SAND2015-5851PE

Fatigue Life of Austenitic Stainless Steel for Hydrogen Service

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Relevance

Challenge:

- **Balance of plant (BOP) onboard vehicles accounts for:**
  - ***30-57% of total system cost***
  - ***15-20% of total system mass***
- **Structural metals for hydrogen storage typically include**
  - ***Annealed type 316L austenitic stainless steel (Ni content >12 wt%)***
  - ***A286 precipitation-strengthened austenitic stainless steel (Ni ~30 wt%)***
- **Relatively little data in literature to identify component relevant metrics for performance**

Project Outline

Objectives:

- ***Identify alternatives to high-cost metals for high-pressure BOP components***
- ***Use CHMC 1-2014 methodology to efficiently establish relevant selection metrics to compare materials***
- ***Identify alternatives to high-cost alloys for high-pressure BOP components***

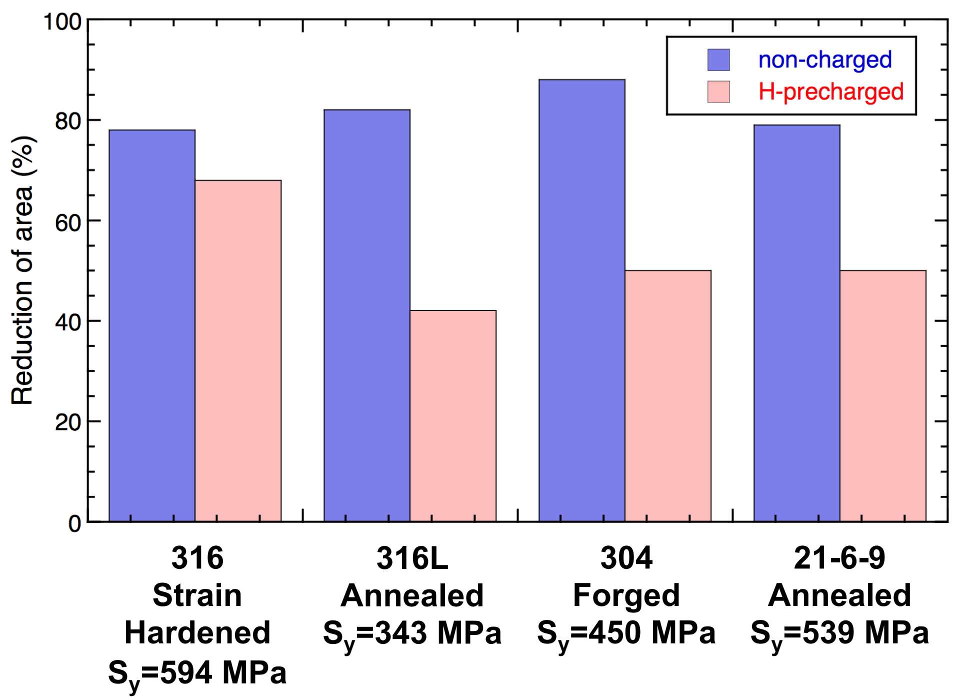
Outstanding questions:

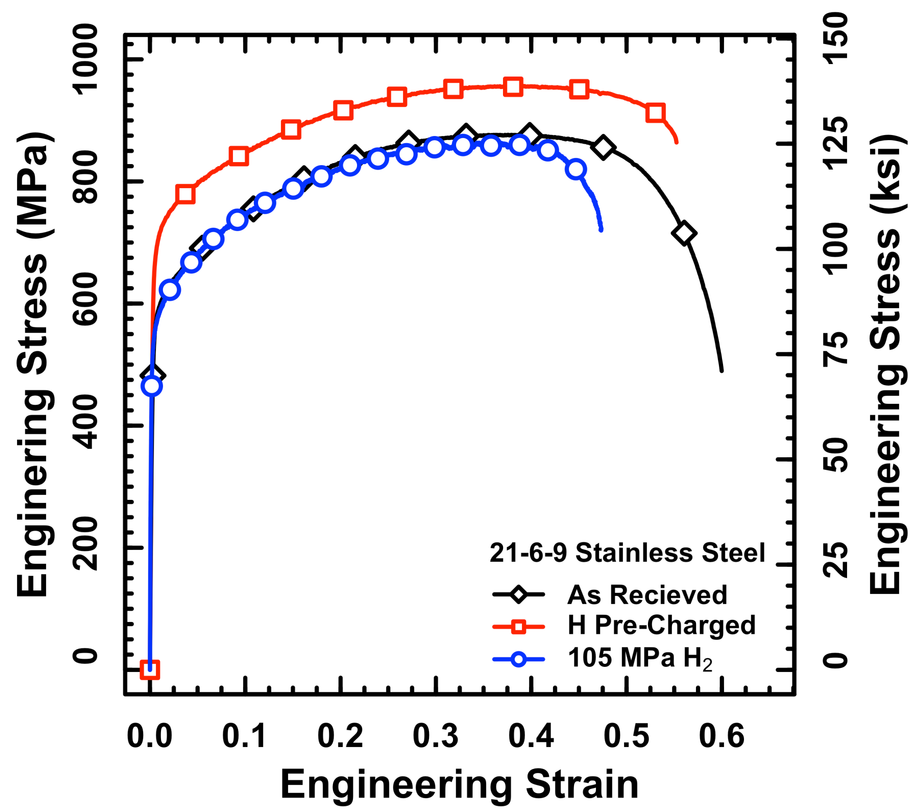
- **How effectively can stress-based fatigue testing be used to compare material performance in presence of hydrogen?**
- **Can thermally pre-charged samples be used in place of testing in external hydrogen?**

Most hydrogen compatibility decisions based on tensile data

- Strength is unchanged by hydrogen
- Ductility is decreased by hydrogen

How well do metrics match component service?





C. San Marchi, et al., Int. Hydrogen Conf. 2012, Jackson, WY

Experimental Methods: Stainless Steels of Interest

Composition

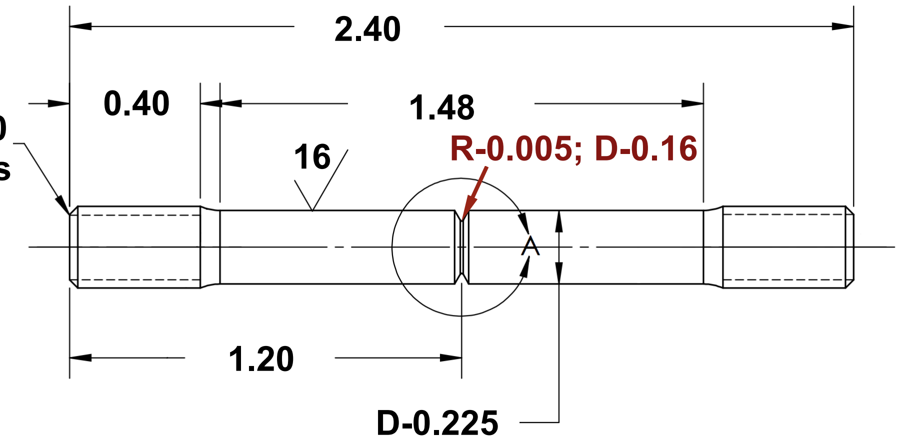
Alloy ID	Cr	Ni	Mn	Mo	C	N	Si	*H_2 Charged*
316L	17.54	12.04	1.15	2.05	0.020	0.04	0.51	*150 wppm*
21Cr-6Ni-9Mn	20.45	6.15	9.55	NR	0.033	0.265	0.52	*~210 wppm*

Tensile properties

Alloy ID	S_Y (MPa)	S_U (MPa)	S_Y (ksi)	S_U (ksi)	RA (pct.)	El_T (pct.)
316L - Cold Worked	589	967	85.5	140.5	74	44
21Cr-6Ni-9Mn - Annealed	539	881	78.2	127.8	79	61
21Cr-6Ni-9Mn - H Charged	669	977	104	142	-	55

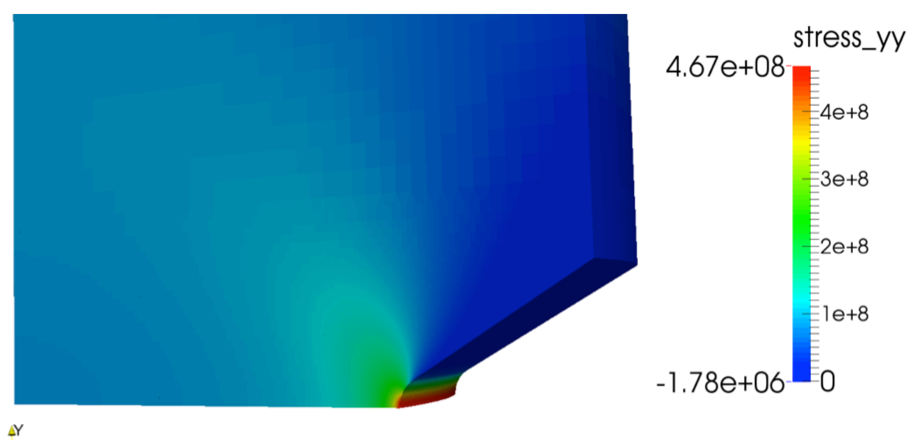
Experimental Methods: Fatigue Conditions

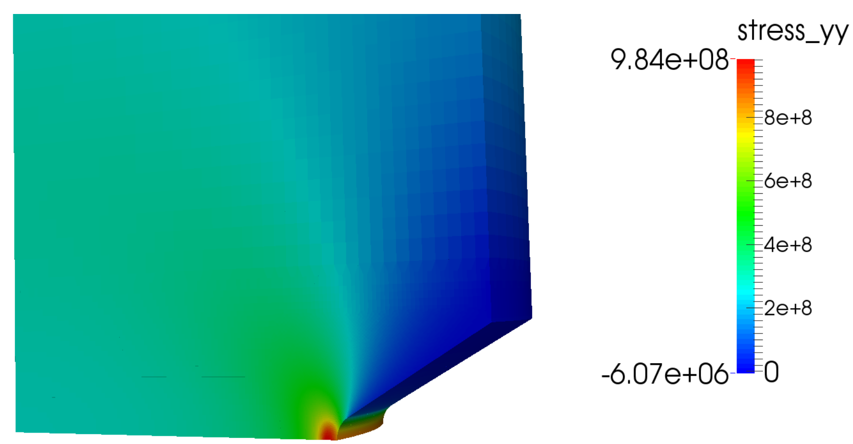
- ***Testing conditions represent <u>pressure loading:</u>***
  - ***R = 0.1 (tension-tension)***
  - ***Notched specimens***
  - ***Net-section $S_{max} < S_Y$***



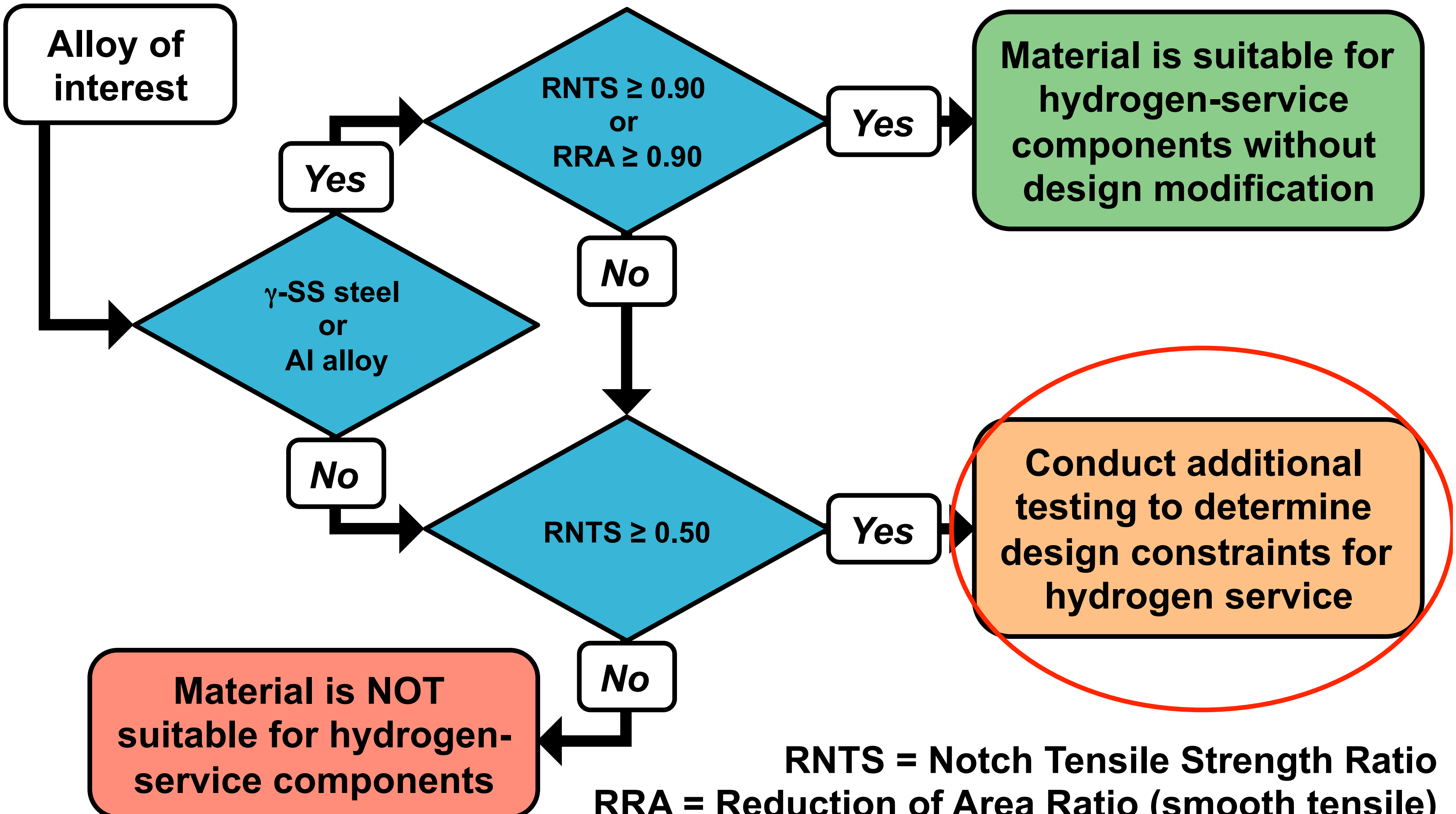
$$K_{t,el} = \frac{\sigma_{max}}{\sigma_{min}} = \frac{467}{119.7} = 3.90$$

$$K_{t,el-pl} = \frac{\sigma_{max}}{\sigma_{min}} = \frac{984}{406.4} = 2.42$$





CSA CHMC1 – 2014: Part 3: Material qualification



RNTS = Notch Tensile Strength Ratio

RRA = Reduction of Area Ratio (smooth tensile)

Safety Factor Multiplier Method

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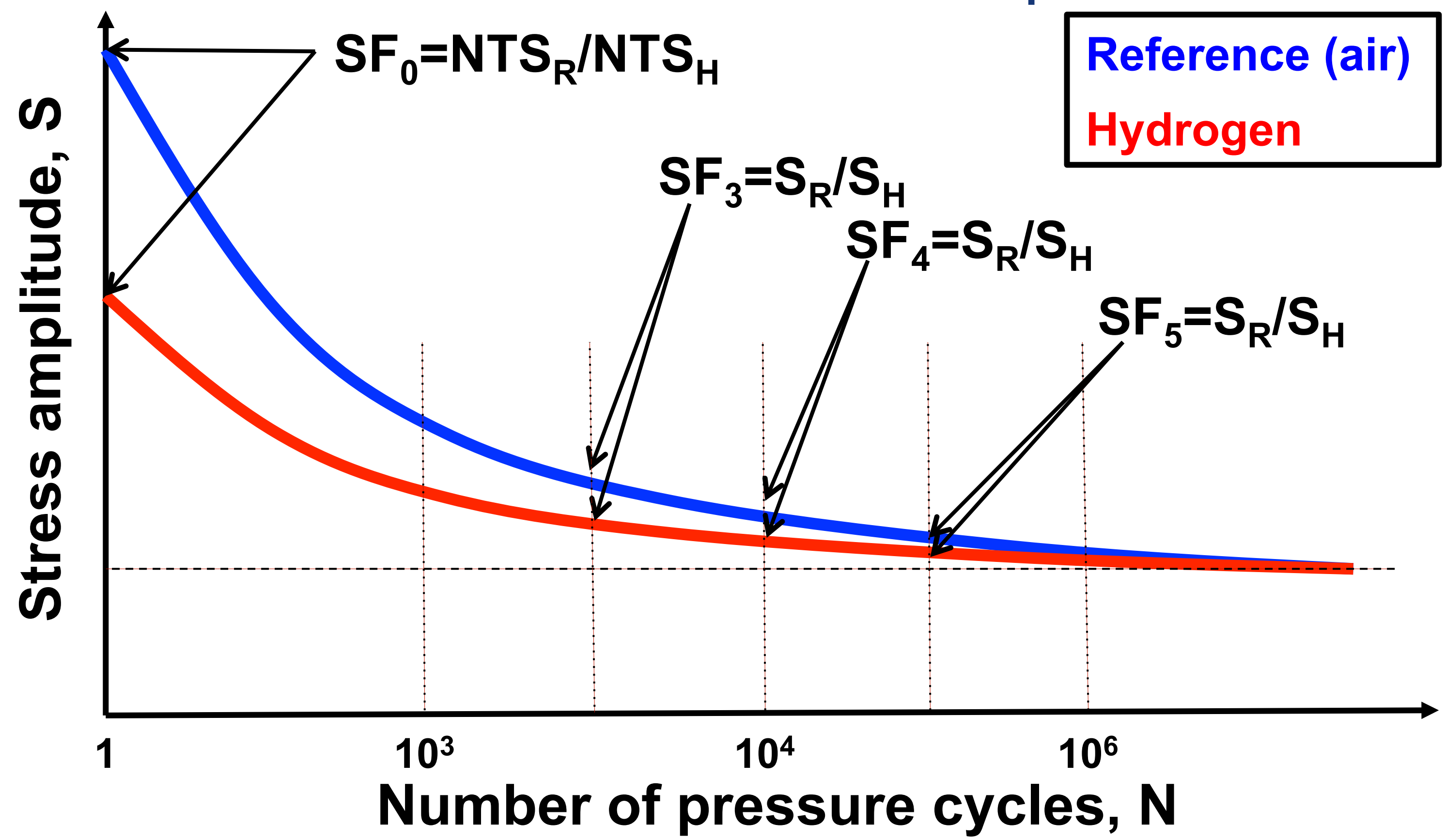
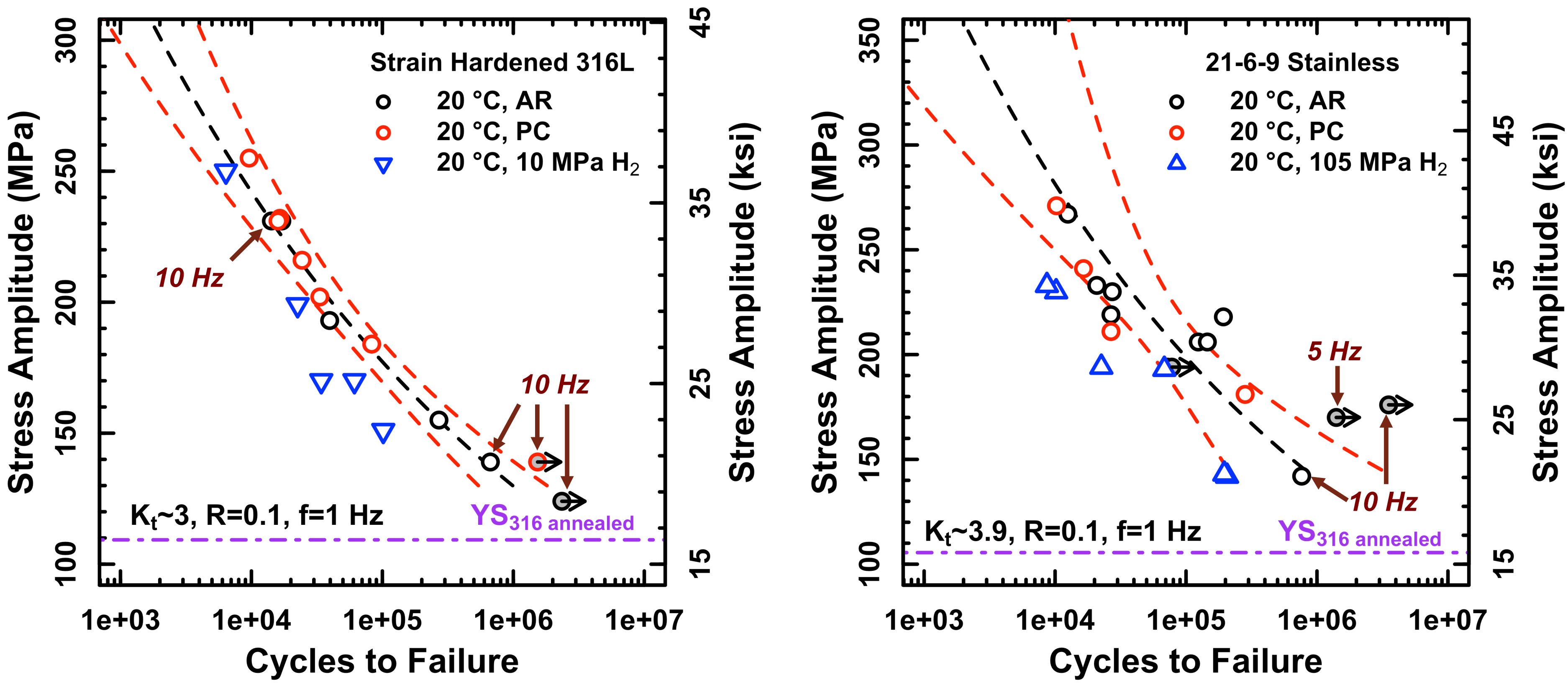
Hydrogen safety factor: $SF_H = max(SF_0, SF_3, SF_4, SF_5)$

Safety factor for design ➔ $SF_{component} \times SF_H$



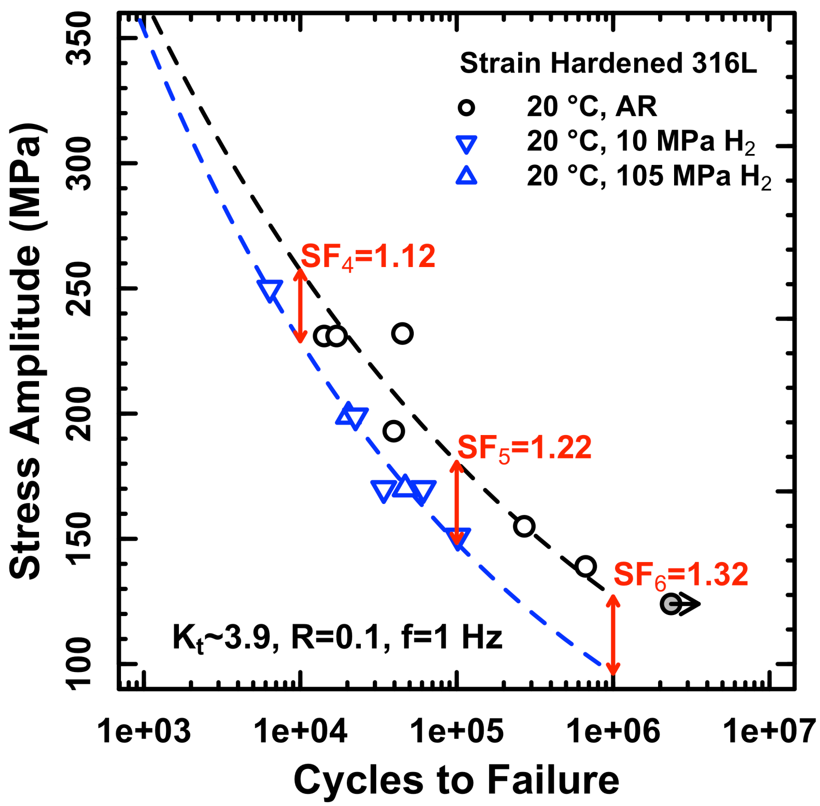
Fatigue Life

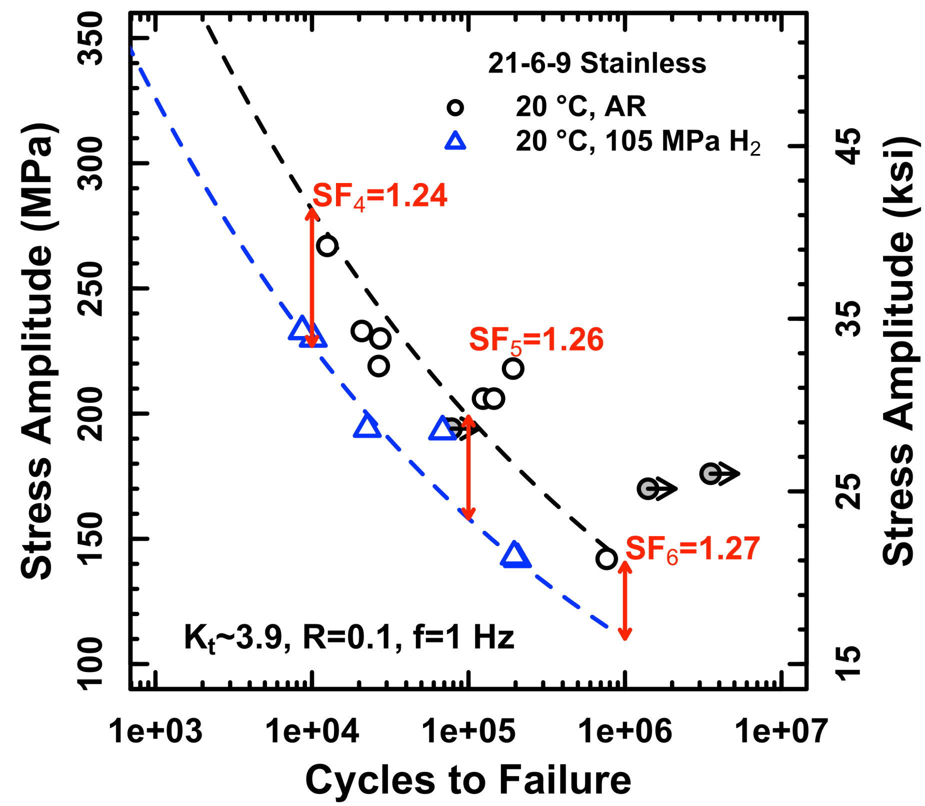
- No *apparent* change in performance with internal hydrogen
- Decrease in fatigue life in External hydrogen



Safety Factor Multiplier: External Hydrogen

- 316L converges at low cycle regime
- 21-6-9 essentially constant SFM

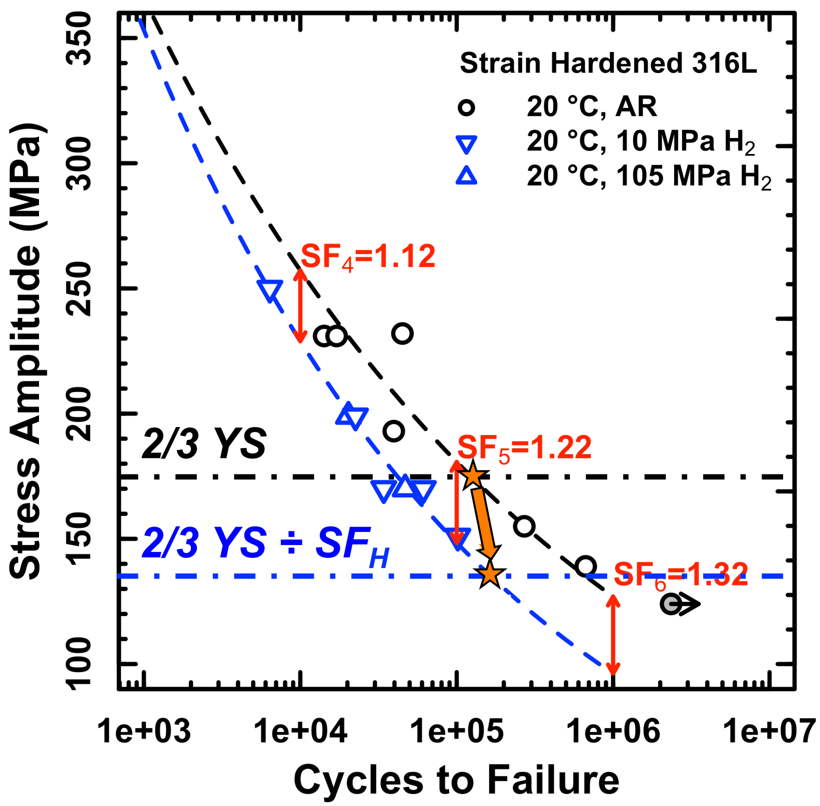


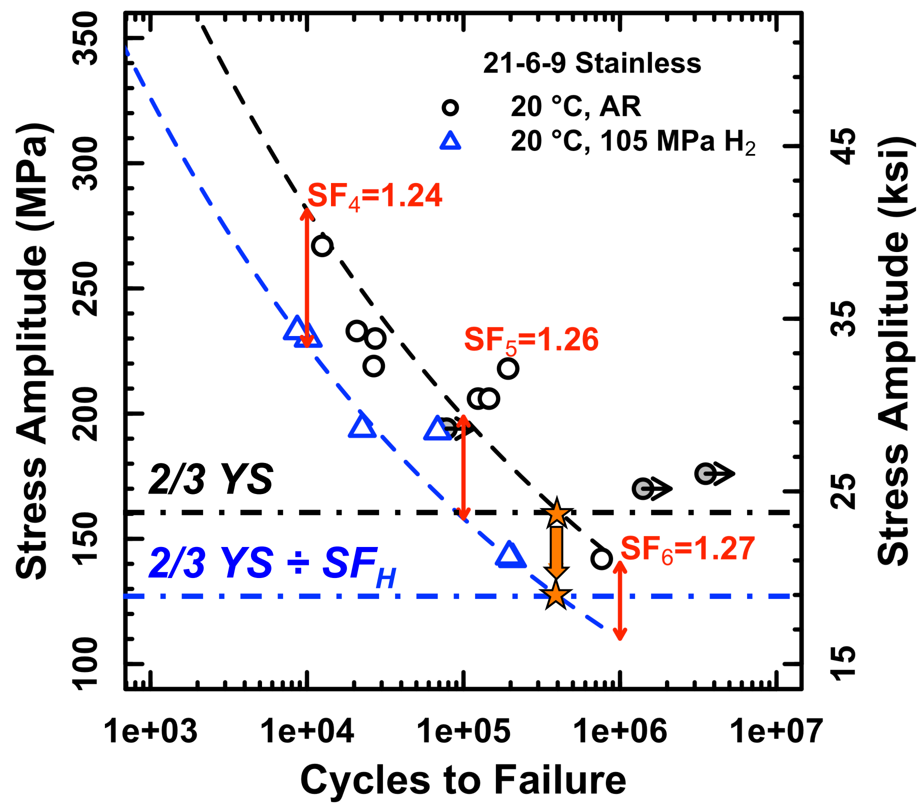


Safety Factor Multiplier: External Hydrogen

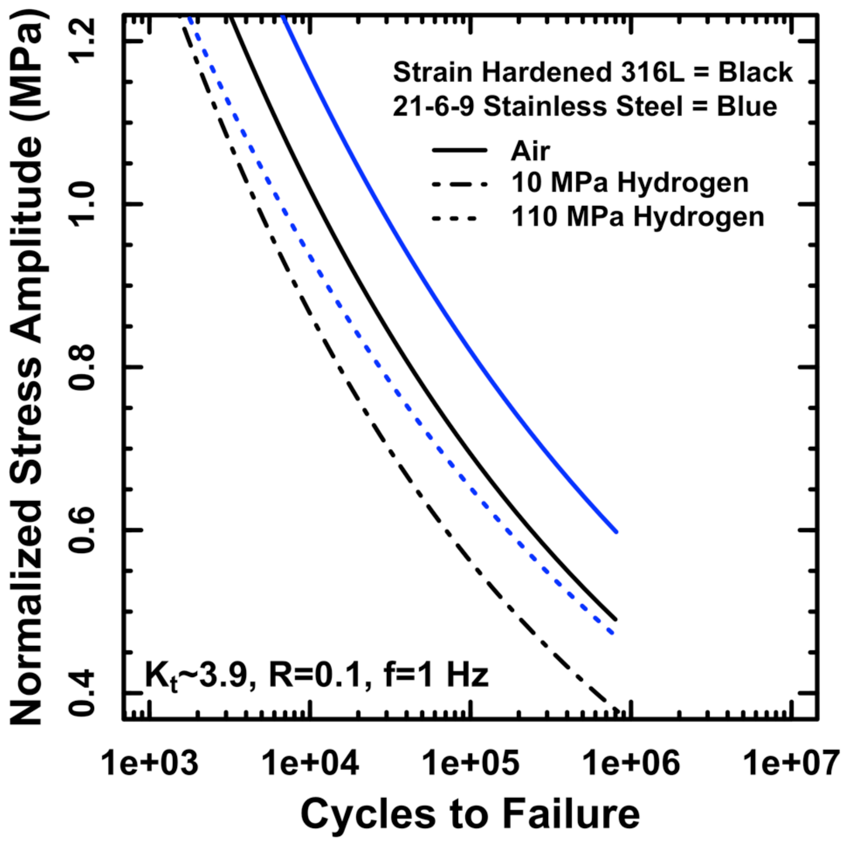
- **Multiplier on *existing safety factor* results in consistent fatigue life in hydrogen**

Anticipated component life >30k cycles





Comparison between alloys



- **21-6-9 demonstrates improved fatigue life compared to hardened 316L**
  - ***YS of annealed 21-6-9 less than YS of strain-hardened 316L***
  - ***Cost of 21-6-9 bar material is ~80% of type 316L bar***

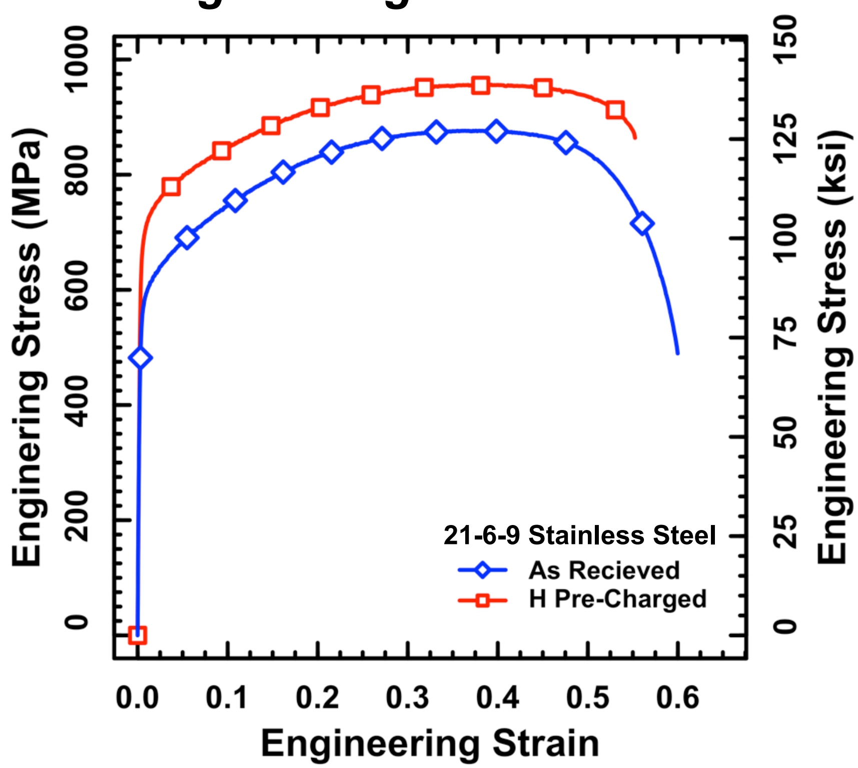
Stress Amplitude Normalization

$$SA_N = \frac{1}{2}\frac{\left(S_{Max} - S_{Min}\right)}{S_{Yield}}\left(1-R\right)$$

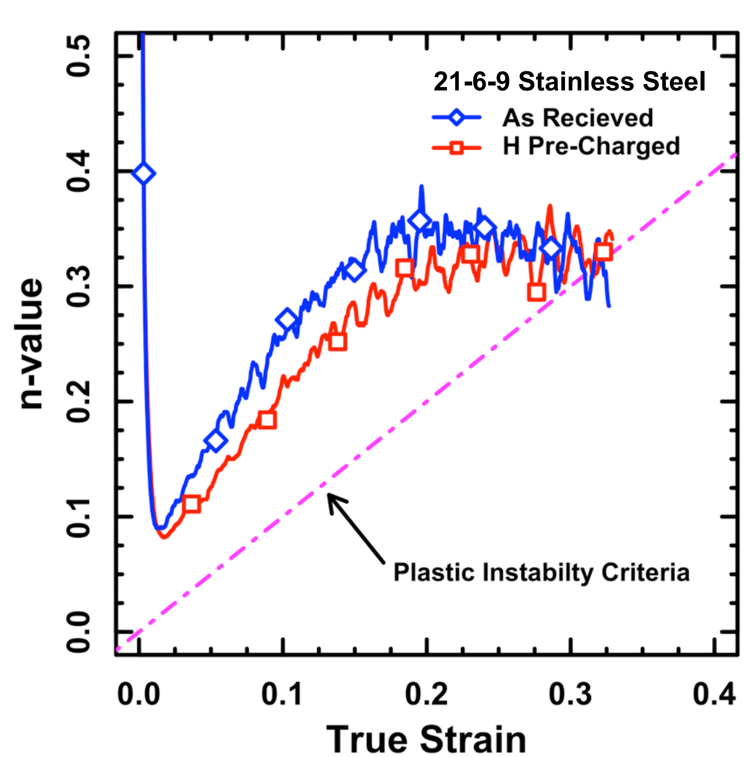
Hydrogen pre-charging to high H-levels changes the quasi-static tensile behavior

- **~5-10% increase in *Yield Strength*, minor change in *Hardening Rate***
- ***May not be representative of in-service properties***

Engineering Stress-Strain



Instantaneous n-value



ASTM E-8 sub-size round samples, 12.7 mm gauge

Safety Factor Multiplier: Internal Hydrogen

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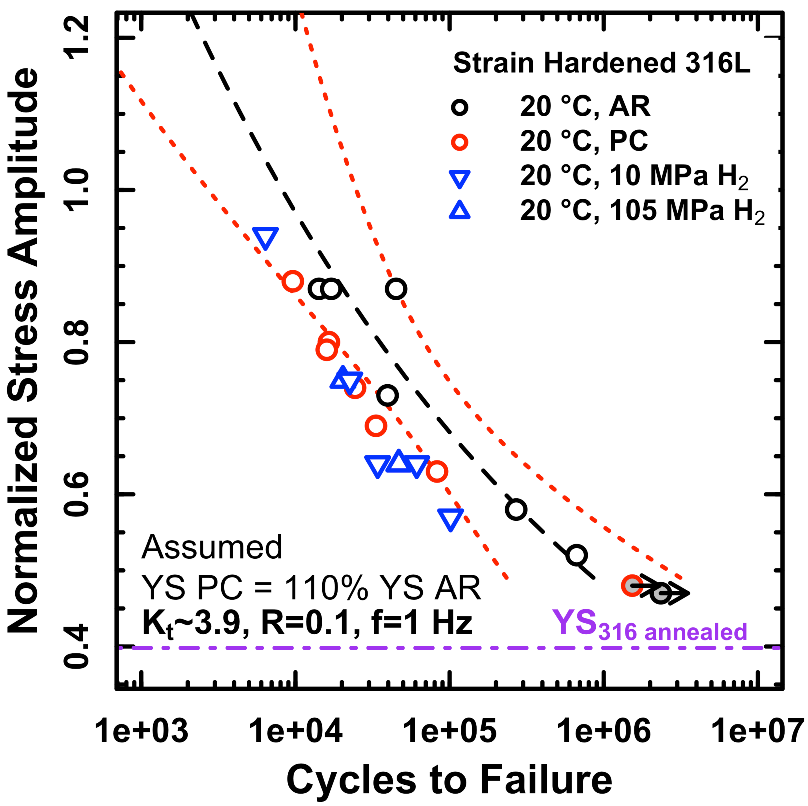
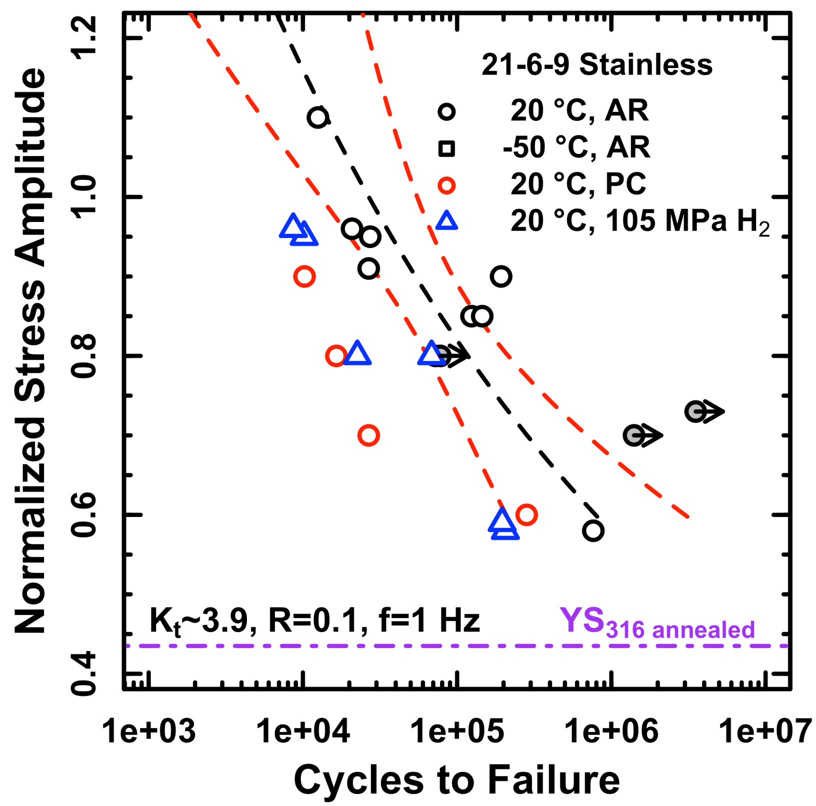
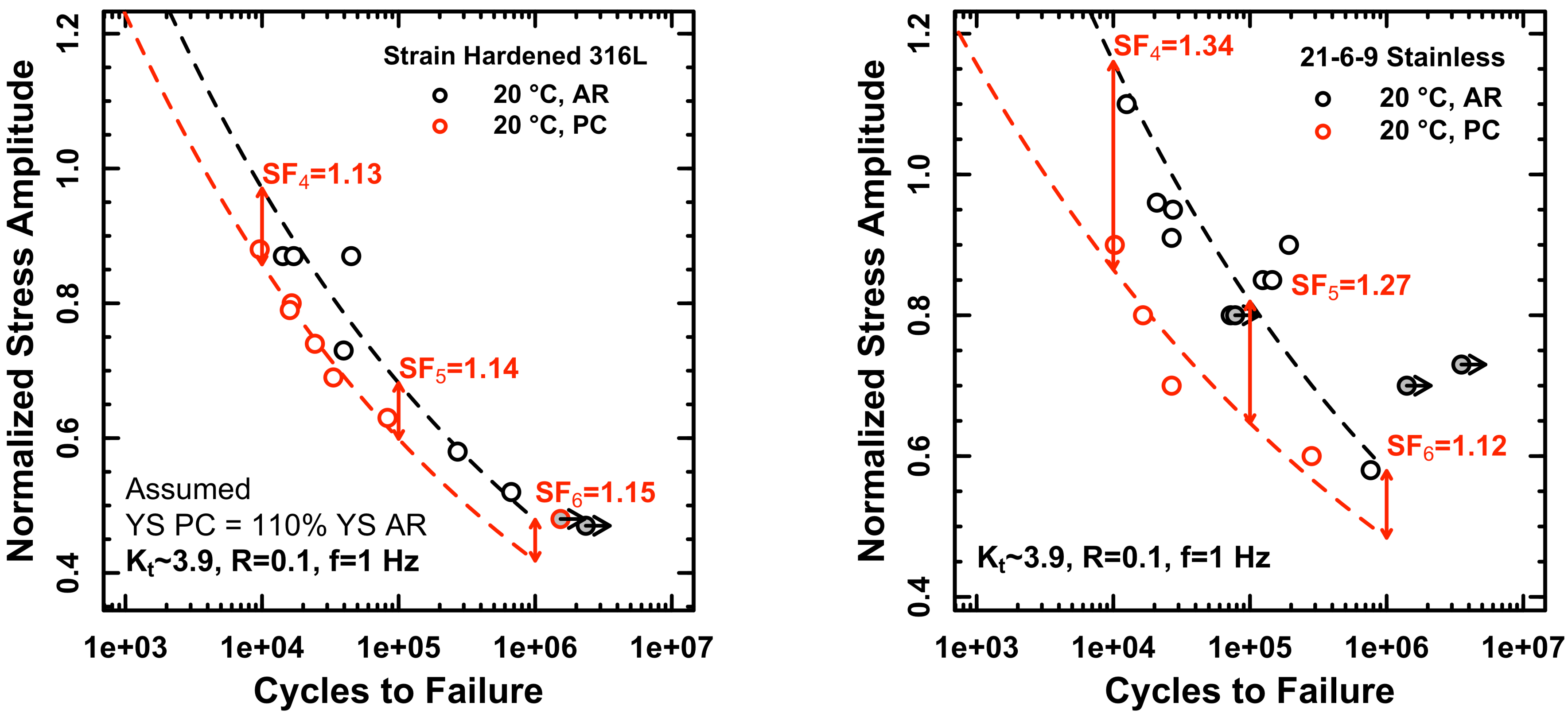
- **Accounting for yield strength increase during thermal pre-charging results in all hydrogen data agreeing**





Safety Factor Multiplier: Internal Hydrogen

- **Safety factor determined using pre-charged samples similar to testing in external hydrogen**



Summary

- **Measurement of hydrogen effects on fatigue life enable materials selection based on relevant performance metric**
  - **Fatigue highlights change in stress-performance not necessarily captured in quasi-static stress-strain data**
- **High-strength austenitic stainless steels offer potential cost *and* weight savings**
  - ***Both 316L and 21-6-9 show measurable fatigue life change in presence of hydrogen (external and internal)***
- **Safety factor multiplier results in equivalent fatigue life for a given criteria in air and hydrogen**
- **Thermally pre-charged samples could be an alternative to testing in external hydrogen if yield strength change accounted for**

Acknowledgements

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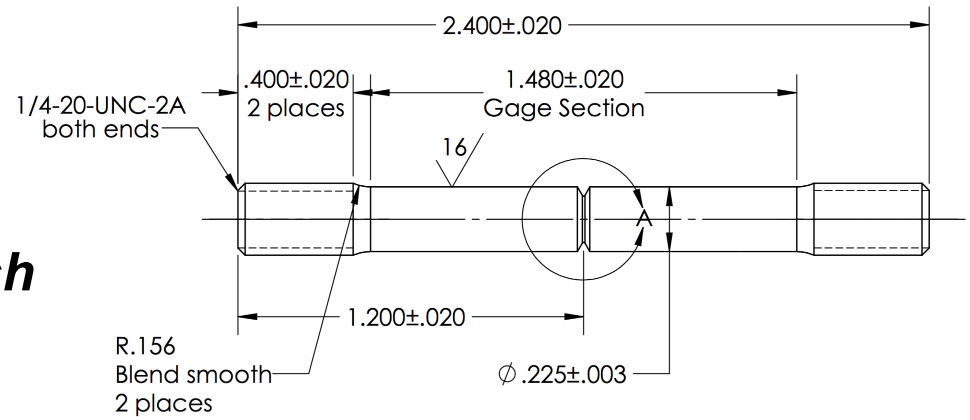
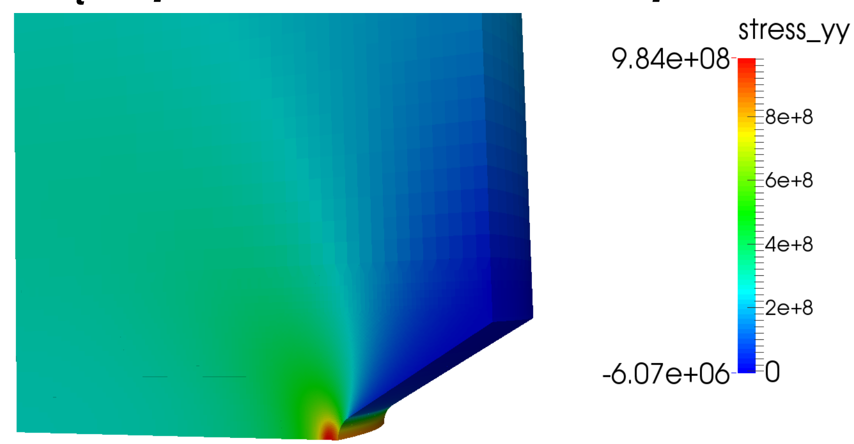
Notched Sample Discussion

- **Relatively straightforward testing**
- ***<u>However</u>*:**
  - ***Difficult to control surface finish of notch (scatter in data, like-like-testing)***
  - ***No analytic solution for K_t (FEM)***
  - ***Notch sensitivity may not be constant (material qualification)***
  - ***Never know how much plasticity is present (artificially 'elastic' stresses) → Notch changes?***
- ***Could smooth samples be tested to avoid these?***



$K_{t,\ elastic}$ ~ 3.9 ***$K_{t,\ elastic\text{-}plastic}$ ~ 2.4***

K_t dependent on stress-amplitude



Estimation of cost and weight reduction

- **Relative component cost is estimated from the relative weight of material and material cost:**
  - ***Weight is determined from required component thickness***
  - ***Cost estimated from price of bar stock***
- **H_2 performance is not limiting use *Yield Strength* for design**

ASME design equation

$$t = \frac{PD}{2(SE + PY)}$$

Material	Relative Material Cost	Yield Strength (MPa)	Relative Weight	Relative Cost Savings
316L	1.0	140	1.0	1.0
CW316L	2	589	0.24	0.52
21-6-9	0.79	539	0.26	0.79
304L	0.84	140	1.0	0.16
CW 21-6-9	1.6	620	0.17	0.73