

Hydrogen Influences on Notched Fatigue Life of Stainless Steels

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- 3. Carpenter Technology***
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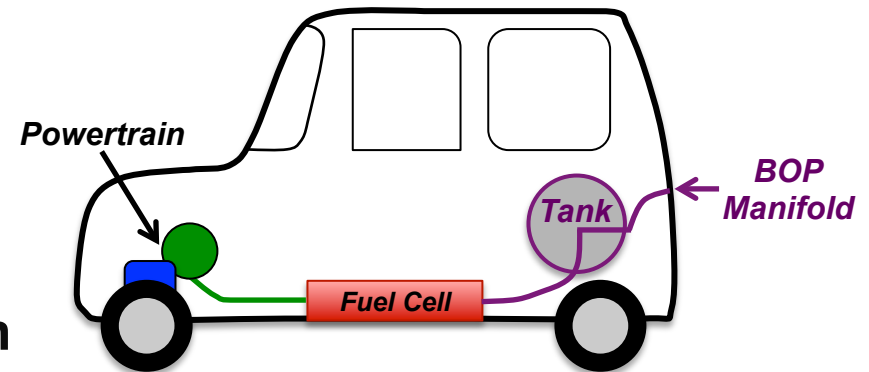


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Need to Optimize Components on H₂ Fuel Cell Vehicles

Challenge:

- Balance of plant (BOP):
 - 30-57% of total system cost
 - 15-20% of total system mass
- Baseline material Annealed 316L
- Systems expected to safely contain and distribute H₂ at:
 - Pressures up to 90 MPa (13 ksi)
 - Temperatures -40°C→85°C



Objective:

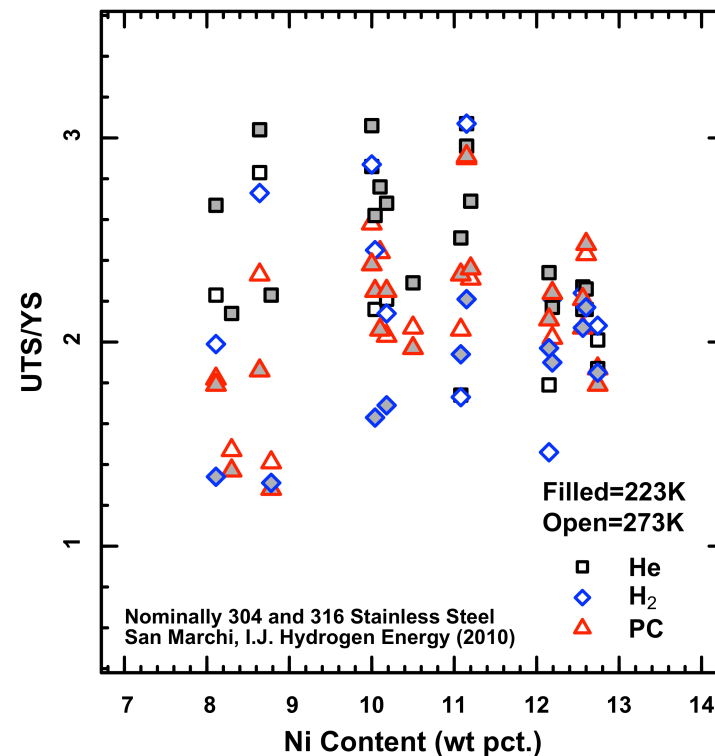
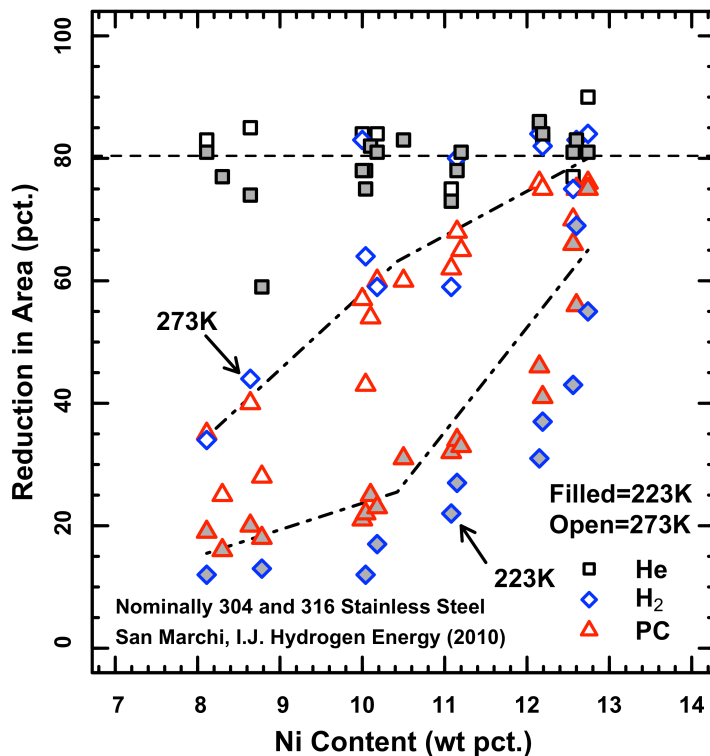
Identify performance-based selection criteria to identify metals for high-pressure BOP components

Reduce cost by 35%
Reduce weight by 50%

Hydrogen degradation decisions based on tensile ductility

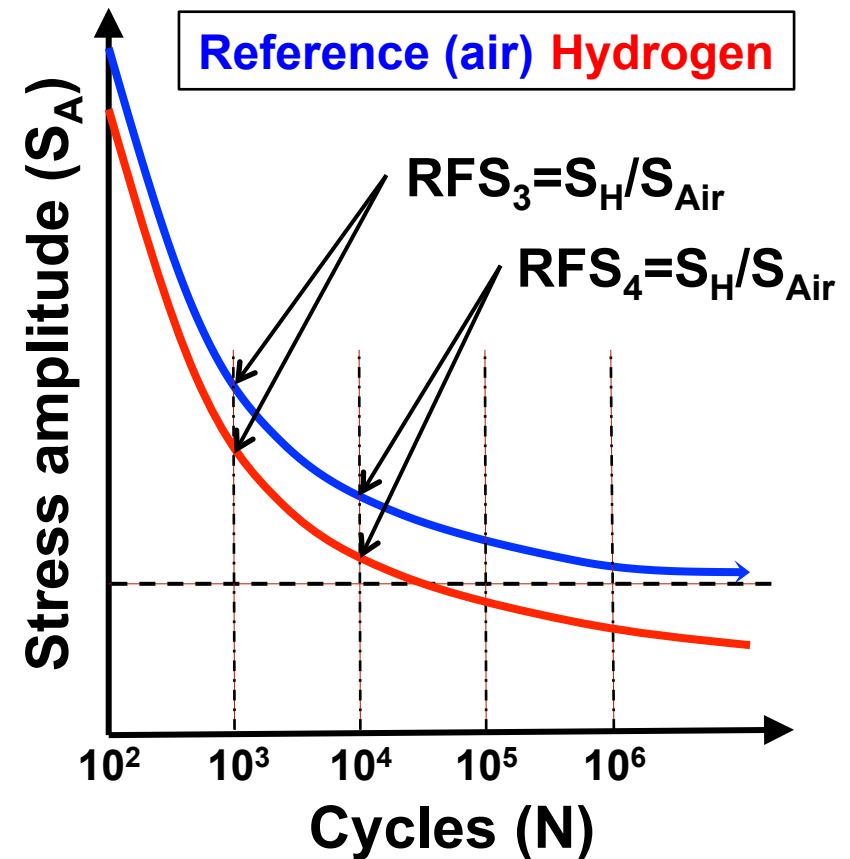
- How do tensile data fit into design?
 - Ductility (RA) decreased by H
 - Strength less sensitive to environment

What is a design-relevant selection metric?



Fatigue life assessment of stainless steels for pressure applications

- Repeated imposed stresses
 - Large S_a (empty-fill cycle)
 - Positive R -ratio
- System Life
 - $BOP > 30,000$ cycles
 - Complex components limit strain-based design
- Environmental degradation
 - Hydrogen and Temperature



Project approach

- Use stress-based notched-fatigue to assess hydrogen degradation of 'low-cost' austenitic stainless steels

- *High-strength alloys*

Higher stresses → less material → Less Cost

Strain hardened & high nitrogen added steels

- *Low nickel compositions compared to 316L*

Nickel content drives cost

21Cr-6Ni-9Mn

Not attempting to develop design curves

Identifying methods to compare alloys

Summary – Alloys of Interest

Composition

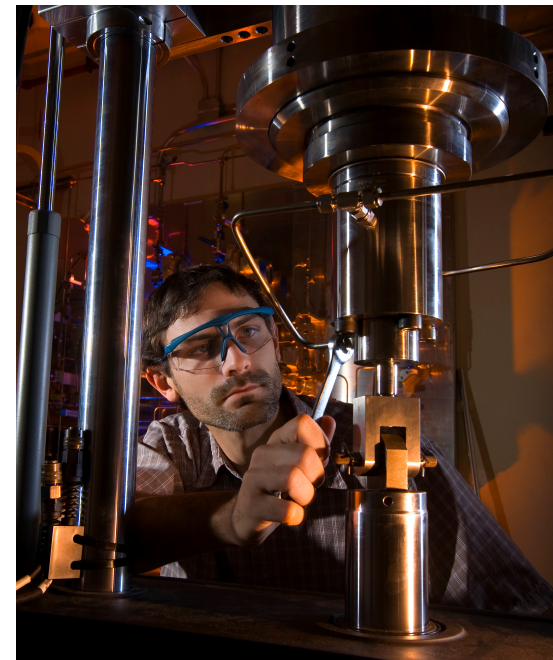
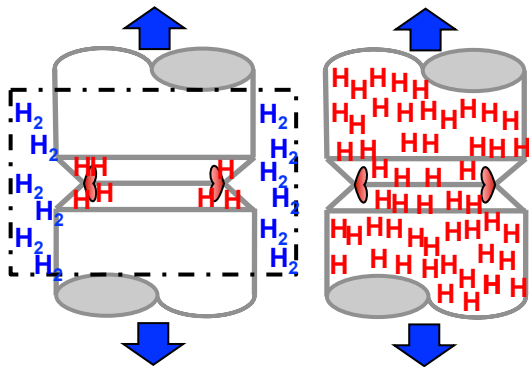
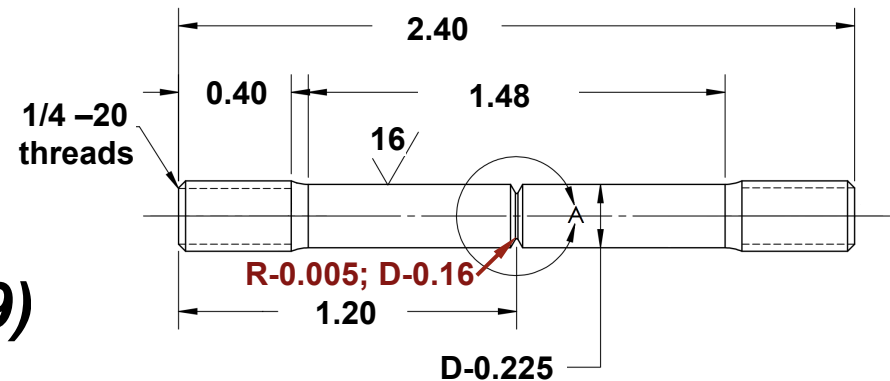
Alloy ID	Cr	Ni	Mn	Mo	C	N	Si
316L	17.54	12.04	1.15	2.05	0.020	0.04	0.51
21-6-9	20.45	6.15	9.55	NR	0.033	0.265	0.52

Tensile properties

Alloy ID	S _Y (MPa)	S _U (MPa)	RA (pct.)	EI _T (pct.)	S _Y (ksi)	S _U (ksi)
316L – Strain hardened	632	772	77	32	91.7	112
<i>316L – H Pre-charged</i>	<i>712</i>	<i>841</i>	<i>60</i>	<i>30</i>	<i>103</i>	<i>122</i>
21-6-9 - Annealed	539	881	79	61	78.2	128
<i>21-6-9 - H Pre-charged</i>	<i>669</i>	<i>957</i>	<i>50</i>	<i>55</i>	<i>104</i>	<i>142</i>

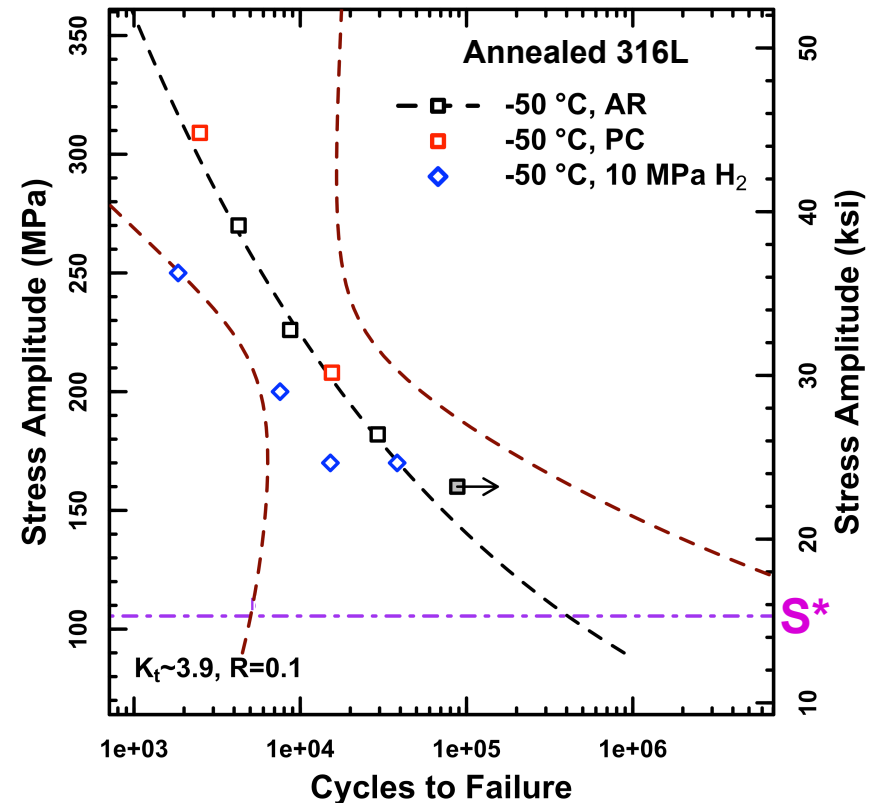
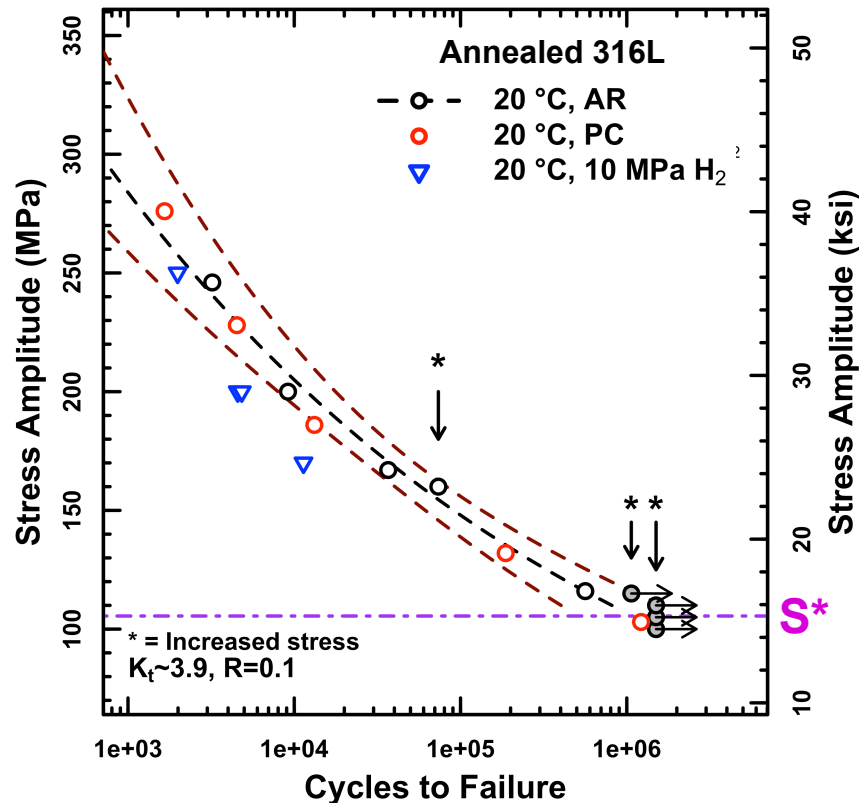
Fatigue Testing Conditions

- $R = 0.1$ (tension-tension)
- Limit to nominal stresses below yield stress
 - *Notched specimens ($K_t \sim 3.9$)*
- Temperature, 20 and -50°C
- *Hydrogen environment:*
 - 10 and 103 MPa external H_2
 - Saturated with internal H (PC)



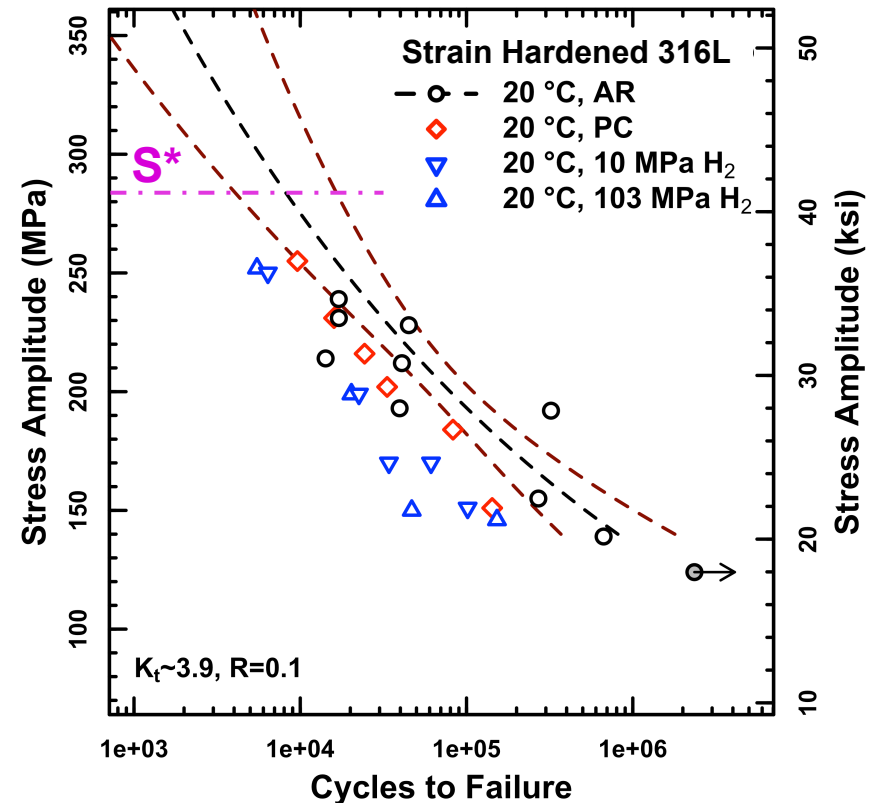
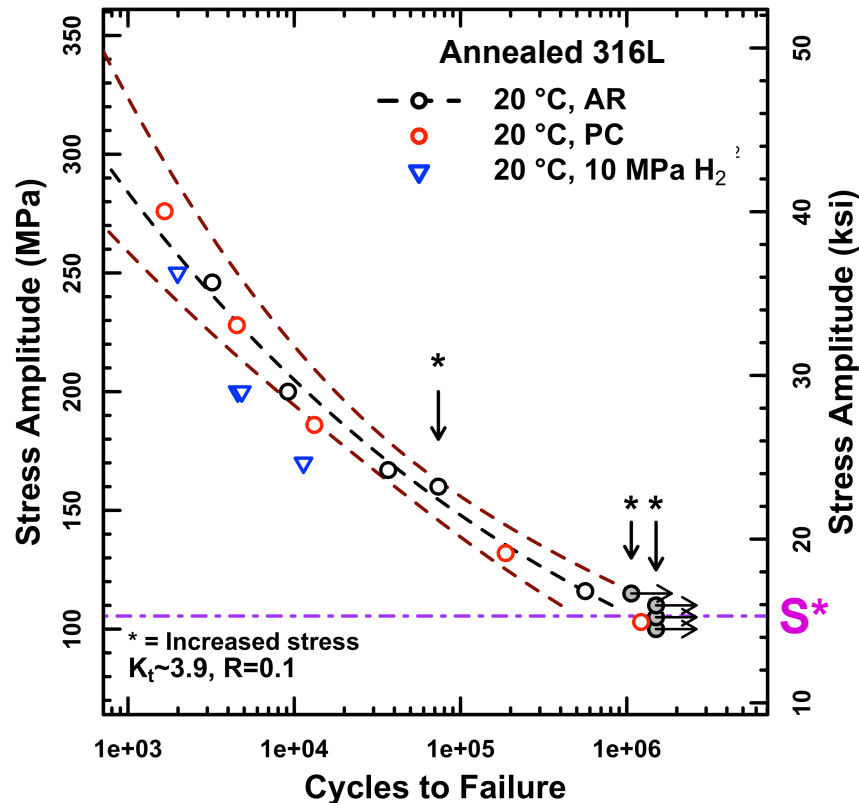
Baseline Fatigue Performance Annealed 316L

- **Annealed 316L is yield strength limited** $S^* = \frac{S_{YS}}{2}(1-R)$
- **Small decrease in stress-life in external hydrogen**



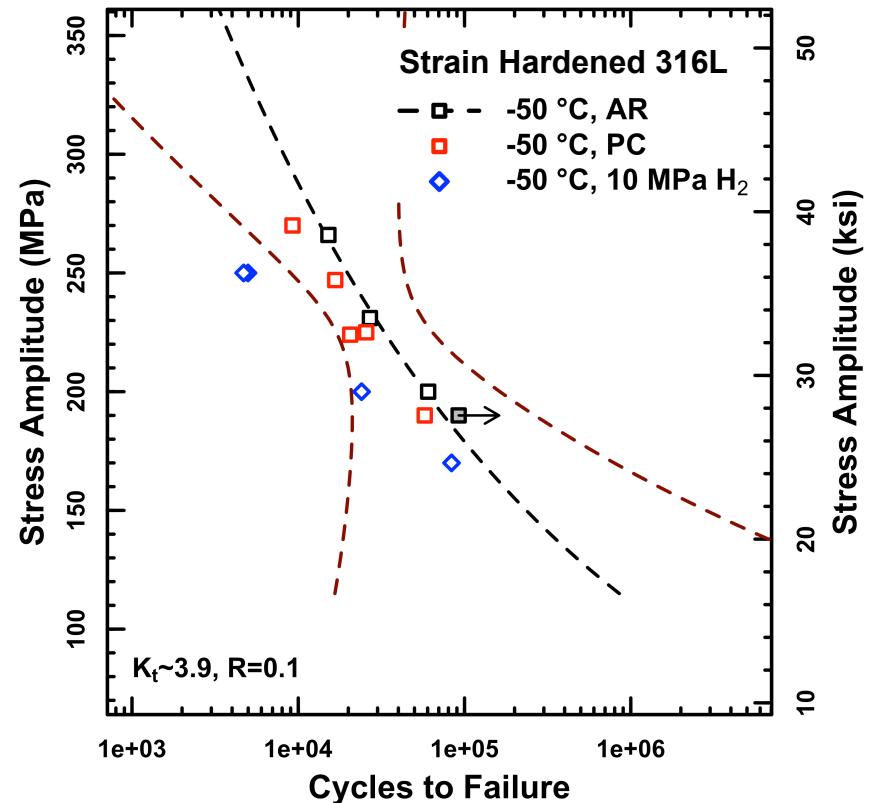
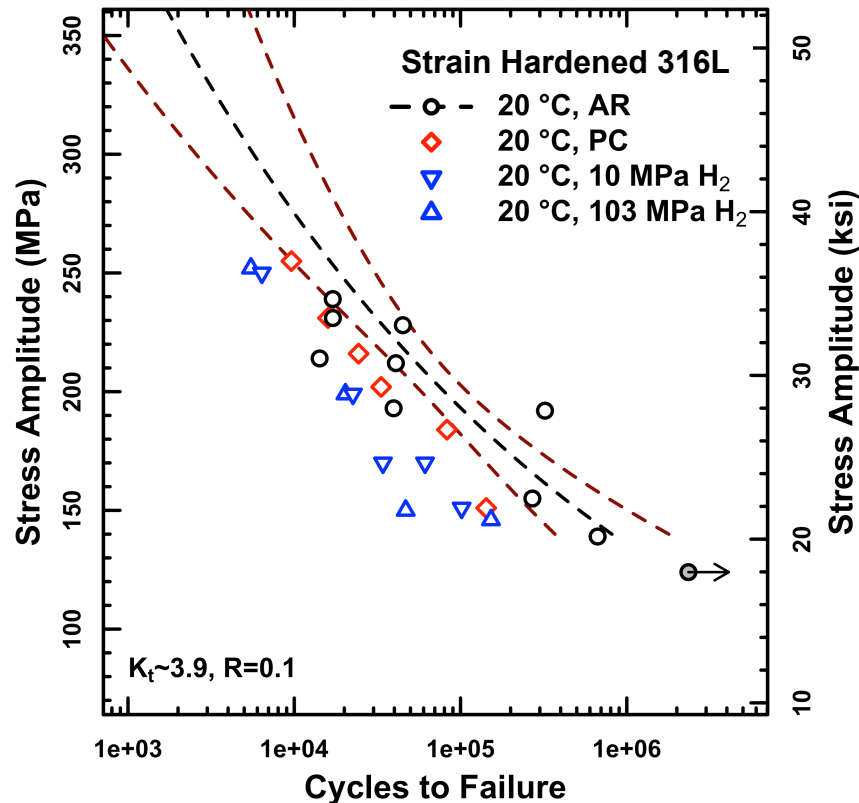
High Strength Stainless Steel: Strain-Hardened 316L

- $YS_{\text{strain-hardened 316L}} \sim 2.5 \times YS_{\text{annealed 316L}}$
- *Both cases small decrease in fatigue life with H_2*



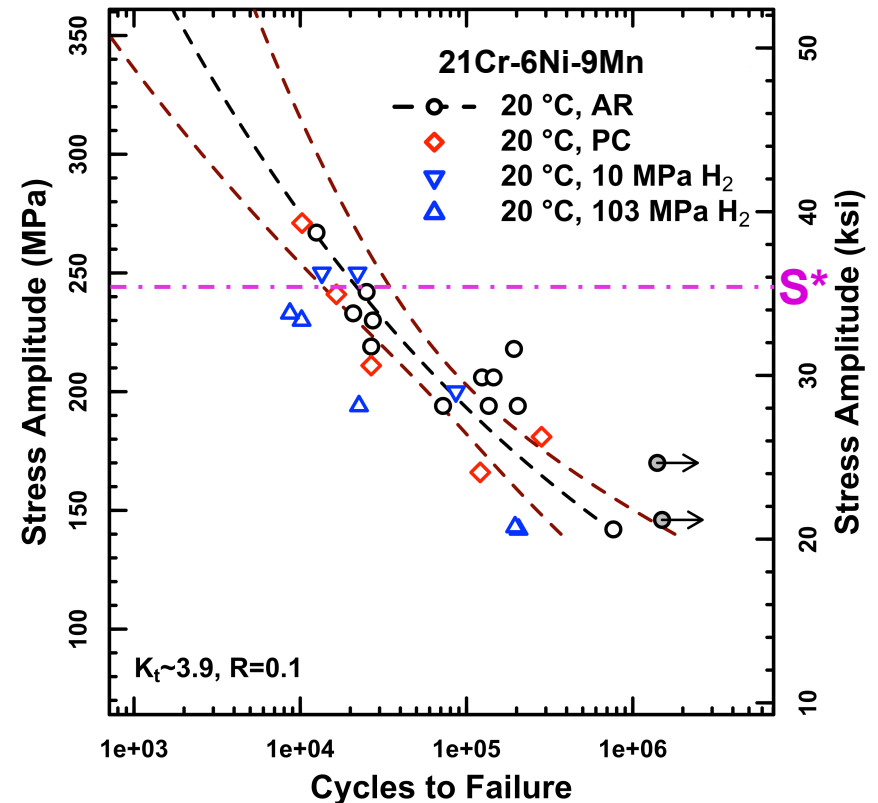
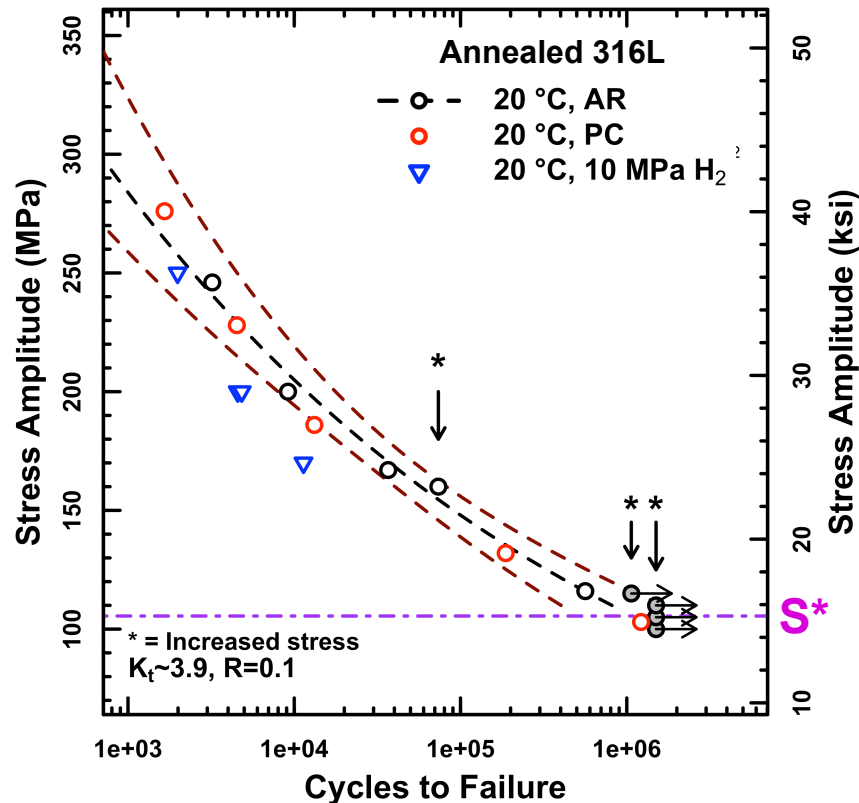
High Strength Stainless Steel: Strain-Hardened 316L

- Steeper Whöler curve at low temperature
- -50 °C data converge at low stresses for -50 °C?



Low Ni Stainless Steel: 21Cr-6Ni-9Mn (*Nitronic 40*)

- Clear influence of 103 MPa H₂, less impact with 10 MPa H₂
- *High stresses still permissible in H₂ than annealed 316L*

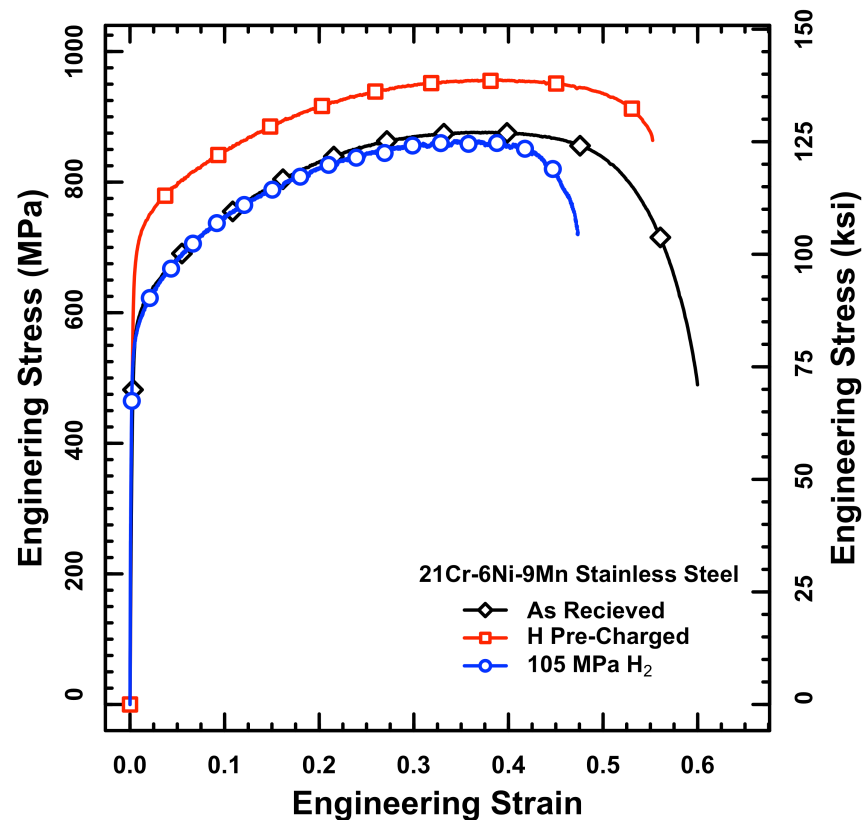


Internal v. External Hydrogen Strengthening after pre-charging

With internal H:

Yield strength **increase**

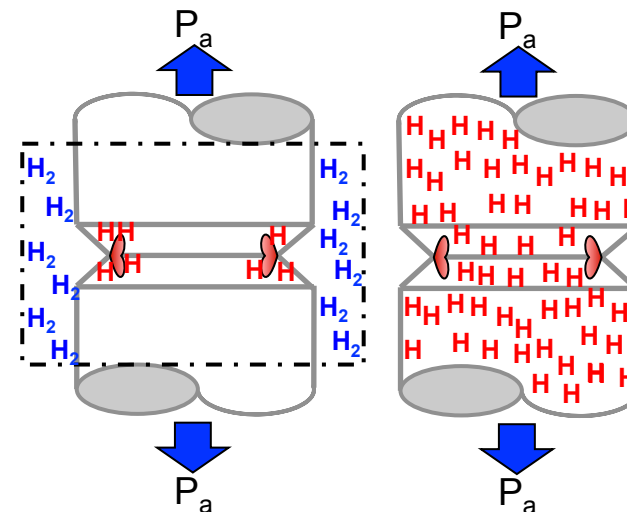
Hardening slightly **decreased**



Testing in hydrogen gas is
costly and impractical for tests
longer than ~5e5 cycles

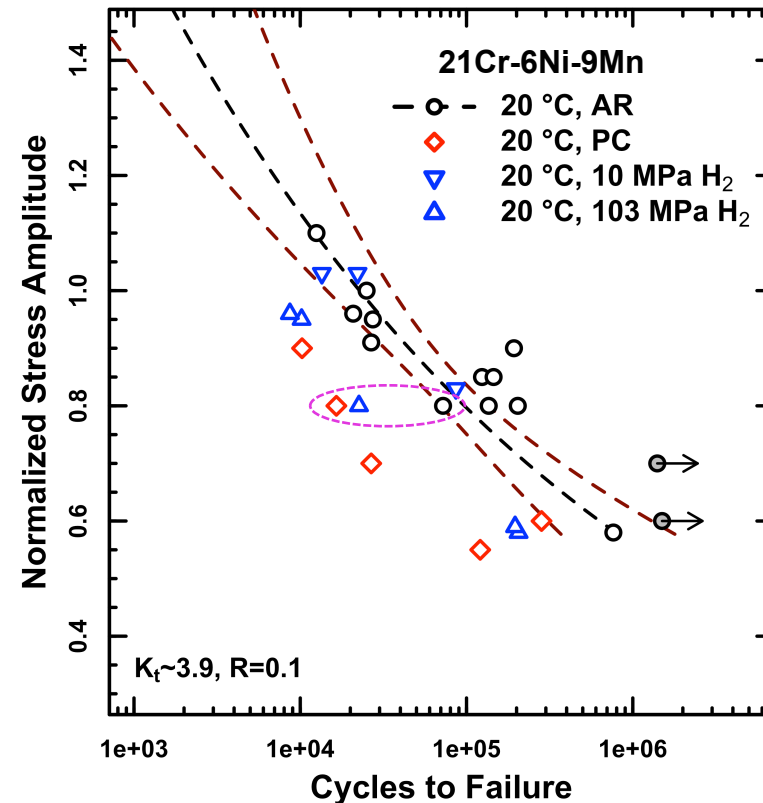
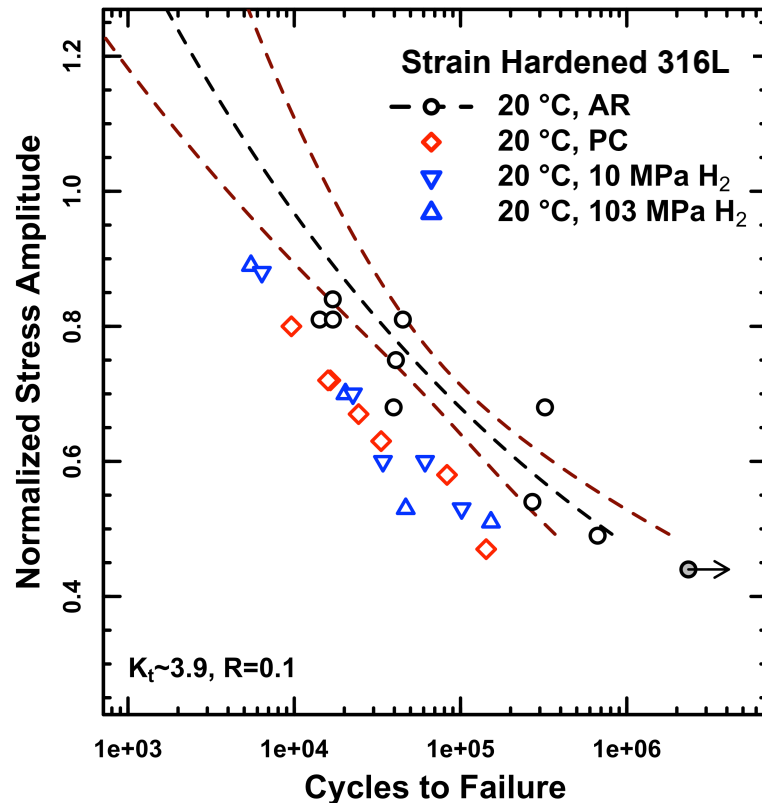
$$YS_{H\text{-charged}} > YS_{\text{as-received}}$$

$$N_A = \left(\frac{S_{Max}}{S_{YS}} \right)$$



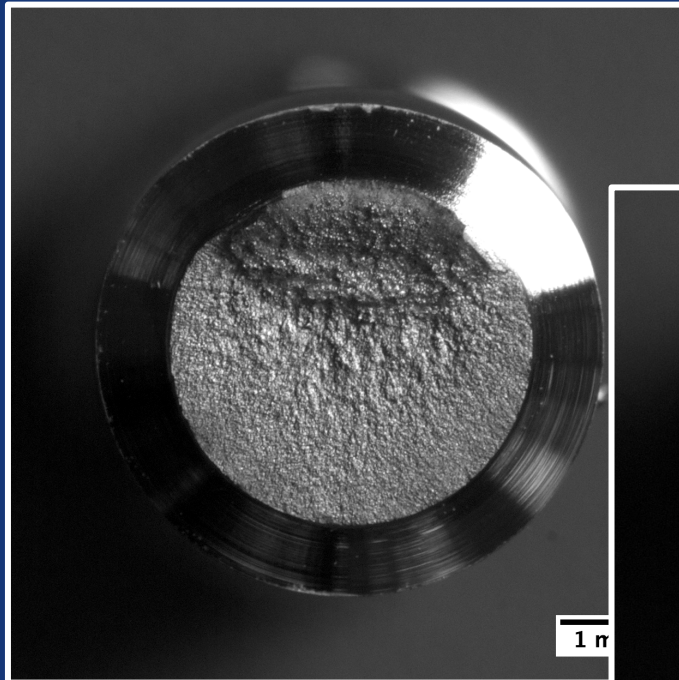
Internal v. External Hydrogen Adjustment of Wöhler Curves

- **Thermal pre-charging appears to capture some of the features of interest for H-degradation**
- **What about the metallurgical influences?**



Internal v. External Hydrogen Fatigue surfaces 21Cr-6Ni-9Mn

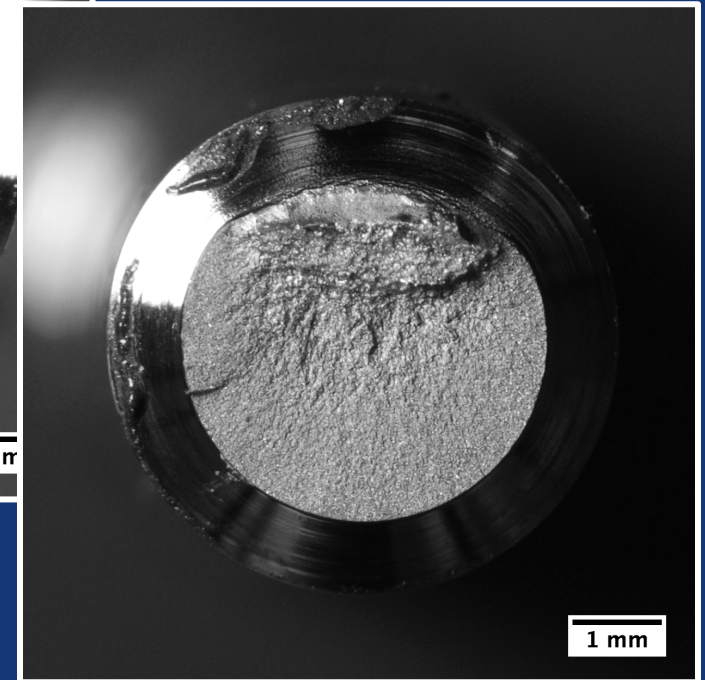
As-received



H pre-charged

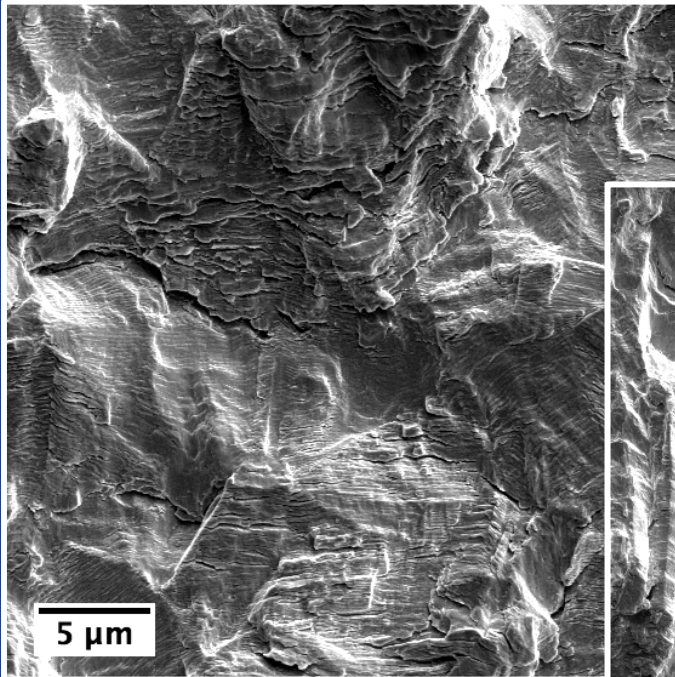


103 MPa H₂

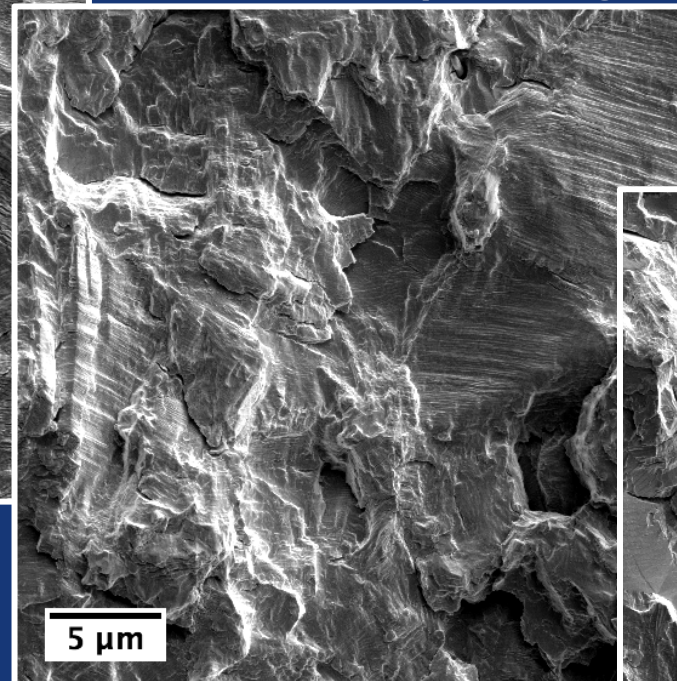


Internal v. External Hydrogen *Fatigue surfaces 21Cr-6Ni-9Mn*

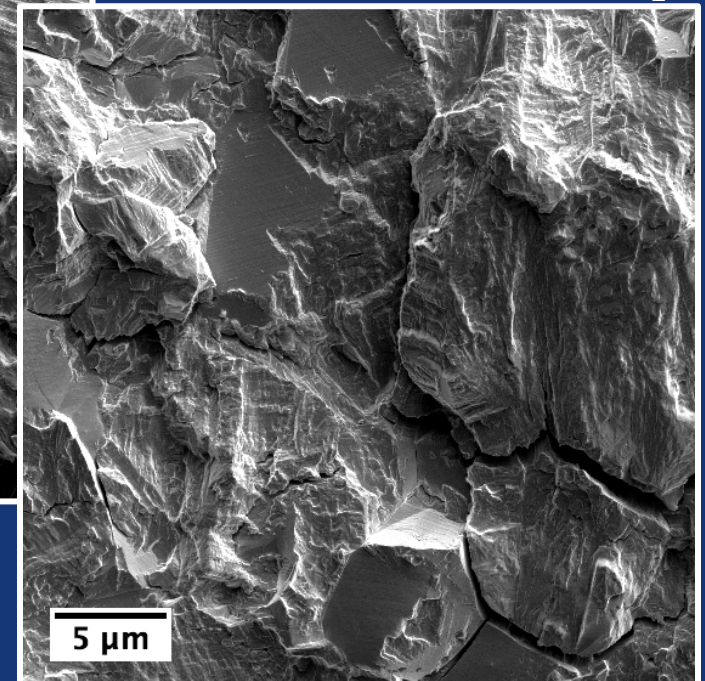
As-received



H pre-charged



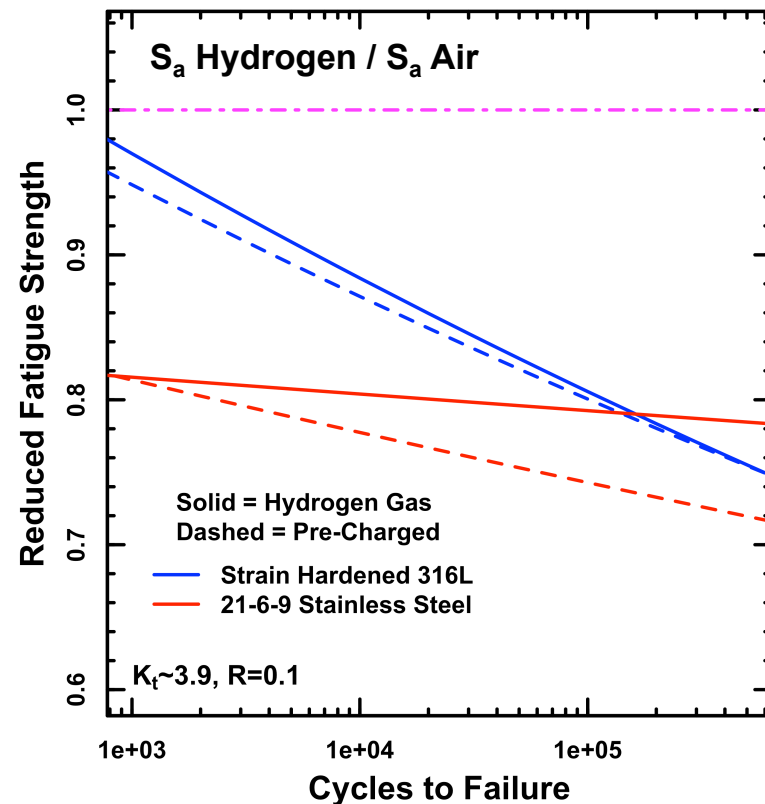
103 MPa H₂



Comparison Between Alloys

- Underlying behavior (shape of the Wöhler Curve) seems unaffected by **strength** or **hydrogen**
- Similar degradation in fatigue strength in strain hardened 316L & 21Cr-6Ni-9Mn alloys

Maximum H influence at highest life



Summary

- Hydrogen decreased the fatigue life of all the alloys tested
- Method to compare internal and external hydrogen testing
 - *Pre-charged condition can represent lower-bound performance when adjusted for yield strength*
- Maximum decrease in fatigue stress with hydrogen ~30-40% in finite life regime
 - Annealed 316L:
 - Finite life only observed with extensive plasticity
 - Strain-Hardened 316L and 21Cr-6Ni-9Mn
 - Improved fatigue life compared to annealed 316L
 - Change in the fatigue crack morphology with hydrogen

Current Status

- **Areas of current investigation/development:**
 - *Separating crack ‘initiation’ from crack growth rates*
 - *Microstructural ‘features of interest’*
 - *What is the effect of the notch on the measured fatigue environment?*
 - *How can this type of testing be incorporated into materials screening approaches for hydrogen?*

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Backup Slides

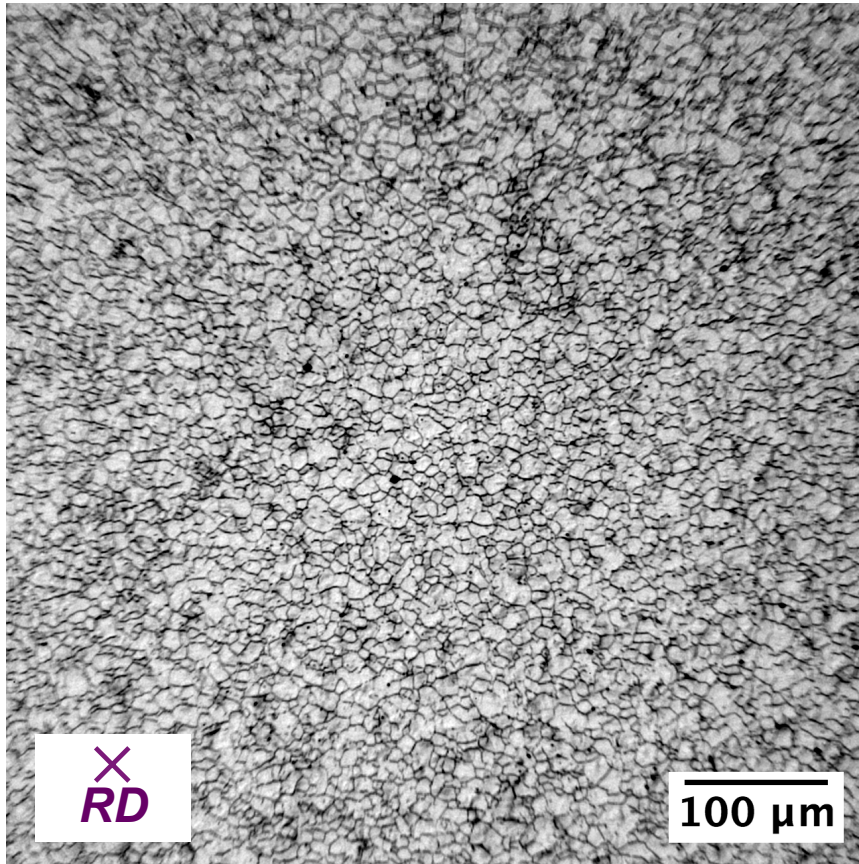


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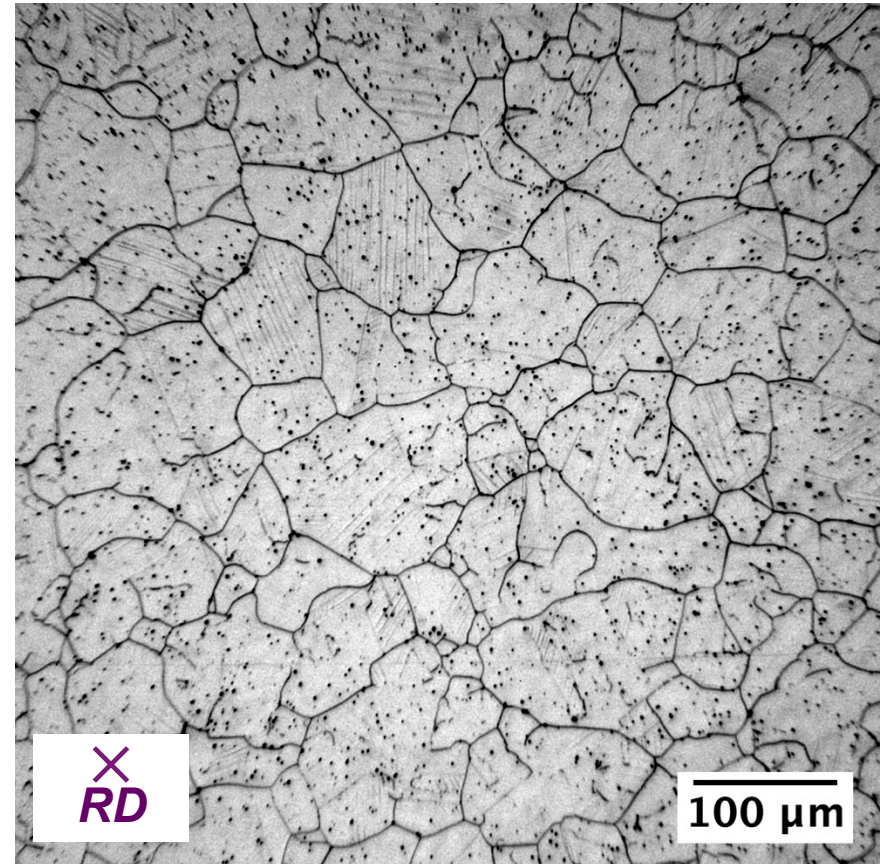
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Microstructure

21Cr-6Ni-9Mn



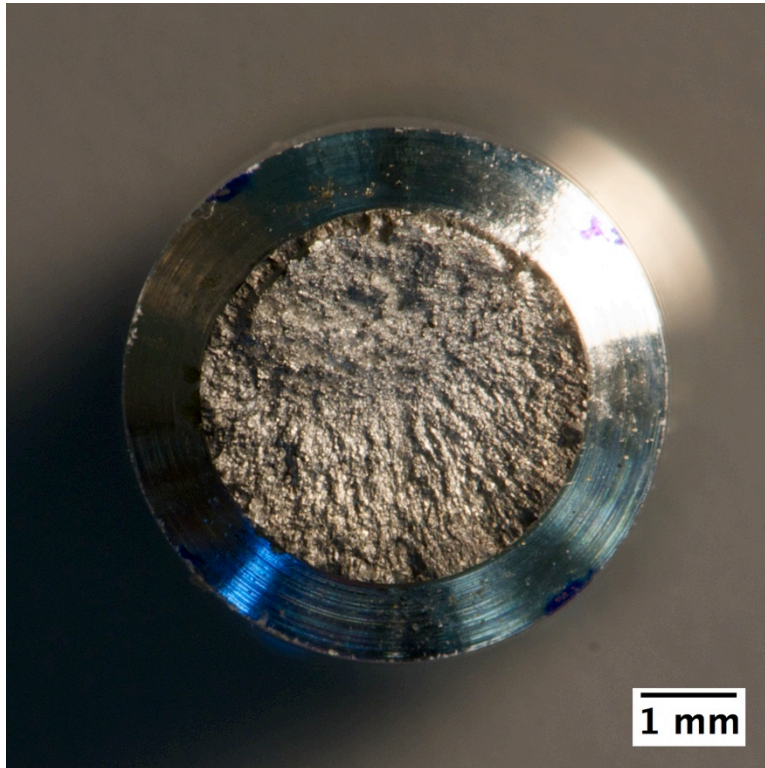
Stain hardened 316L



60% Nitric Acid in Water, 0.6V

Fractography of CW316L

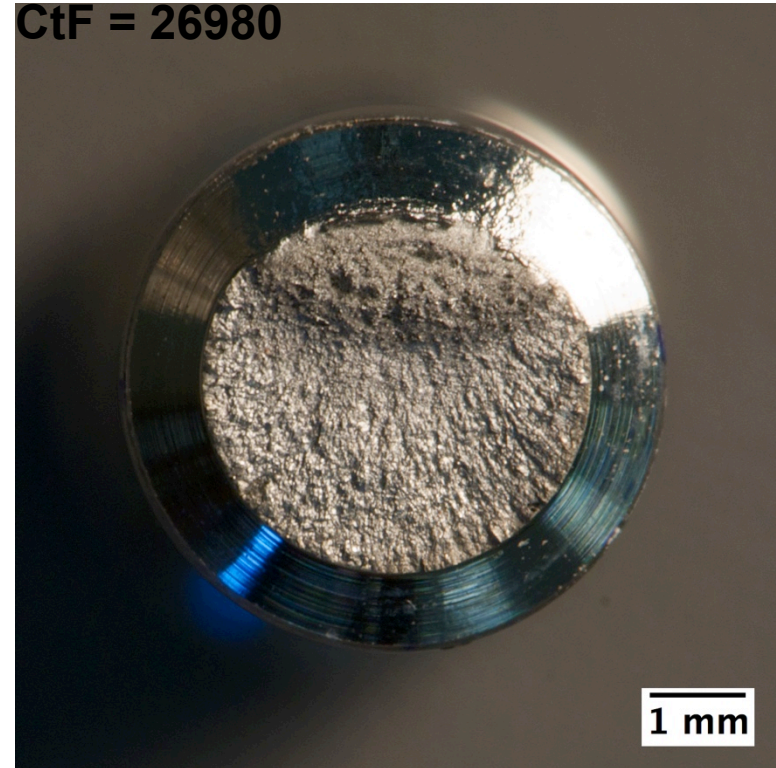
As Received, 20 °C, $S_A = 231$ MPa
CtF = 27150,



Overload region on top

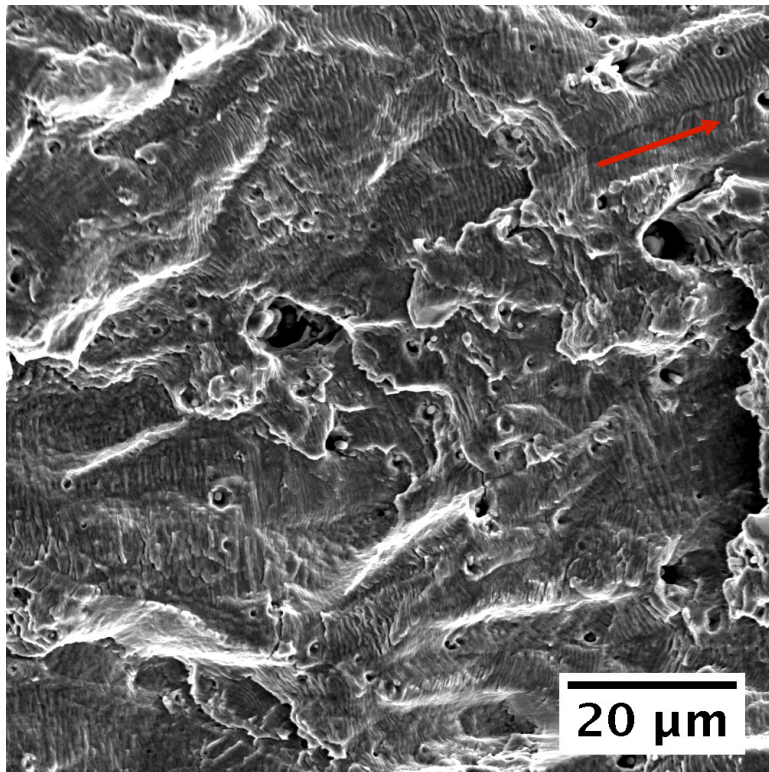
As Received, -50 °C, $S_A = 213$ MPa

CtF = 26980



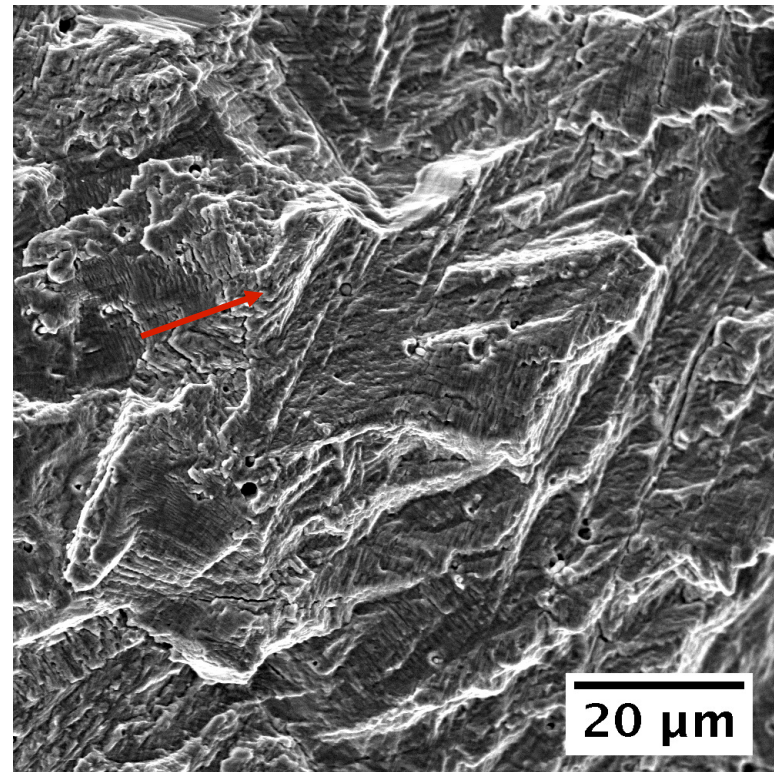
Fractography of CW316L

As Recieved, 20 °C, $S_A = 193$ MPa



Crack Growth Direction → *0.6 μm/cycle*

H₂ Charged, 20 °C, $S_A = 184$ MPa



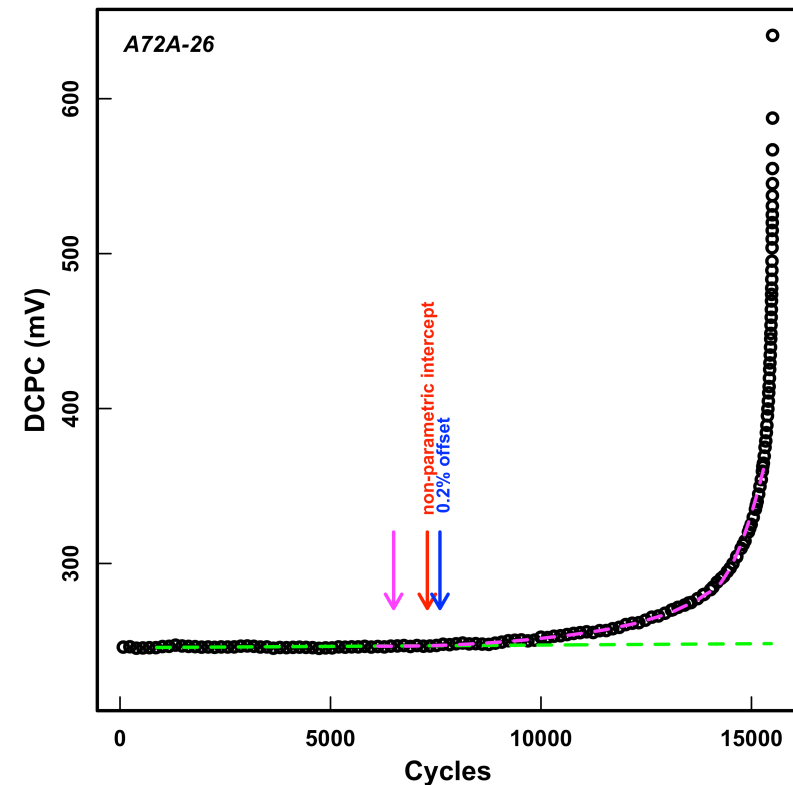
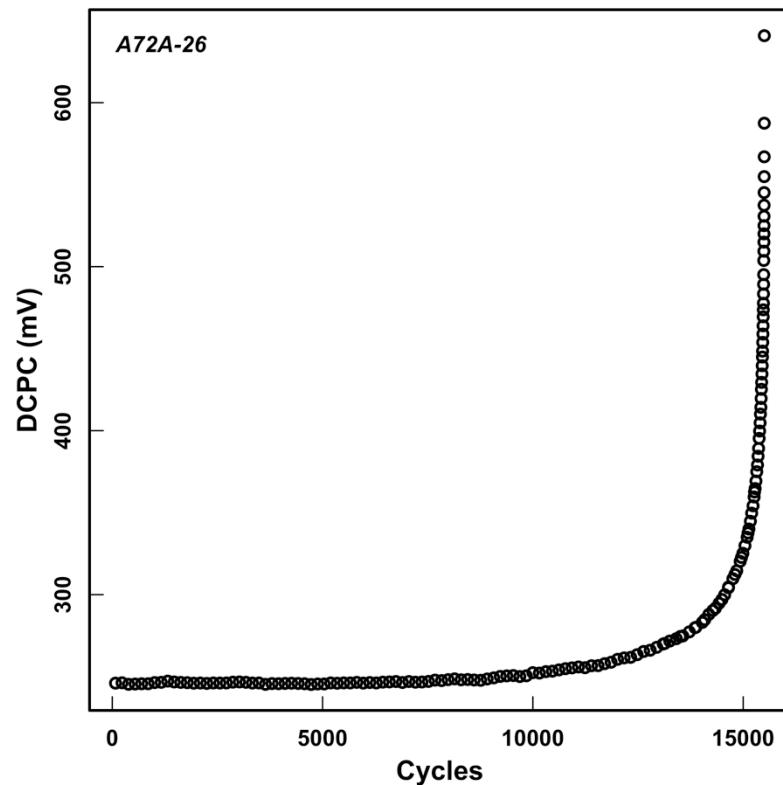
0.6 μm/cycle

*Attempting to get crack growth data from DCPD and
microscopy measurements (striation size)*

Analysis of DCPD

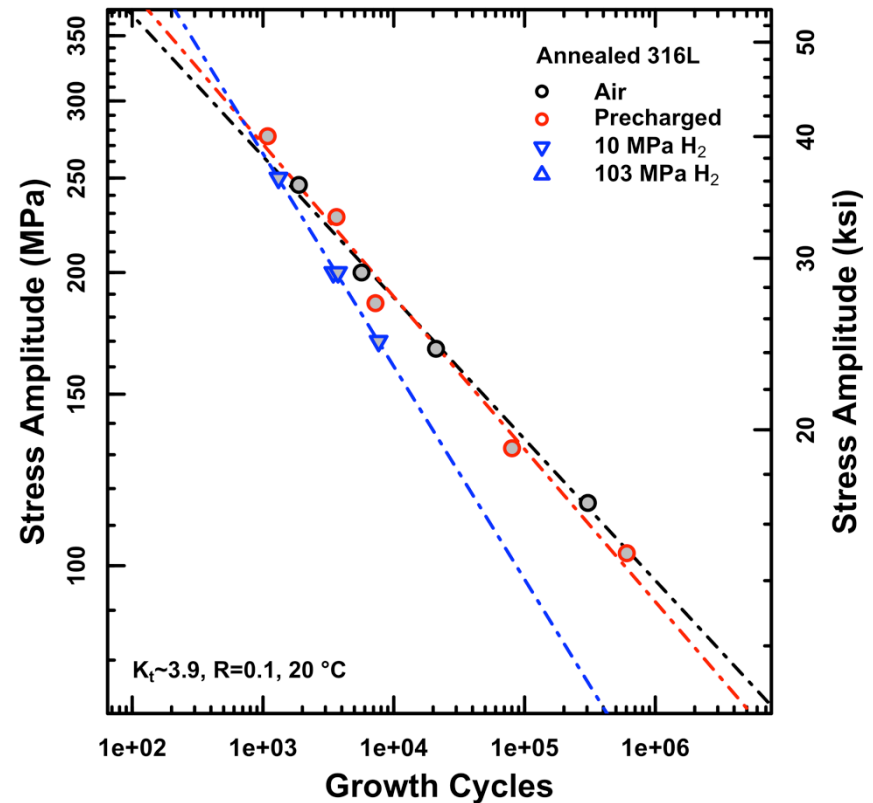
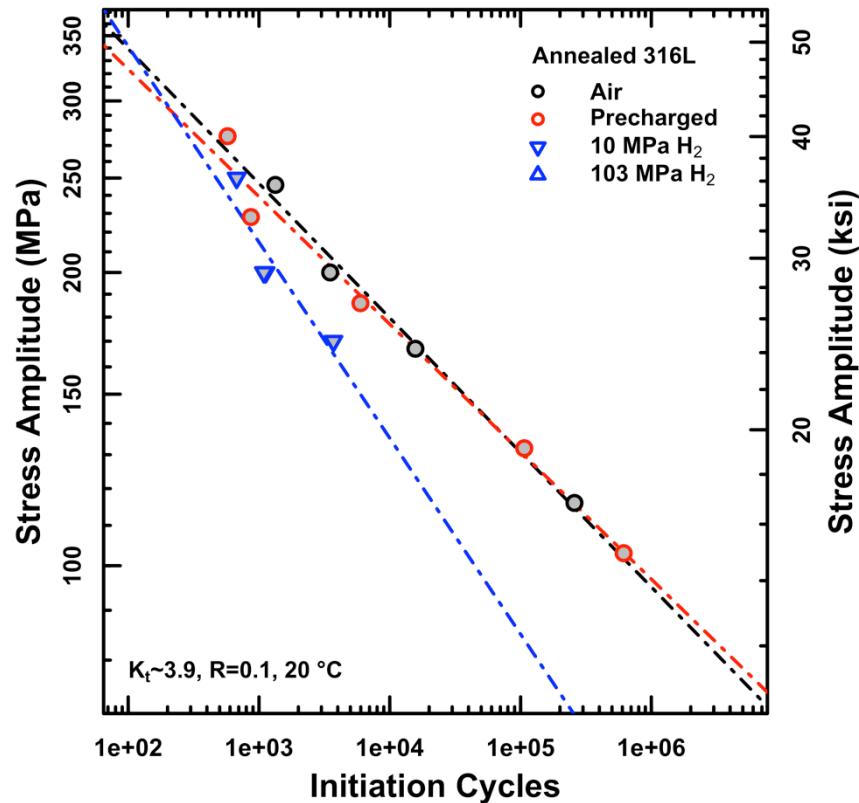
Challenge: Where is the crack?

- Often see linear DCPD signal early during test
- *Inflection in voltage signal interpreted as crack 'initiation'*



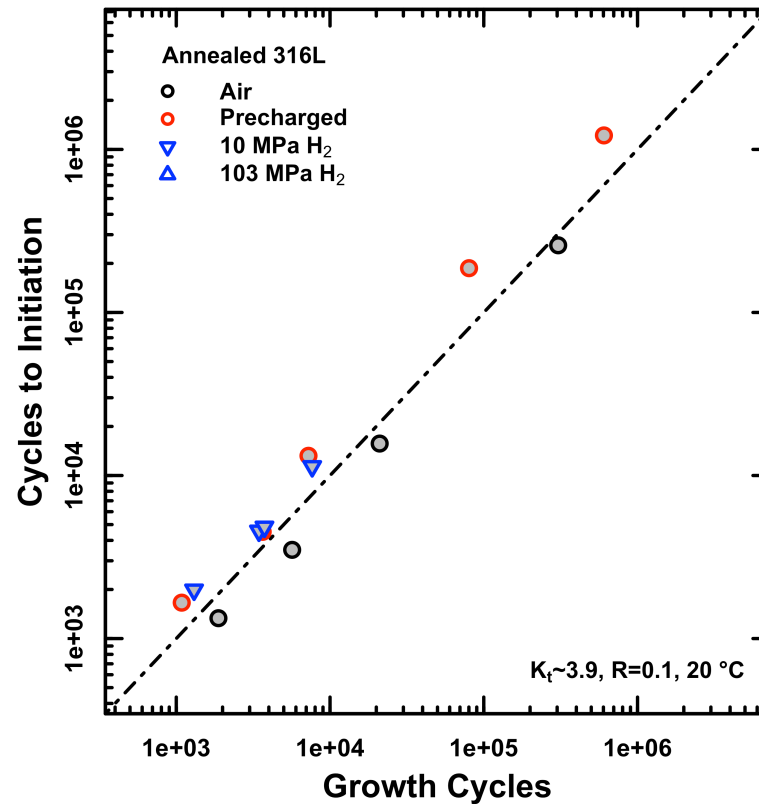
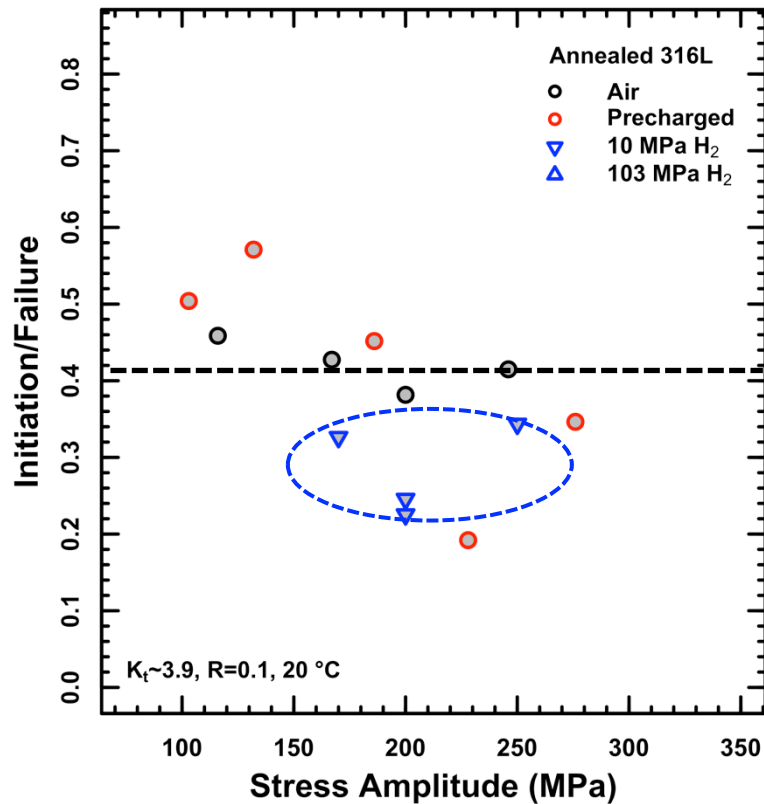
Initiation & Growth Life: Annealed 316L

- Plotted using linearized Whöler-type curves
- Decrease in both the initiation and growth life in hydrogen



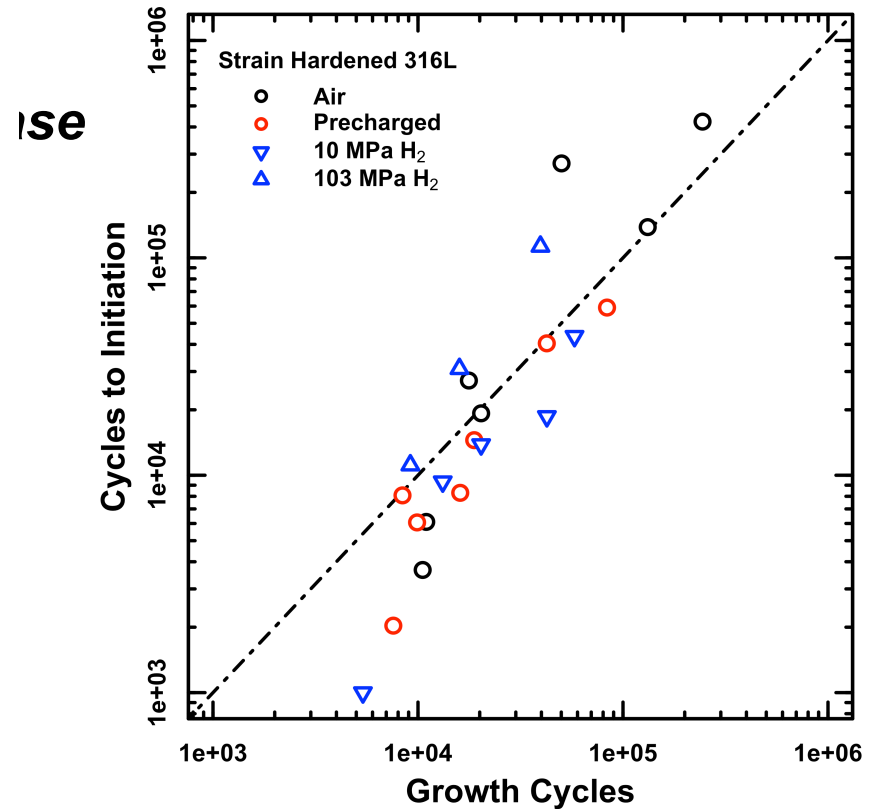
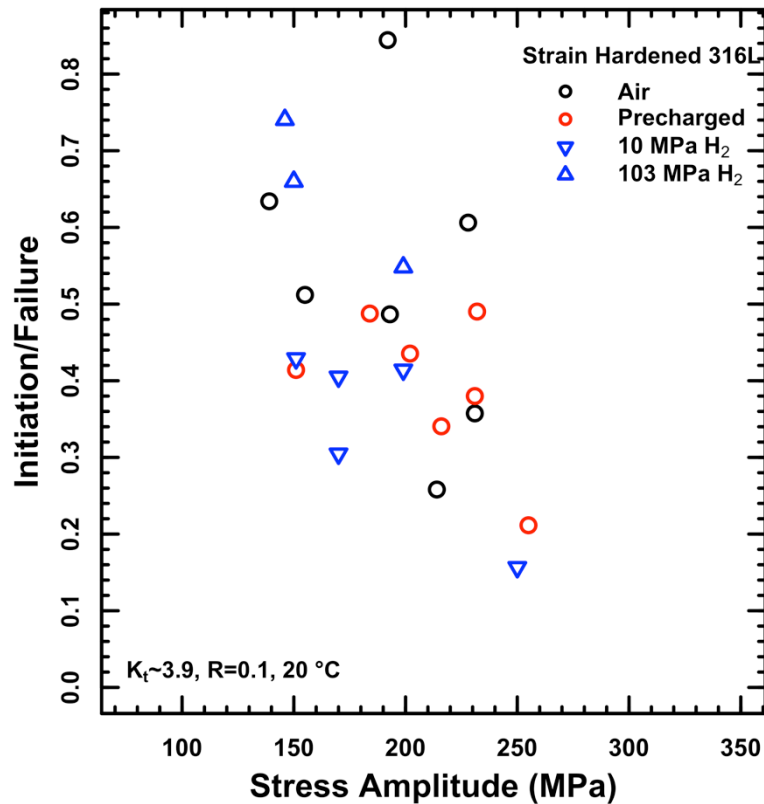
Initiation & Growth Life: Annealed 316L

- Hydrogen does slightly decrease relative contribution of crack initiation to total life



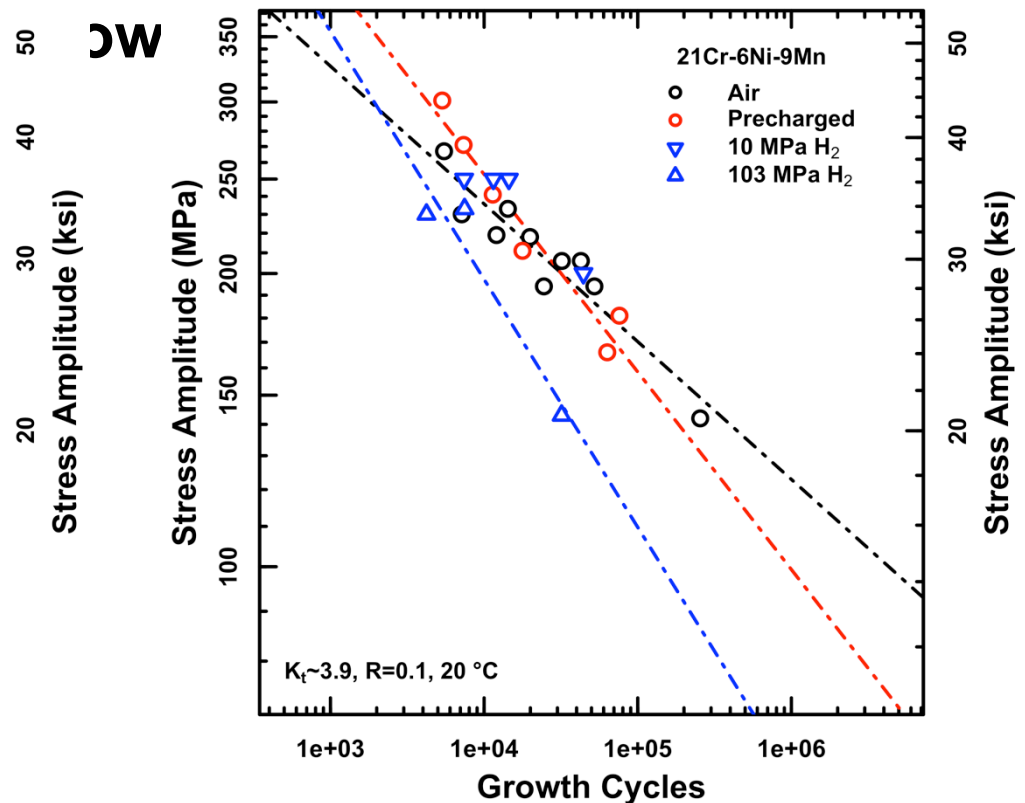
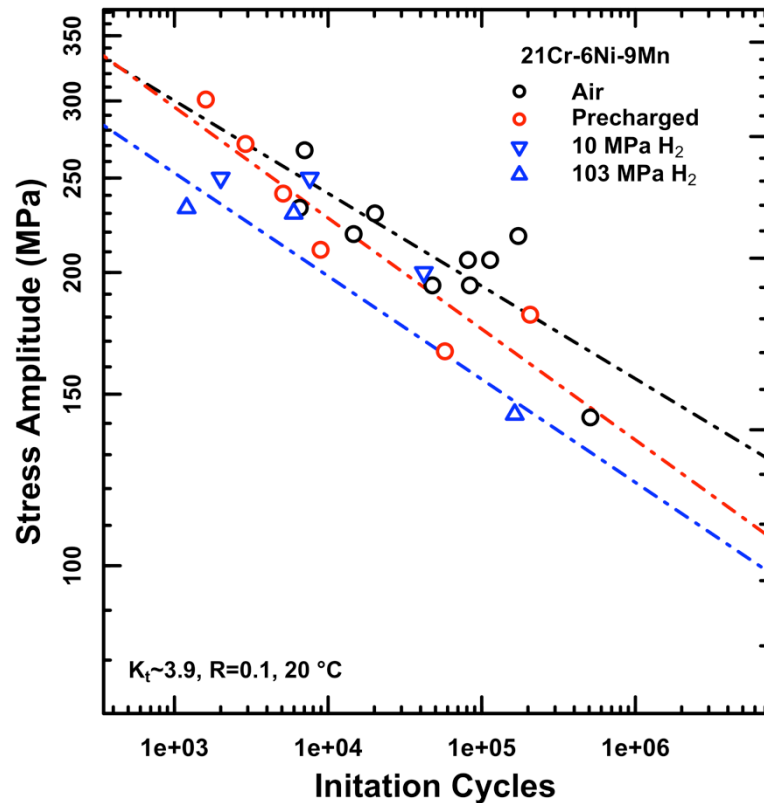
Case 2: Strain-hardened 316L

- Increasing fraction initiation at low stresses
 - *Up to 80% of life*
- No clear decrease in fraction of life in initiation with



Case 2: 21Cr-6Ni-9Mn

- Decrease in both the initiation and growth life in hydrogen
- Hydrogen slope to fit lines straddle trends:



Uncertainty typically less than plotted symbol size

Case 2: 21Cr-6Ni-9Mn

- Appears to be more impact on initiation in presence of hydrogen
 - *More rapid transition to crack growth*

