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Comparison of Internal and External Hydrogen on Fatigue Life of Austenitic Stainless Steels

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3. *Swagelok Company*

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U.S. DEPARTMENT OF ENERGY

NNSA National Nuclear Security Administration

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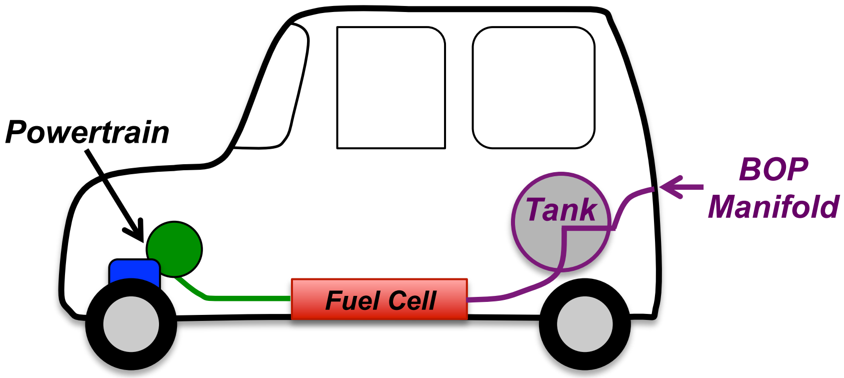
Need to Optimize Components on H_2 Fuel Cell Vehicles

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 H_2 at:
  - *Pressures up to 90 MPa (13 ksi)*
  - *Temperatures -40°C→85°C*



Objective:

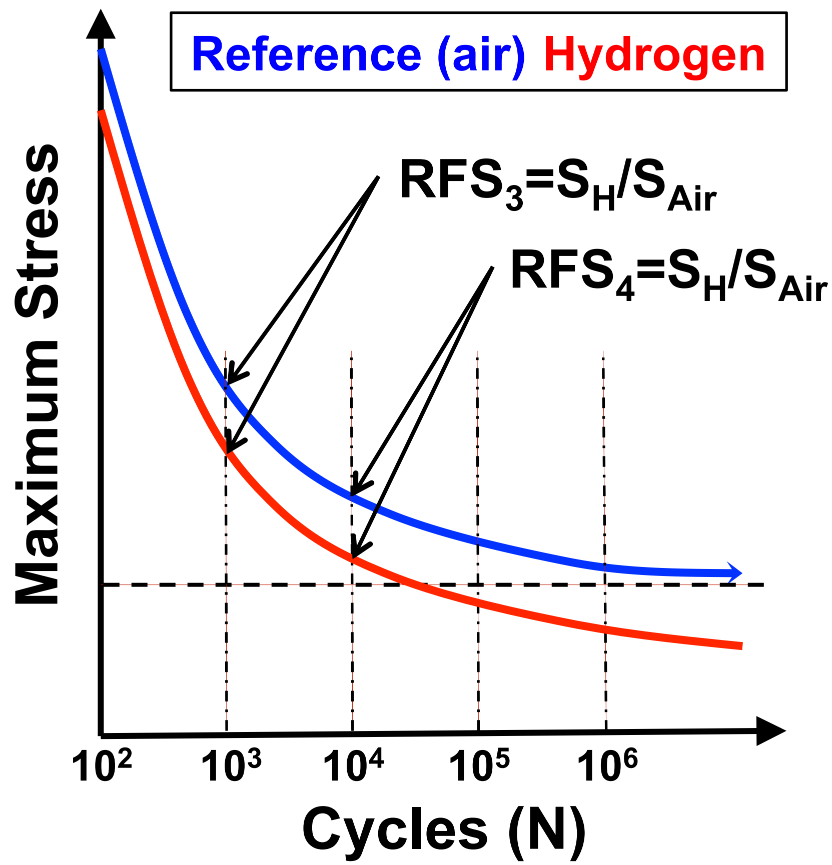
Identify performance-based selection criteria to identify metals for high-pressure BOP components

Reduce cost by 35%

Reduce weight by 50%

Hydrogen degradation of stainless steels: Fatigue-life Assessment

- 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

Need to directly compare relative performance of alloys

Summary – Alloys of Interest

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Composition

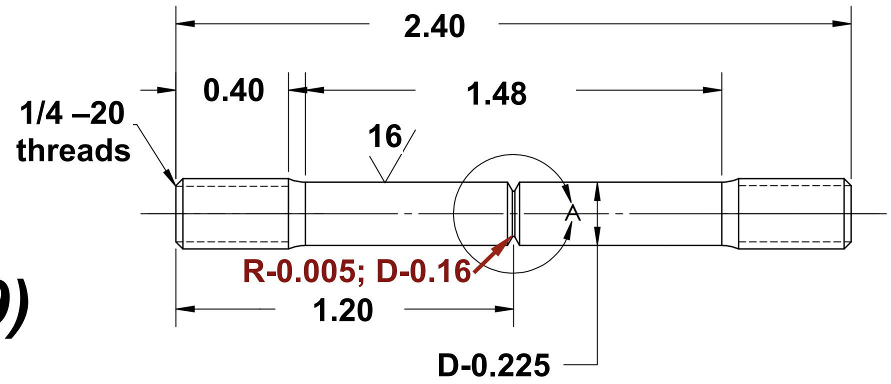
Alloy ID	Cr	Ni	Mn	Mo	C	N	Si
316L	17.54	12.04	1.15	2.05	0.020	0.04	0.51
21-6-9	20.45	6.15	9.55	NR	0.033	0.265	0.52

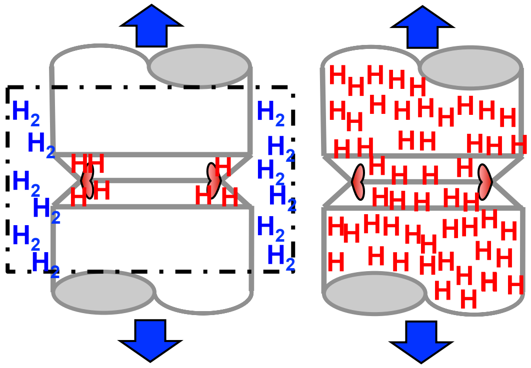
Tensile properties

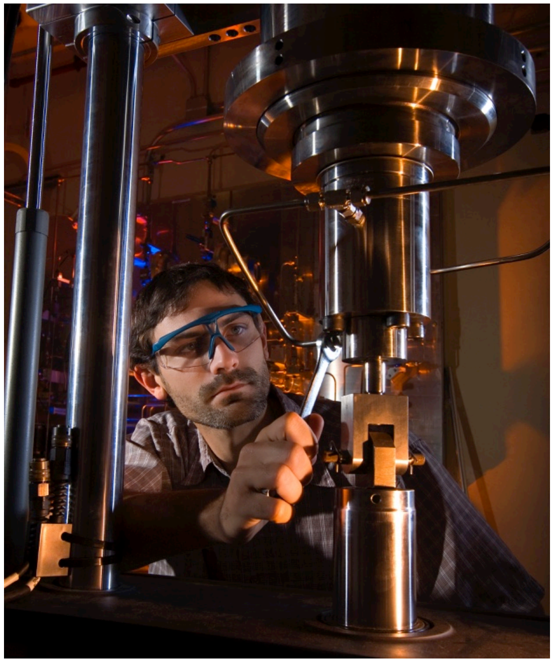
Alloy ID	S_Y (MPa)	S_U (MPa)	RA (pct.)	El_T (pct.)	S_Y (ksi)	S_U (ksi)
316L – Strain hardened	632	772	77	32	91.7	112
316L – H Pre-charged	*712*	*841*	*60*	*30*	*103*	*122*
21-6-9 - Annealed	539	881	79	61	78.2	128
21-6-9 - H Pre-charged	*669*	*957*	*50*	*55*	*104*	*142*

Fatigue Testing Conditions

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

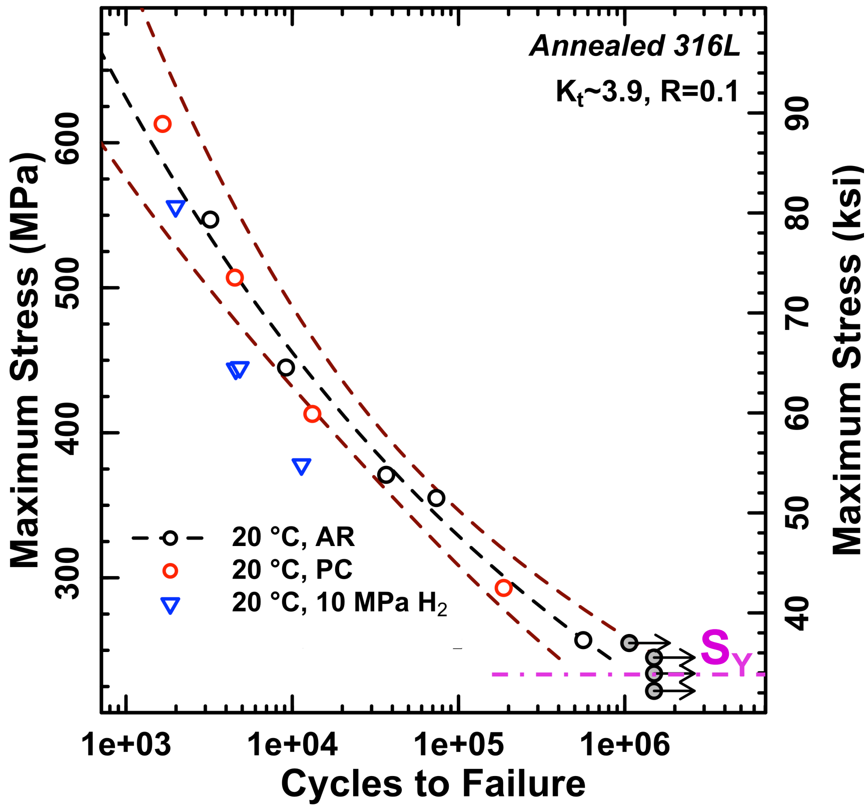






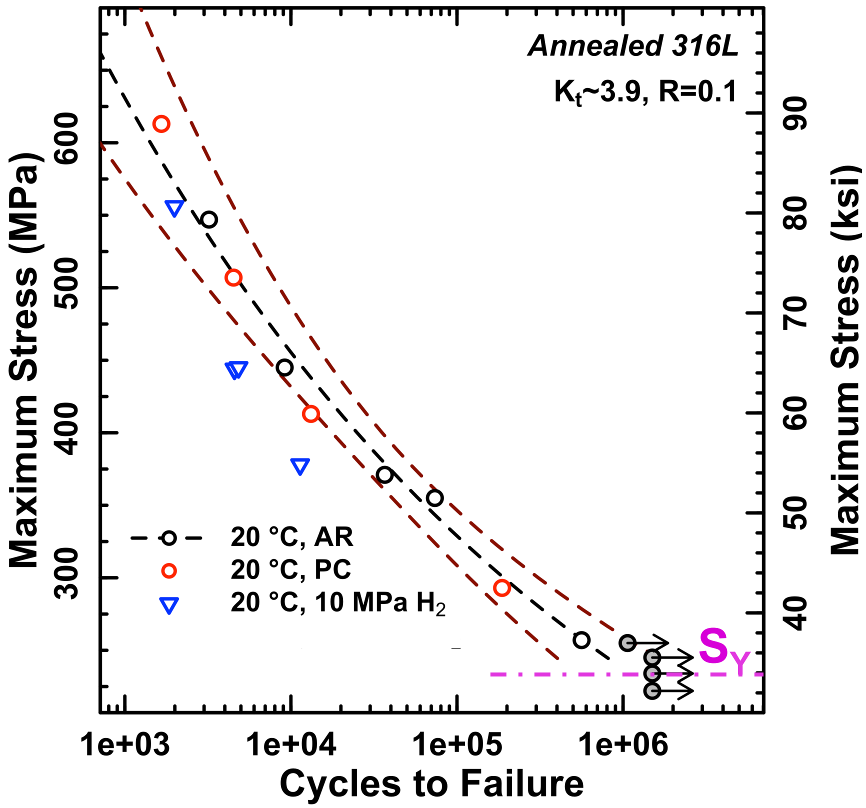
Baseline Fatigue Performance Annealed 316L

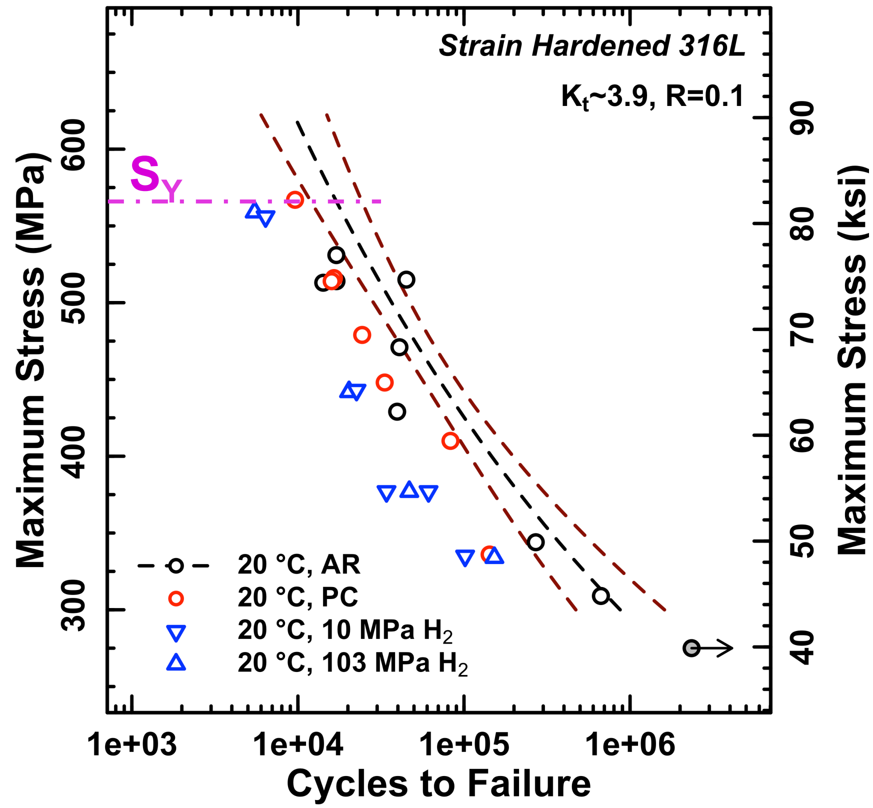
- ***Annealed 316L is yield strength limited***
- ***Small decrease in stress-life in external hydrogen***



High Strength Stainless Steel: Strain-Hardened 316L

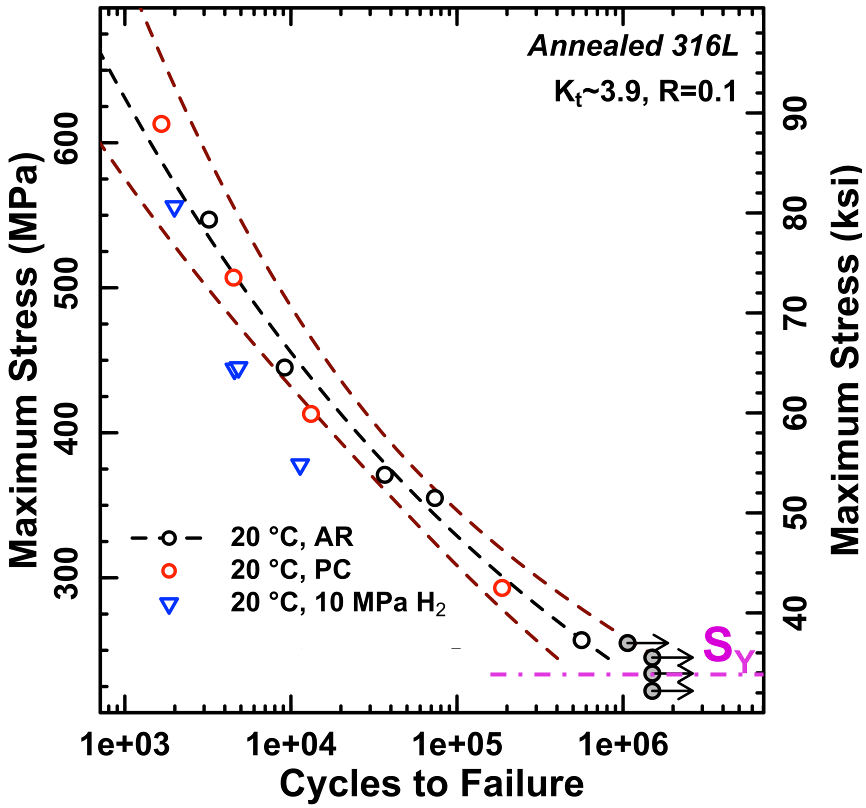
- $YS_{\text{strain-hardened 316L}} \sim 2 \times YS_{\text{annealed 316L}}$
- ***Both conditions small decrease in fatigue life with H_2***

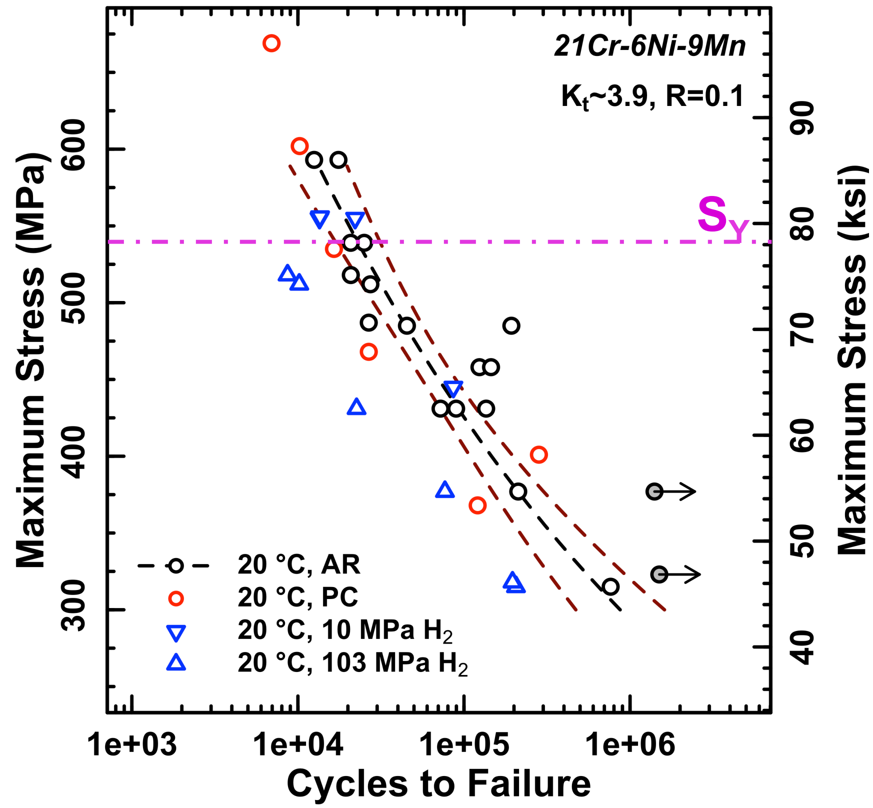




Low Ni Stainless Steel: 21Cr-6Ni-9Mn *(Nitronic 40)*

- ***High stresses still permissible in H_2 than annealed 316L***
  - ***Clear influence of 103 MPa H_2, less impact with 10 MPa H_2***
    - **Change in surface and bulk H diffusion kinetics with nitrogen***





*Ningshen, et al., Corrosion Sci., 43, (2001)

Internal *v.* External Hydrogen
Strengthening after pre-charging

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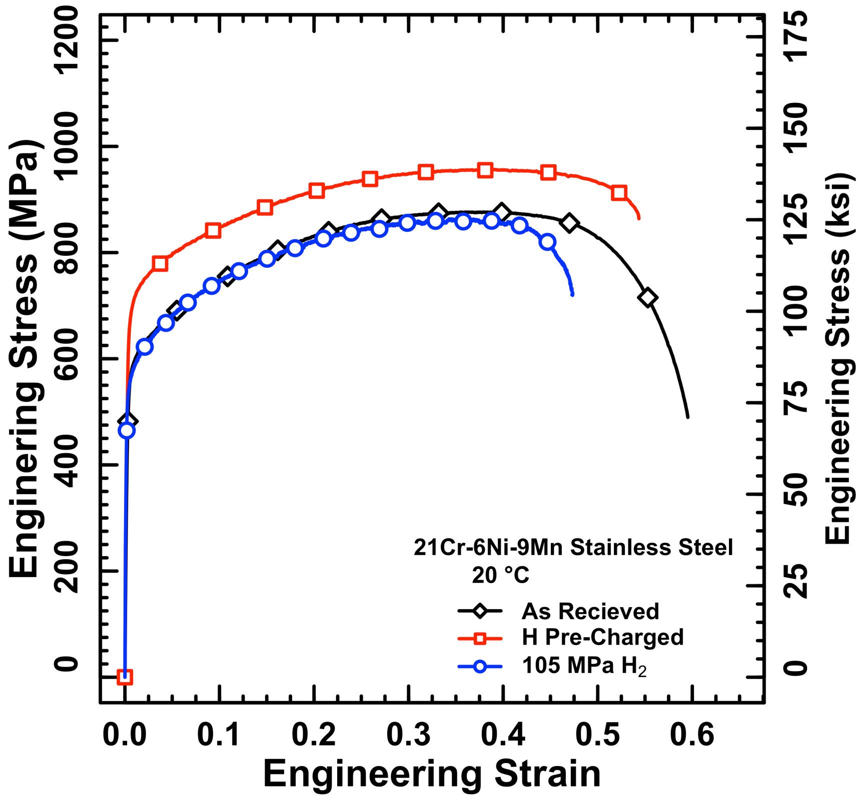
With internal H:

Yield strength increase

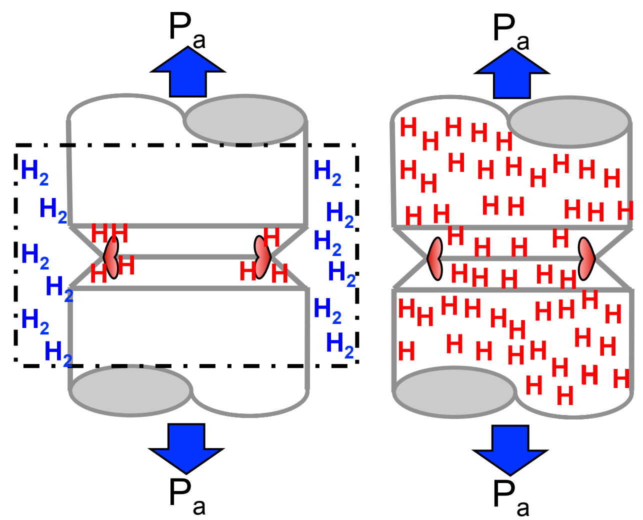
Hardening slightly decreased



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

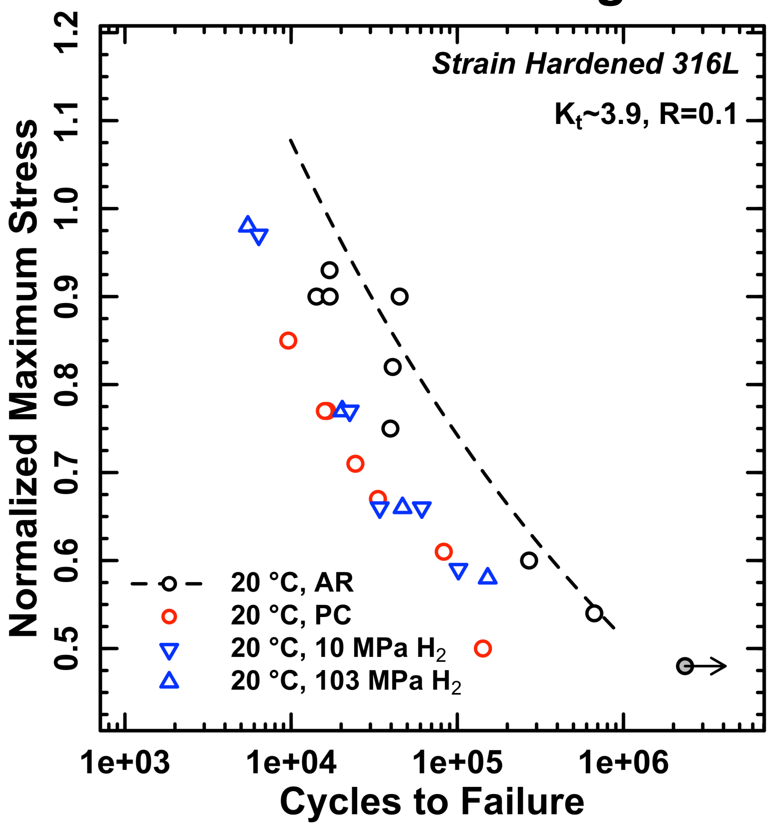
$YS_{H\text{-}charged} > YS_{as\text{-}received}$

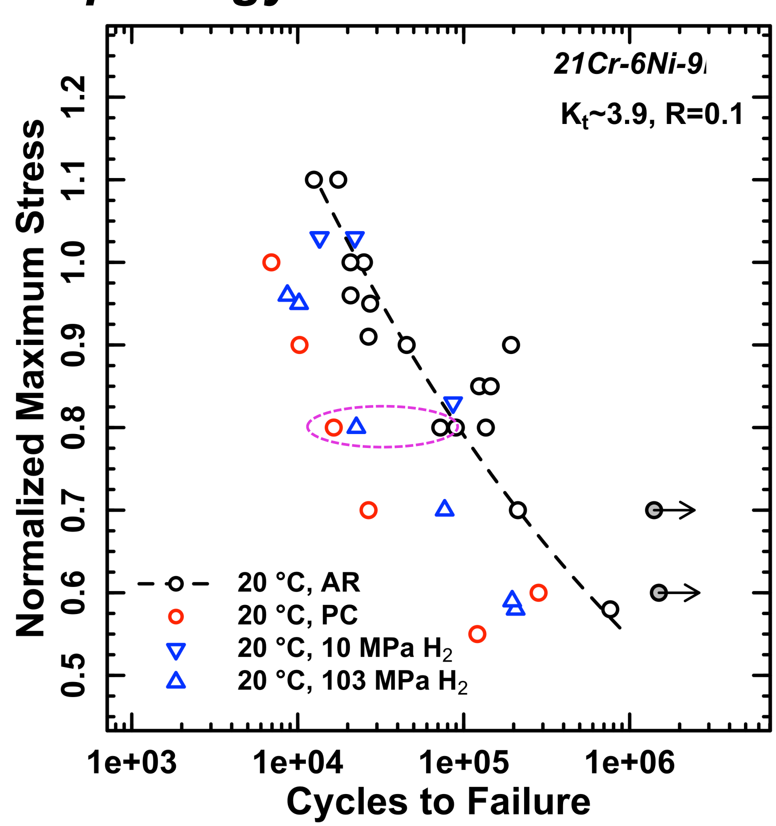
$$N_A = \left(\frac{S_{Max}}{S_{YS}} \right)$$



Internal *v.* External Hydrogen
Adjustment of Wöhler Curves

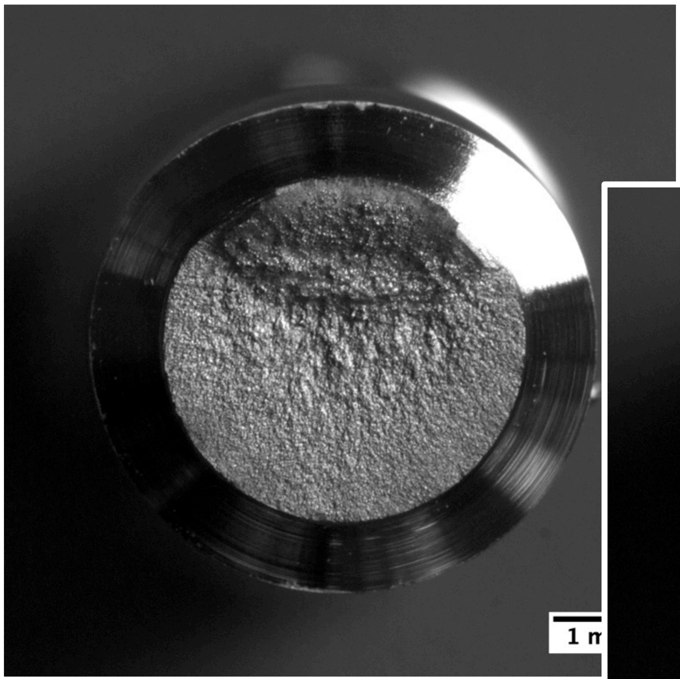
- ***Thermal pre-charging appears to capture some of the features of interest for H-degradation***
  - ***What about the fatigue surface morphology?***





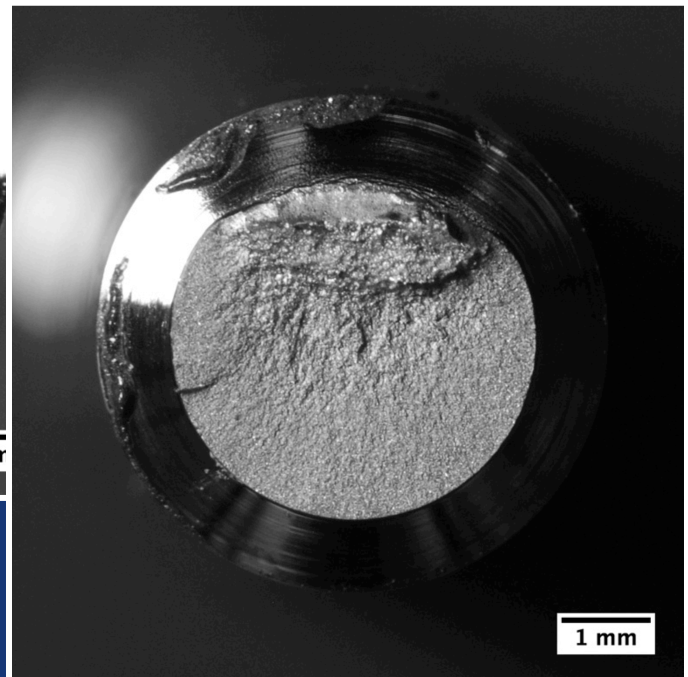
Internal *v.* External Hydrogen
Fatigue surfaces 21Cr-6Ni-9Mn

As-received



H-precharged

103 MPa H_2



Internal *v.* External Hydrogen
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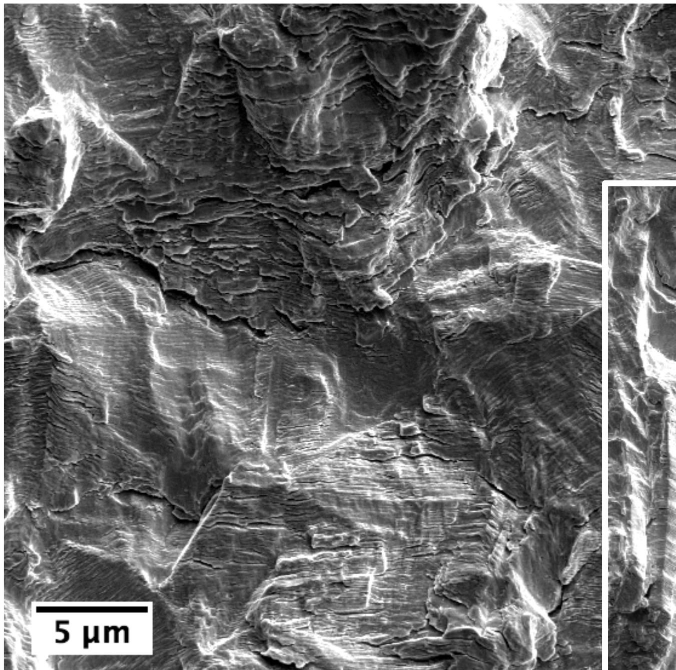
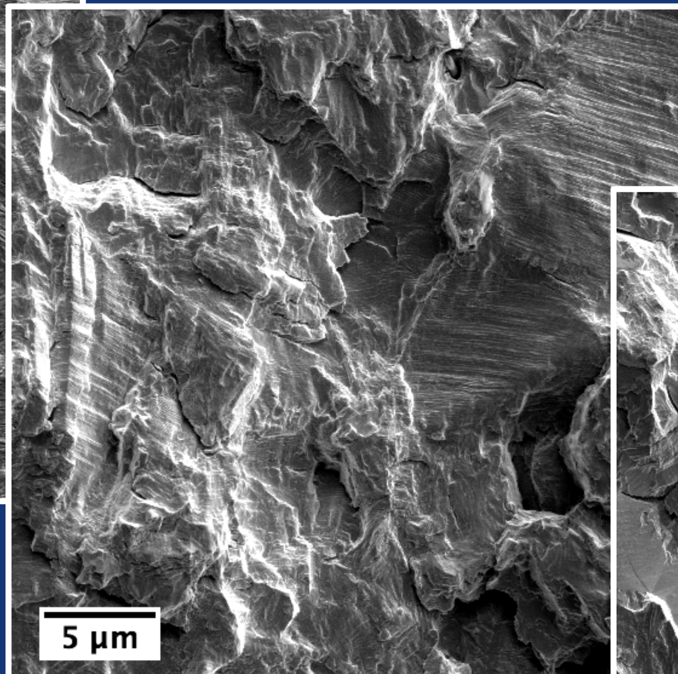
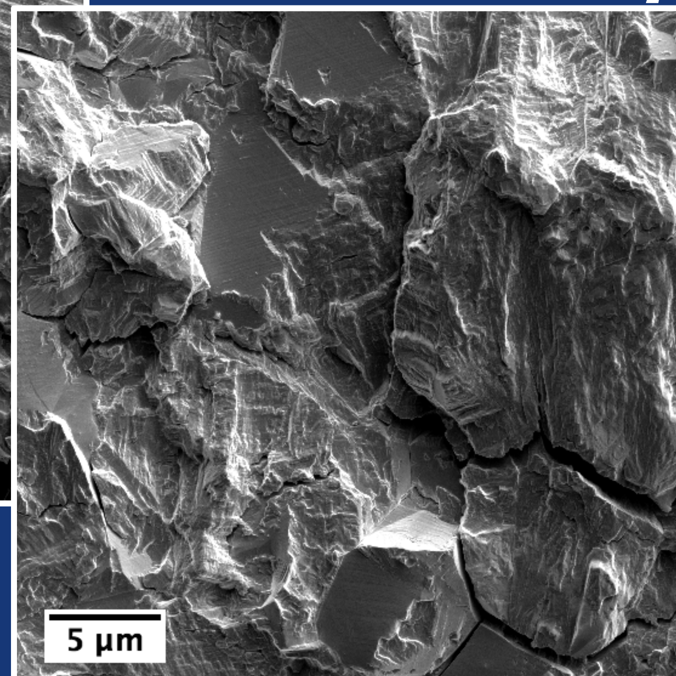


H-precharged



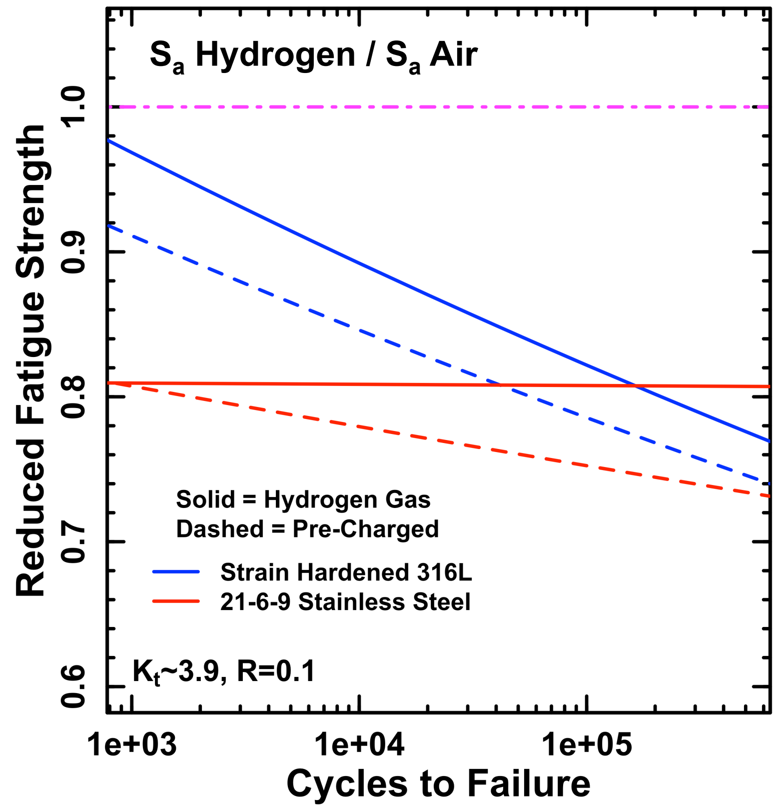
103 MPa H_2



Comparison Between Alloys

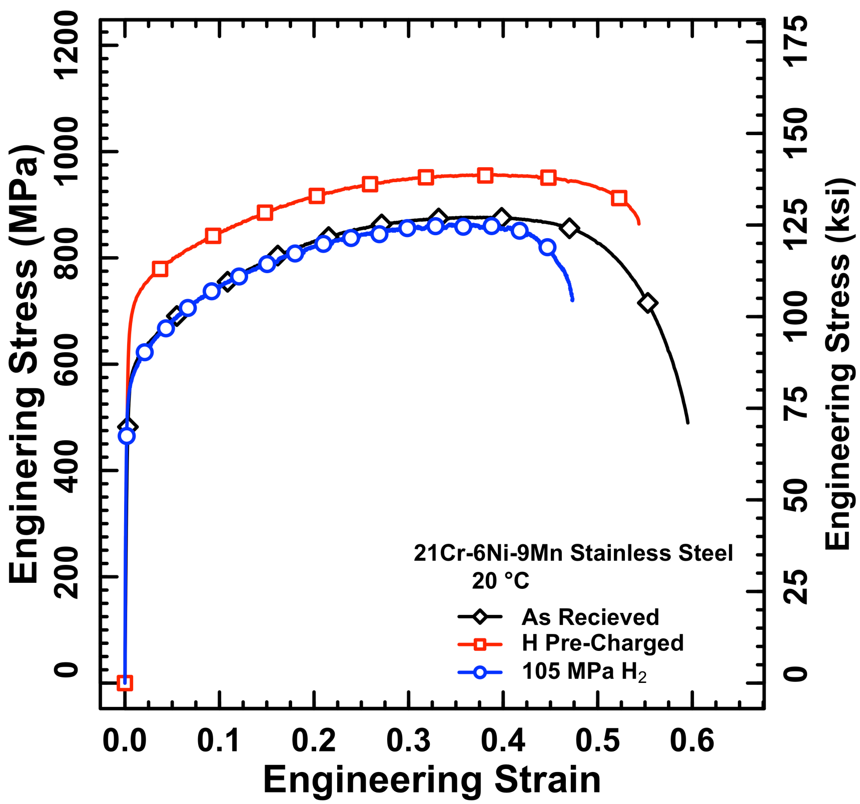
- **Underlying behavior (shape of the Wöhler Curve) seems unaffected by strength or hydrogen**
- **Similar degradation in fatigue strength in strain hardened 316L & 21Cr-6Ni-9Mn alloys**

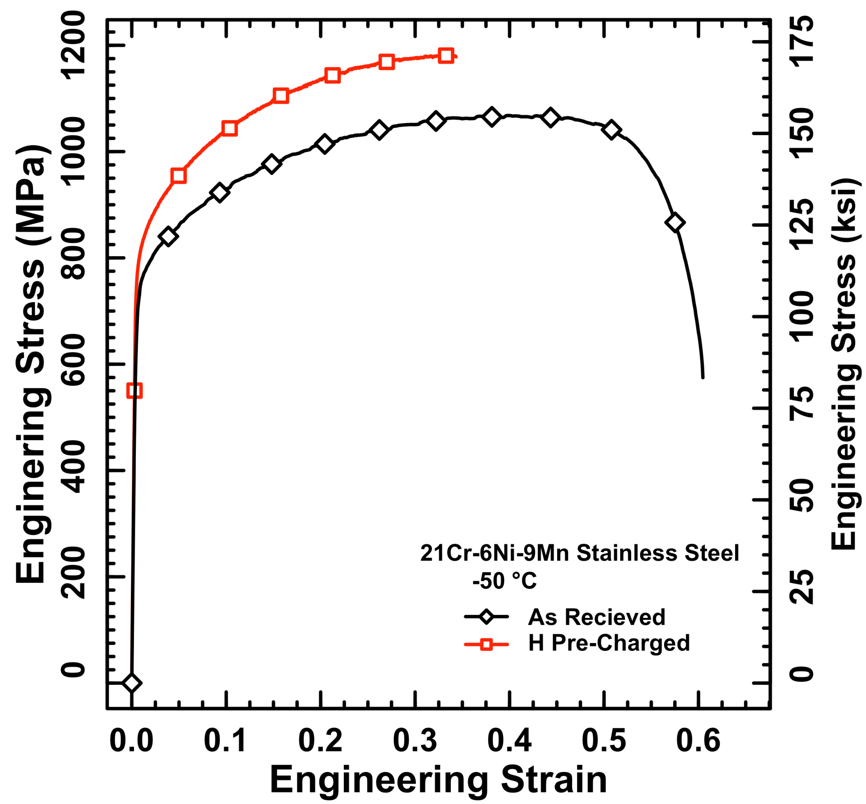
Maximum H influence at highest life



Low temperature hydrogen performance: 21Cr-6Ni-9Mn *(Nitronic 40)*

- **Environmental factors other than hydrogen alter strength**
  - ***Confounds results of stress controlled fatigue***

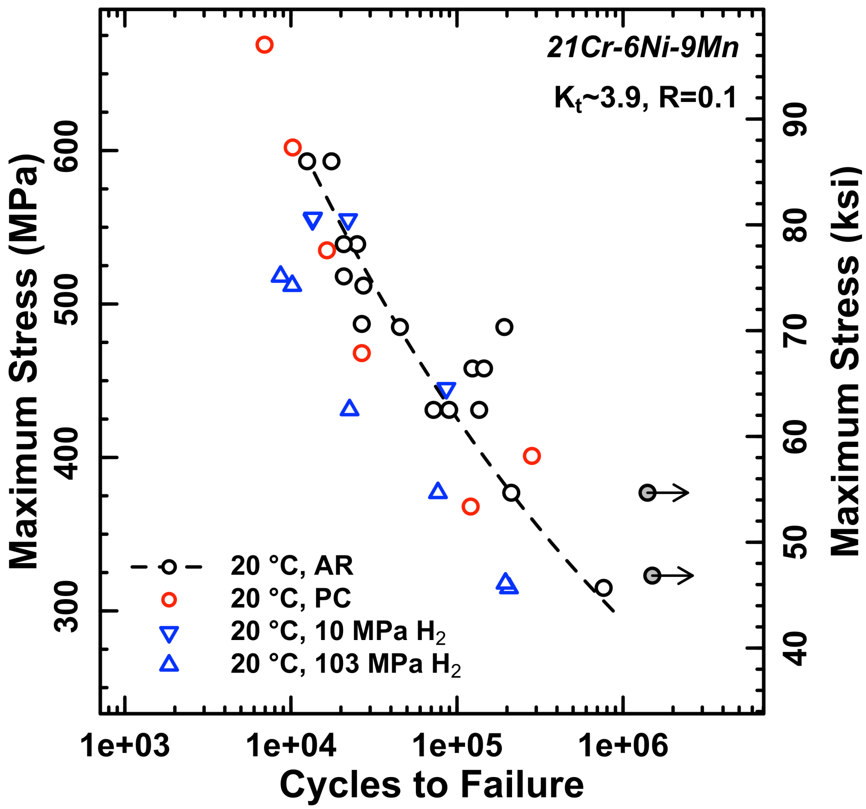


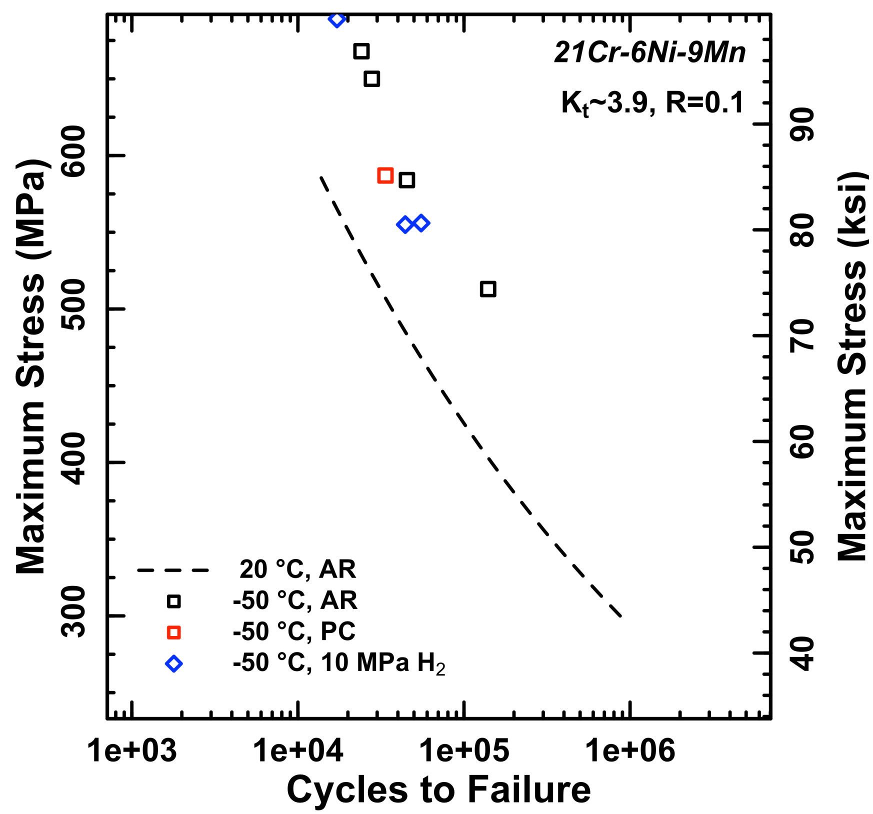


Low Ni Stainless Steel: 21Cr-6Ni-9Mn *(Nitronic 40)*

- ***Increase in fatigue-life at low temperature***

Regression line fit to both 21Cr-6Ni-9Mn and strain-hardened 316L

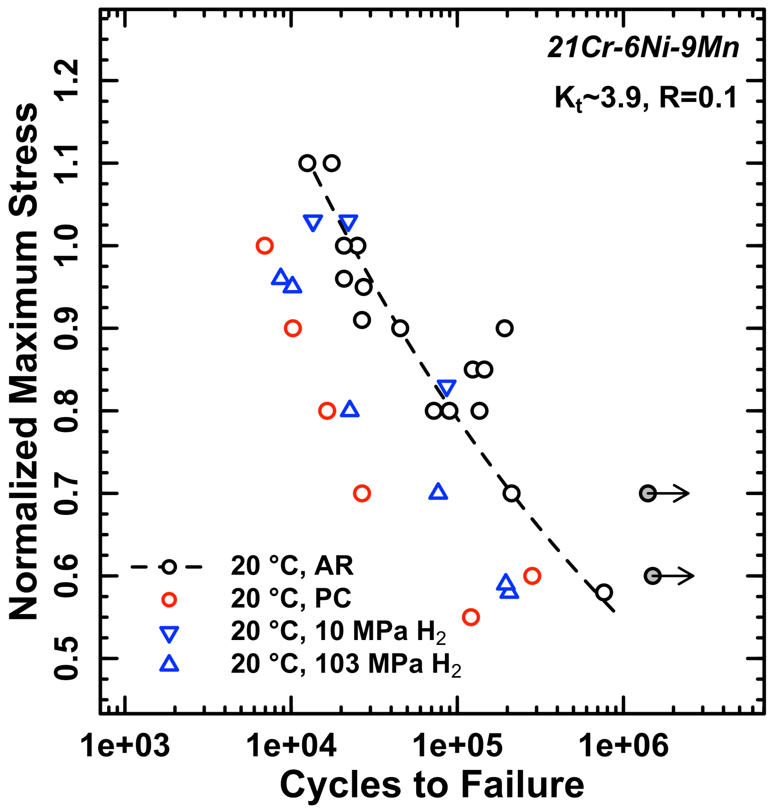


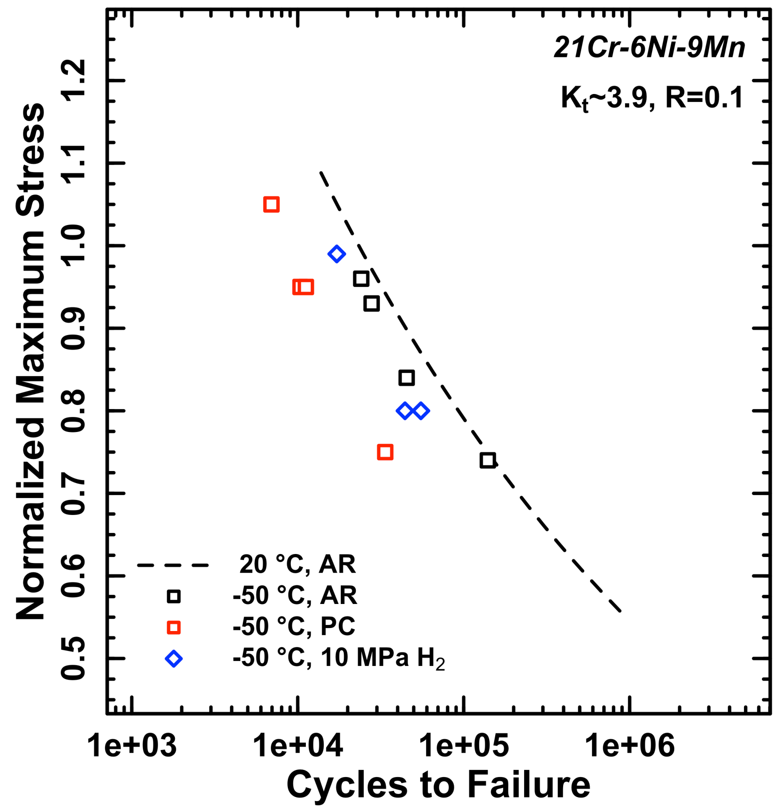


Low Ni Stainless Steel: 21Cr-6Ni-9Mn *(Nitronic 40)*

- ***Increase in fatigue-life at low temperature***
  => due to increased yield strength

Regression line fit to both 21Cr-6Ni-9Mn and strain-hardened 316L





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
- Limiting fatigue life of 21Cr-6Ni-9Mn at room temperate

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