide range of Ni/Mn content

Hydrogen effects are naively correlated with nickel content or nickel equivalent in tensile tests

Tensile ductility

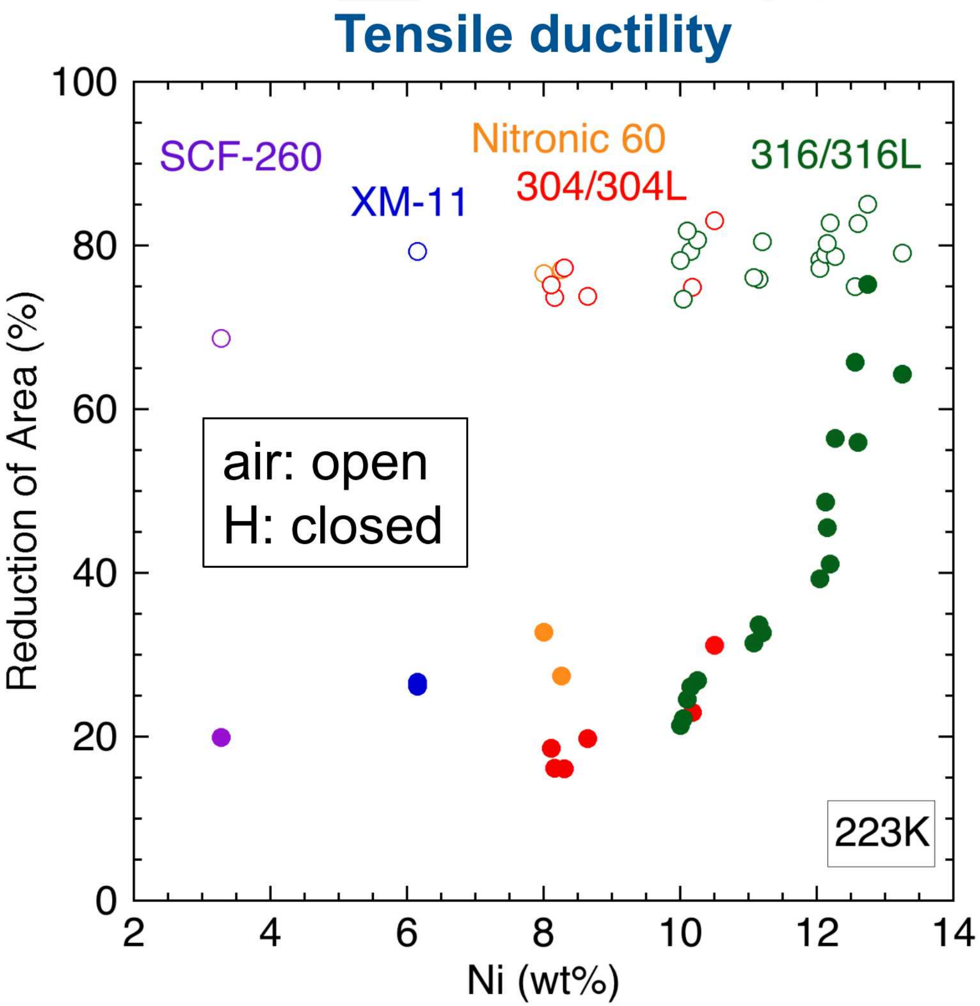


- Strength properties are generally not affected by hydrogen
- Relative tensile ductility is used in the literature as a metric for performance in hydrogen

However

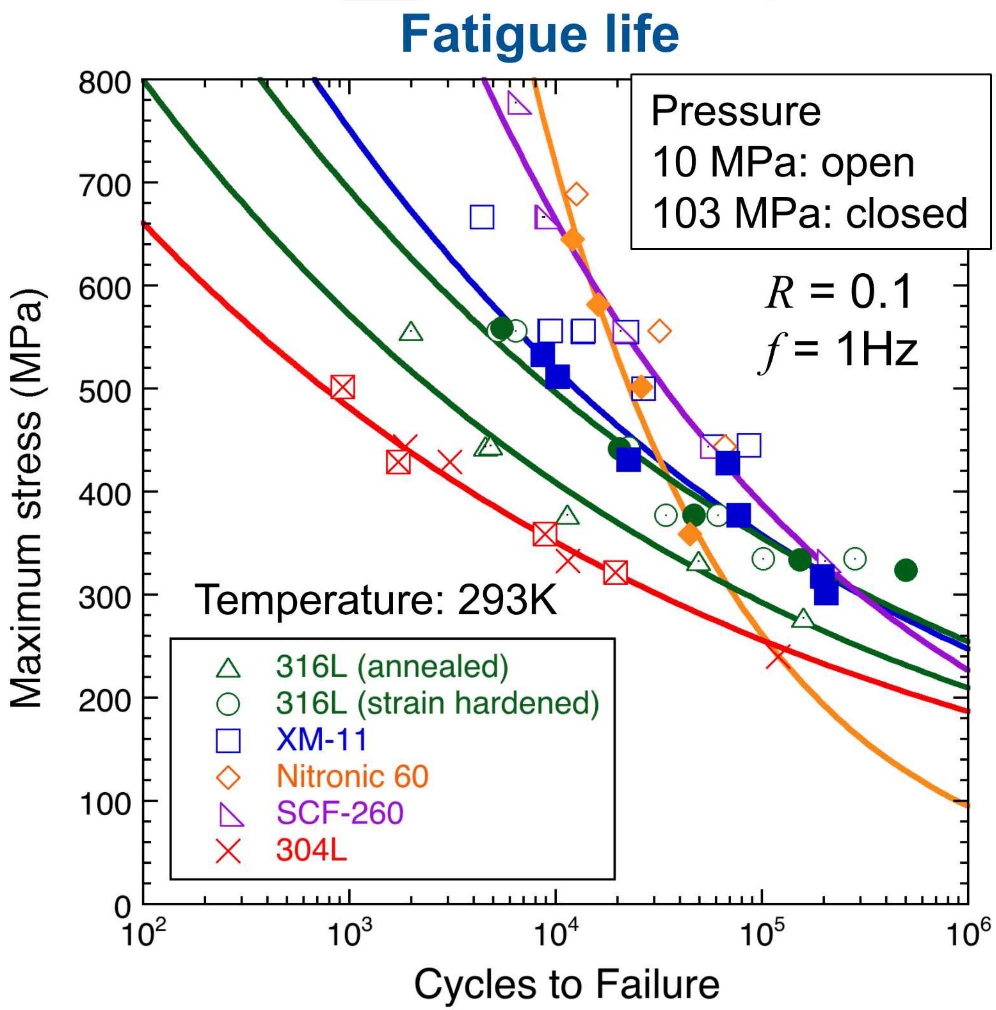
- Tensile ductility is not a design parameter
- Tensile ductility does not correlate with fatigue and fracture properties

Hydrogen effects are naively correlated with nickel content or nickel equivalent in tensile tests



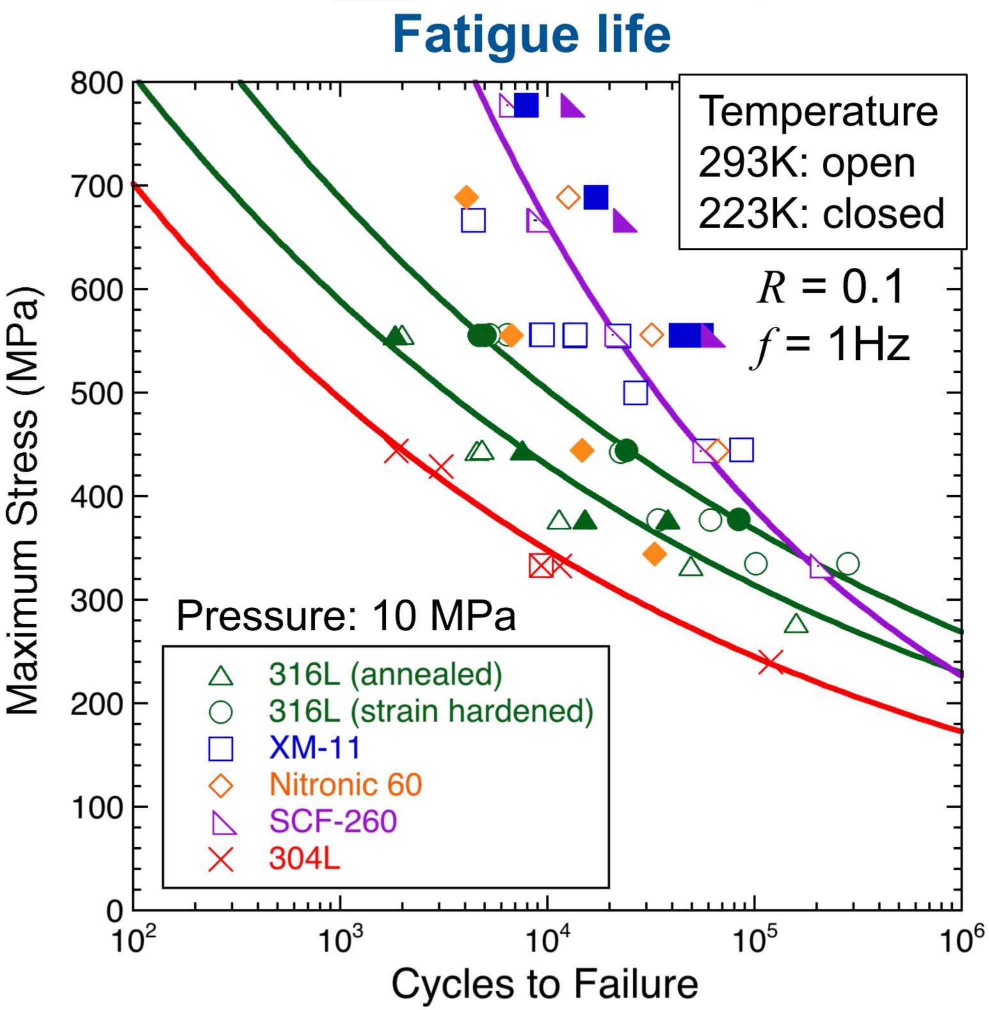
- Literature assumes effects on ductility related to formation of strain-induced martensite (i.e., austenitic stability)
- Causal effect of martensite has not be mechanistically demonstrated
- Deformation mechanisms also correlate with nickel content
- Fatigue and fracture properties do not correlate with nickel content

Pressure does not have a significant effect on fatigue life of most austenitic stainless steels



- **In general, notched fatigue data shows low scatter**
- **Scatter in these data is related to the quality of the machined notch**
  - **Surface hardening can delay crack initiation**
- **Pressure has little, if any, effect on fatigue life of these austenitic stainless steels**
- **Nitronic 60 may be an exception**

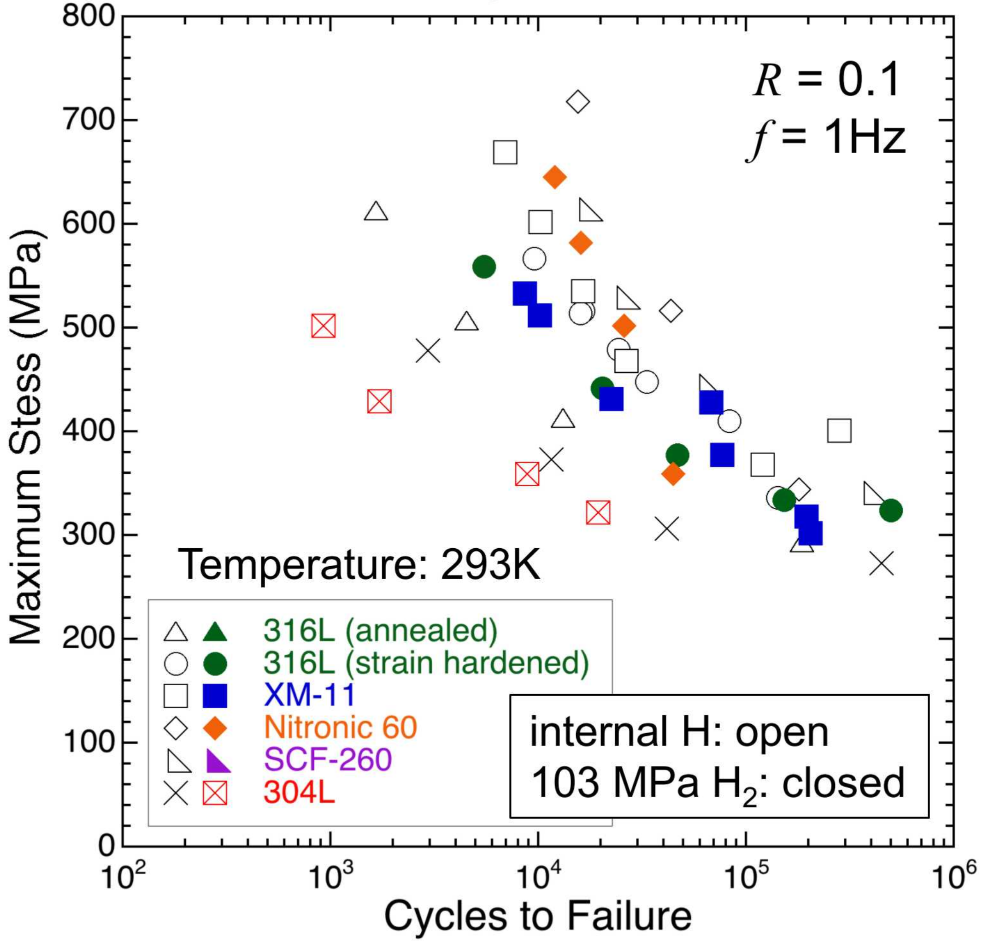
Low temperature often increases fatigue life relative to room temperature, *but not always*



- Temperature does not significantly affect fatigue life of Type 304L and 316L
- Fatigue life of strain-hardened 316L is greater than annealed 316L
- XM-11 and SCF-260 display improved fatigue life at low temperature
- Fatigue life of Nitronic 60 is decreased at low temperature

Internal H generally increases fatigue life relative to tests in gaseous hydrogen

Fatigue life



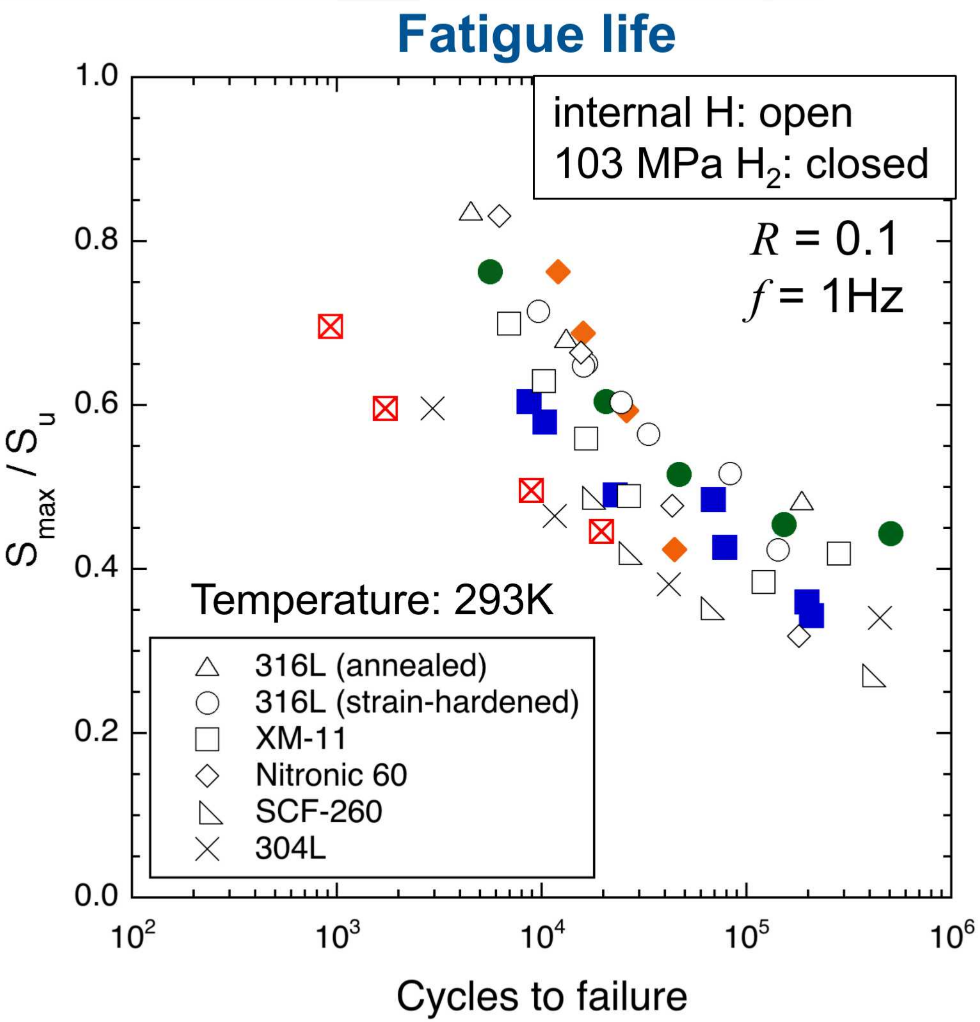
- **Internal H improves fatigue life**

However

- **Internal H increases the strength of austenitic stainless steels by 10-20%**
- **Fatigue limit scales with alloy strength**

Strengthening associated with internal H must be considered

Normalization of fatigue stress by tensile strength collapses external and internal H data



- **When normalized by the tensile strength, fatigue life with internal H is the same as measured in gaseous H_2**

Thermal precharging to high (internal) H concentration can be a surrogate for testing in gaseous hydrogen

Notched geometry provides a simple configuration to evaluate environmentally-assisted fatigue

- Conservative stress-based fatigue life for pressure system applications
- Applicable to testing in high-pressure gaseous
- Can address effects of stress concentration

Potential benefits also include:

- General method for evaluating as-manufactured materials and welded configurations
- Method to quantify crack initiation (and growth)

How can these additional benefits of a notched configuration be exploited?

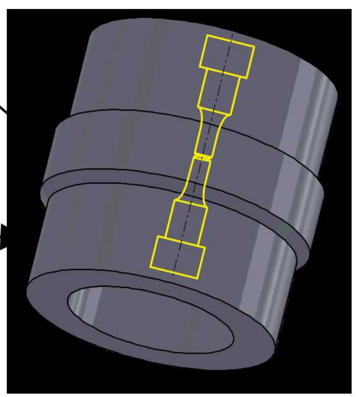
Notched configuration is ideal for evaluating welded structures in components

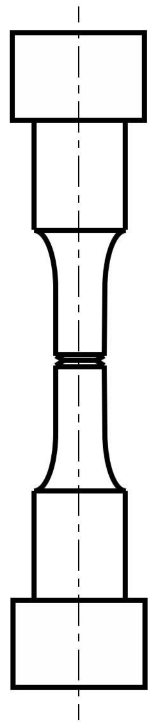
Notched fatigue specimen
K_t ~ 3-4

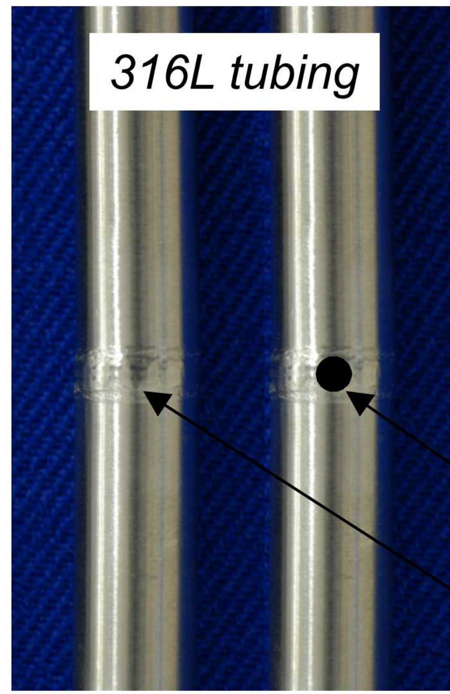
Established for bar and plate materials

weld

Base metal ring







through hole

Orbital tube weld

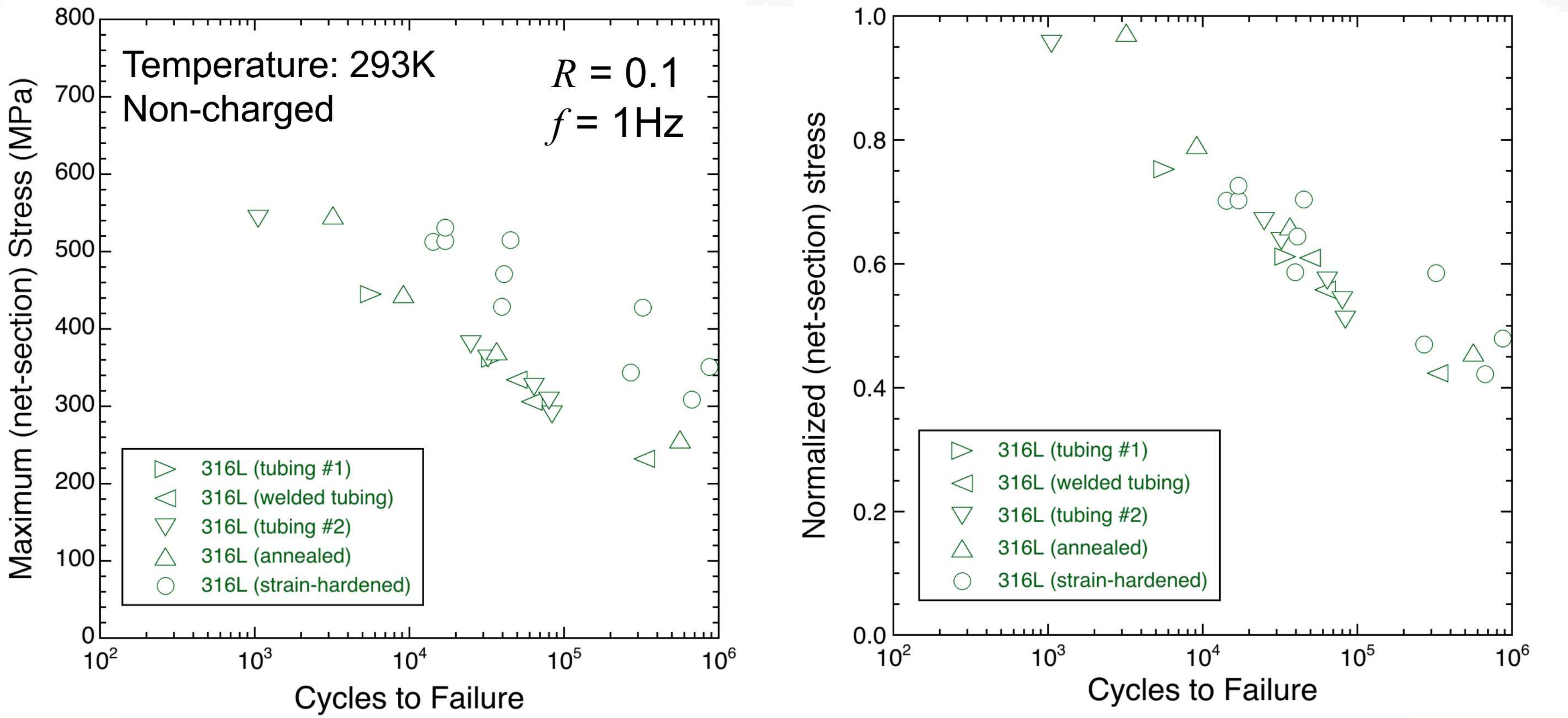
Hole-drilled tubular fatigue specimen
Kt ~ 3

Hypothesis:
behaves nominally the same as bulk specimen

Notched bar is easily applied to large welds, such as GTA welds and EB welds

Hole-drilled tube is ideal for evaluation of common weld configuration, such as orbital tube weld

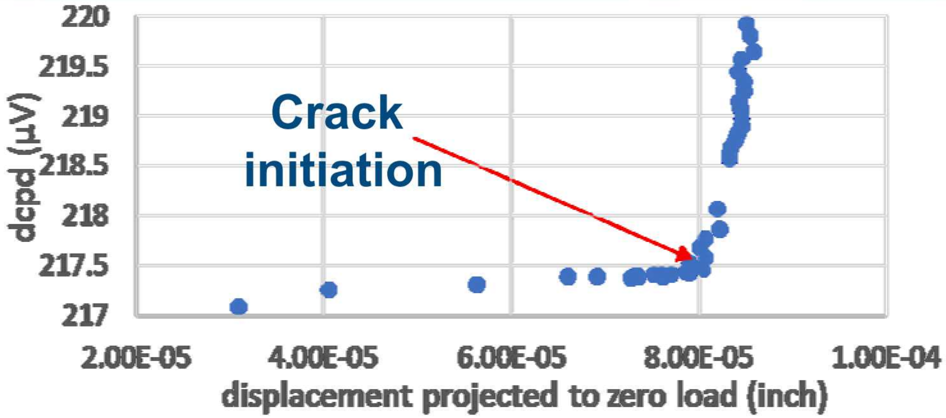
Fatigue life of hole-drilled tubular specimens are consistent with baseline materials

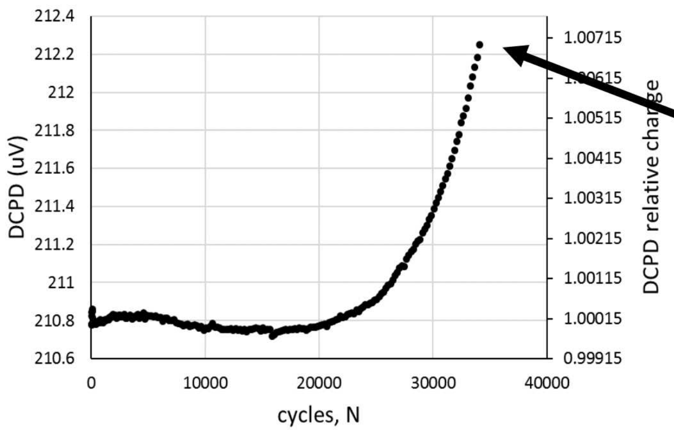


Orbital tube welds behave similarly to base materials in the hole-drilled tube configuration

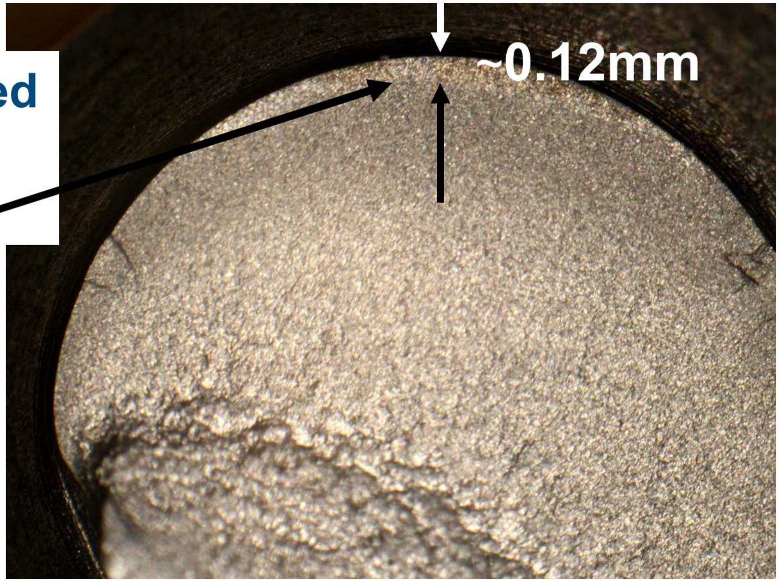
Crack initiation/growth during fatigue can be measured using direct current potential difference (DCPD)

- Constant current applied through specimen
  - Voltage change measured across notch
  - Extensometry can be used to remove effects of deformation



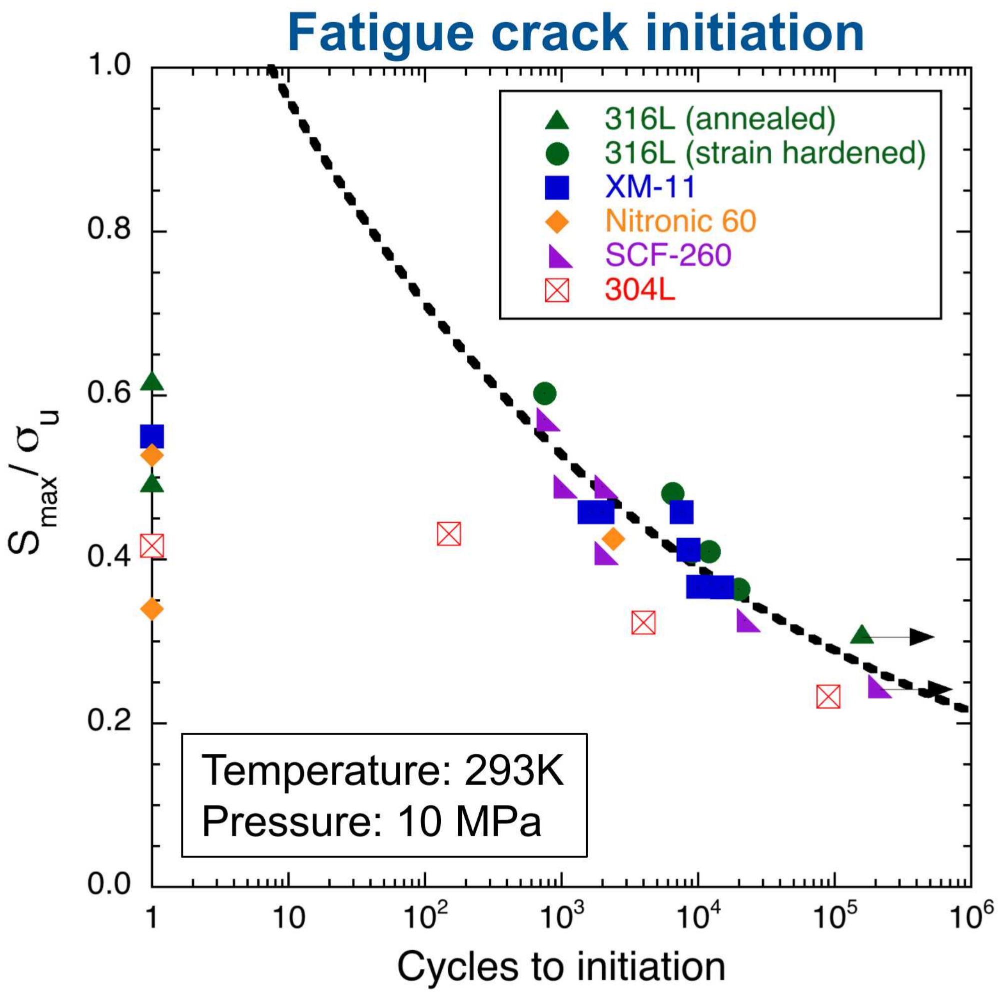


Test interrupted and then heat tinted



Crack lengths <10µm can be resolved with DCPD

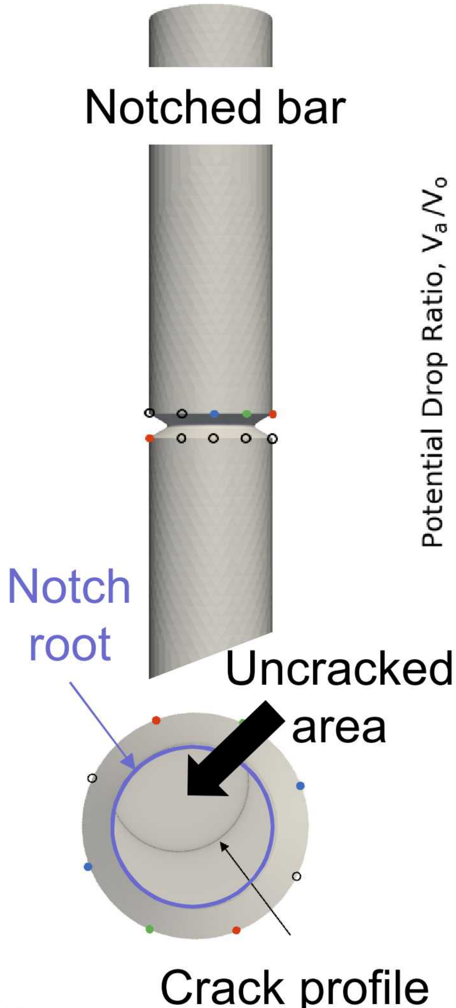
Crack initiation is relatively reproducible and consistent among materials

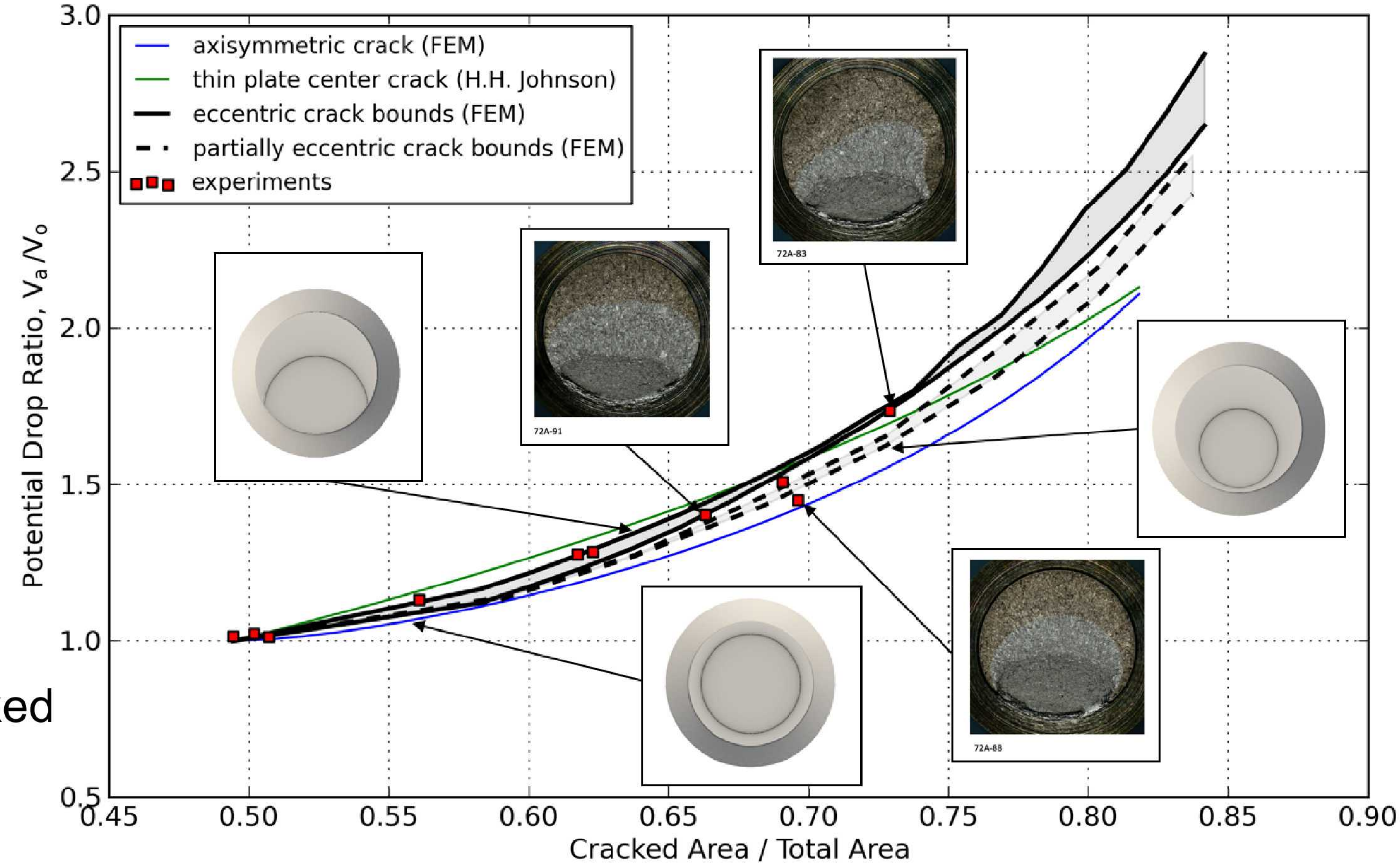


- **For fatigue crack initiation life, stress is normalized to account for alloy strength**
- **With the exception of 304L, data collapses to nominally a single curve**
- **Critical stress can be identified where cracks initiate at first cycle, but trends are not yet clear**

Crack initiation appears to be dominated by specimen mechanics, perhaps analogous to fatigue crack growth rates

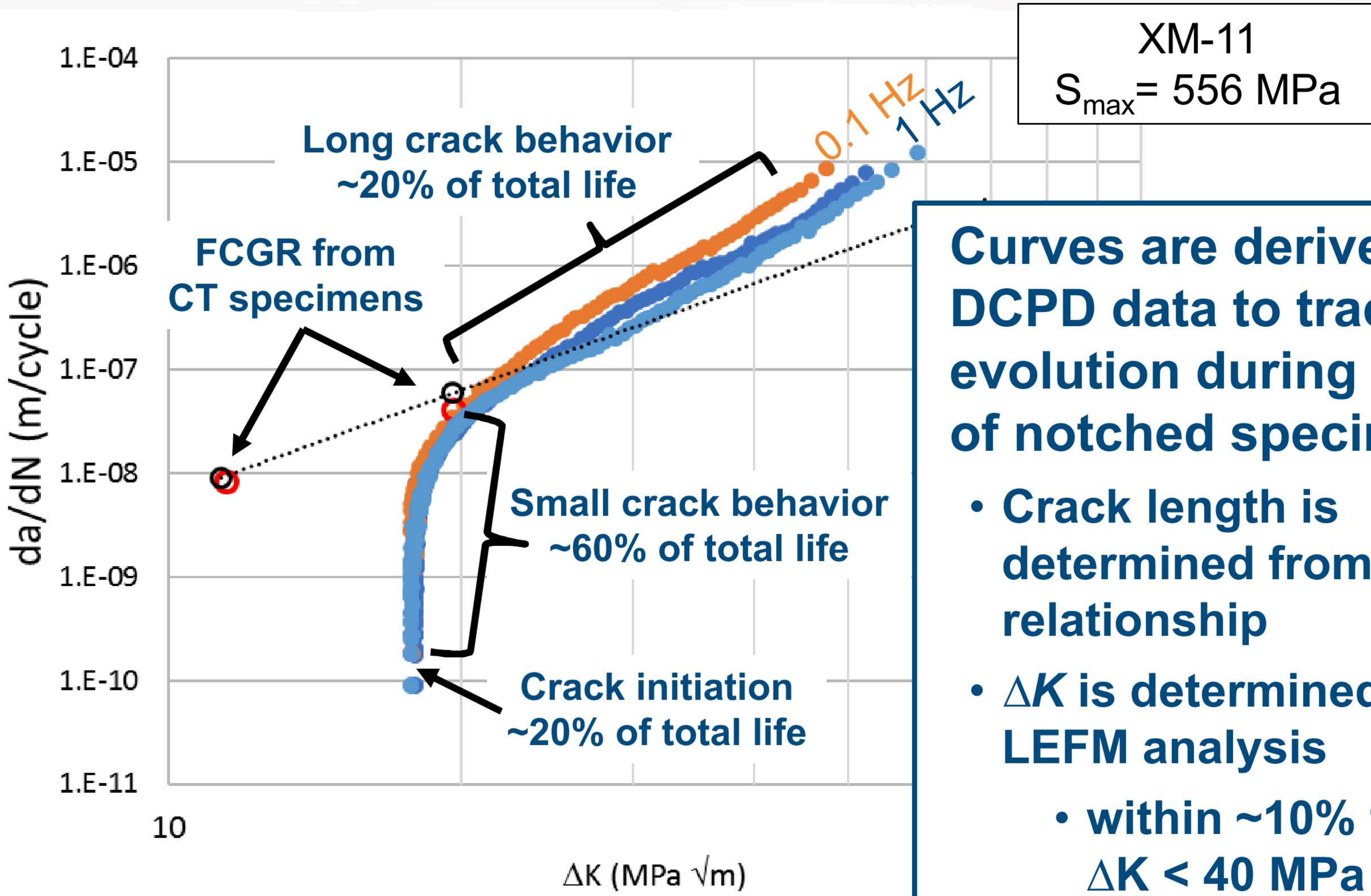
Relationship established relating cracked area to potential difference





Polynomial relationship between cracked area and DCPD signal provides crack growth information

Fatigue crack growth rate can be determined from notched specimens



Curves are derived from DCPD data to track crack evolution during fatigue of notched specimens

- **Crack length is determined from DCPD relationship**
- **ΔK is determined from LEFM analysis**
  - **within ~10% for $\Delta K < 40$ MPa $m^{1/2}$**

Summary

Notched tension-tension fatigue life measurements on austenitic stainless steels were performed

- Environmental variables
  - Pressure has little effect on fatigue life
  - Low temperature generally does not reduce fatigue life
  - Thermal precharging to high [H] has similar effect on fatigue life as testing in gaseous hydrogen – *if normalized*
- Materials variables
  - Wide range of alloy compositions show comparable fatigue life
  - Higher strength materials show superior life at same stress
- Mechanics variables
  - Preliminary evidence suggests other notched geometries show similar results – *facilitates testing of components and welds*
  - DCPD can be used to monitor cracking process and shows stabilization of small cracks