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Fatigue Life of Austenitic Stainless Steels in Hydrogen Environments

Chris San Marchi

Sandia National Laboratories, Livermore CA

Paul Gibbs

now at *Los Alamos National Laboratory*

Jay Foulk

Sandia National Laboratories

Kevin Nibur

Hy-Performance Materials Testing

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Motivation

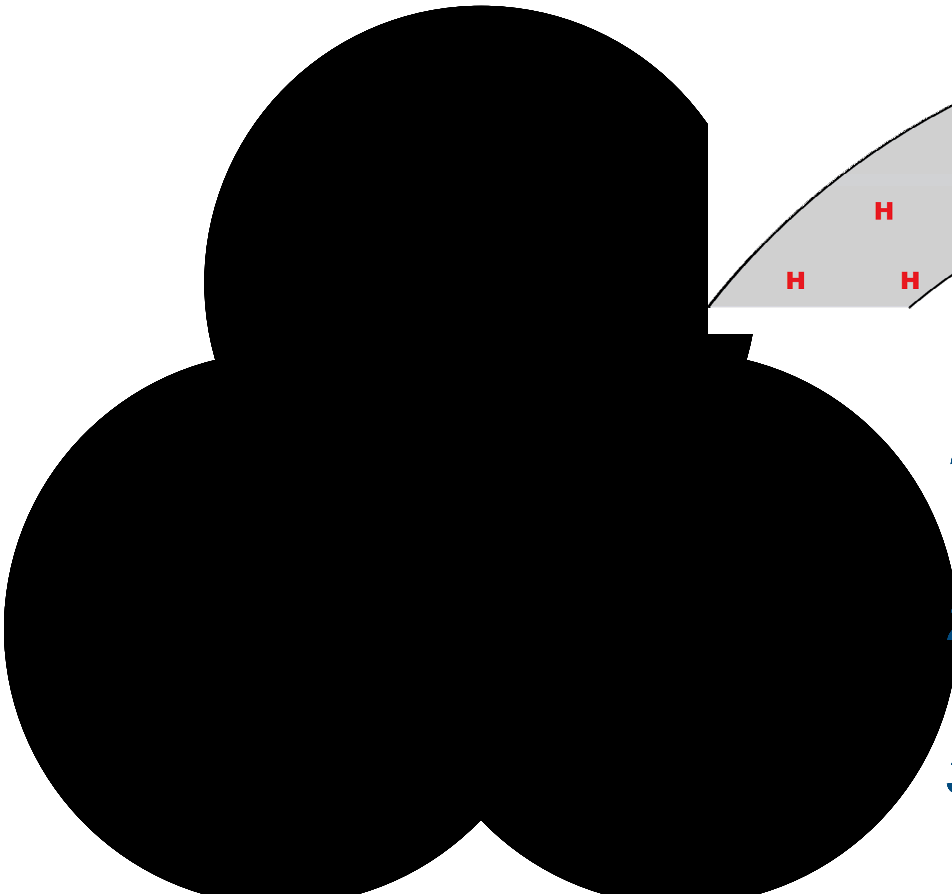
Identify low-cost, light-weight alternatives to annealed type 316L austenitic stainless steels for vehicle applications

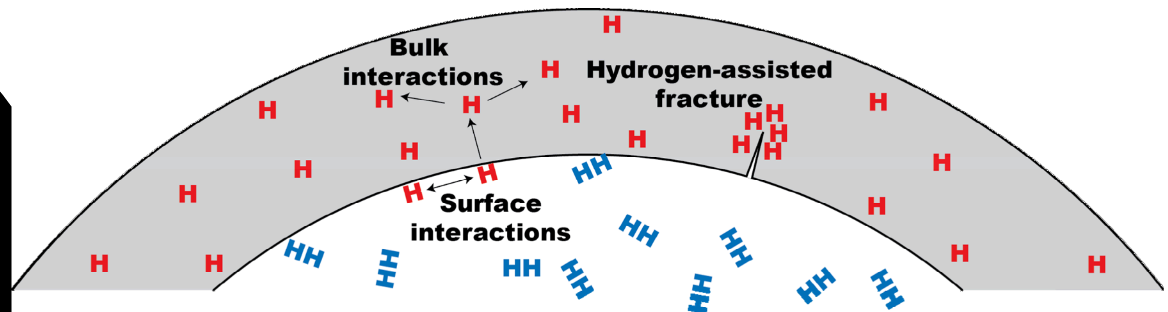
- ***Reduced nickel*** **content is prime candidate for** ***cost reduction***
- ***High-strength*** **is prime candidate for** ***weight reduction***
  - ***Less material*** **also reduces cost**

Methodology:

- **Evaluate fatigue life of commercial austenitic stainless steels in hydrogen environments**
  - **Benchmark existing "standard": annealed type 316L**
  - **Evaluate alloys with low-nickel content and in high-strength conditions**
  - **Compare hydrogen-precharging with testing in gas**

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





1) *Hydrogen-surface interactions*
    - *Adsorption and dissociation*
2) *Bulk metal-hydrogen interactions*
    - *Diffusion and trapping*
3) *Hydrogen-assisted cracking*
    - *Deformation and fracture*

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

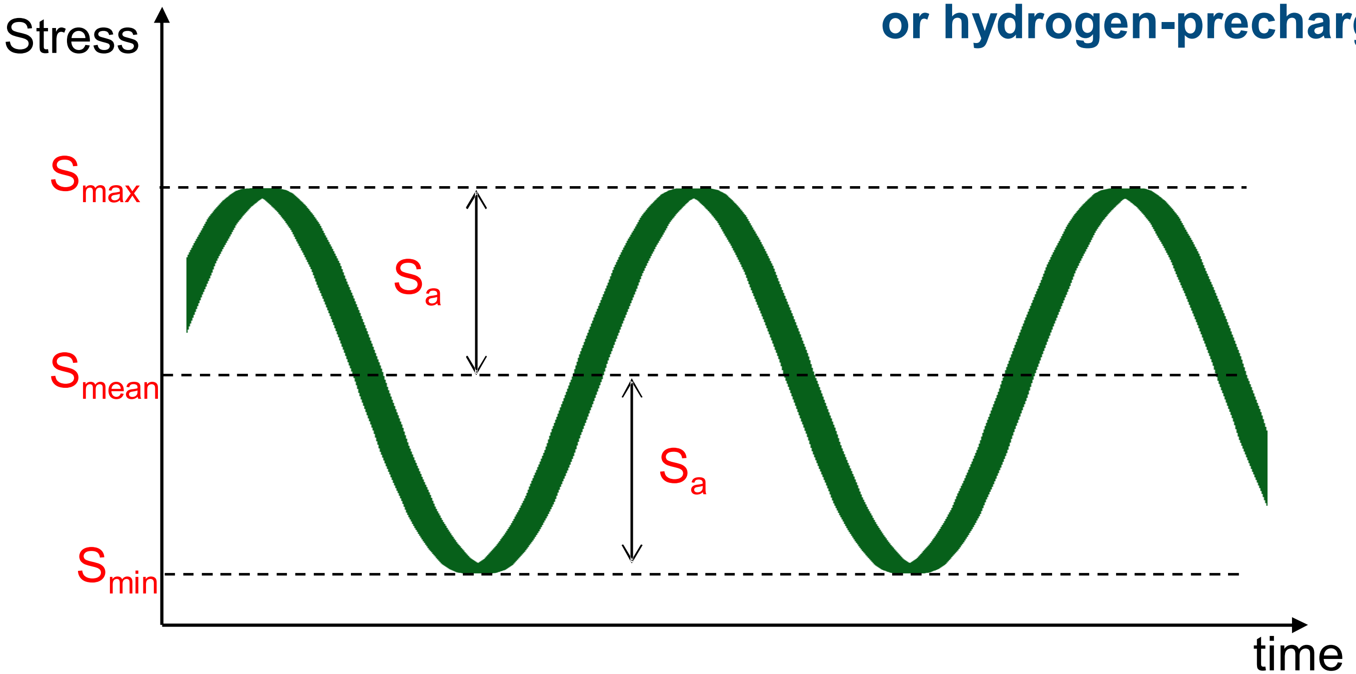
Mechanics: fatigue life methodology to assesses design-relevant performance

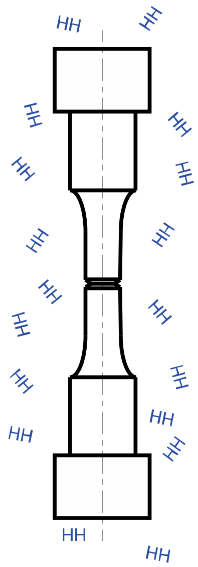
Conventional fatigue life testing

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

Hydrogen fatigue life testing

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

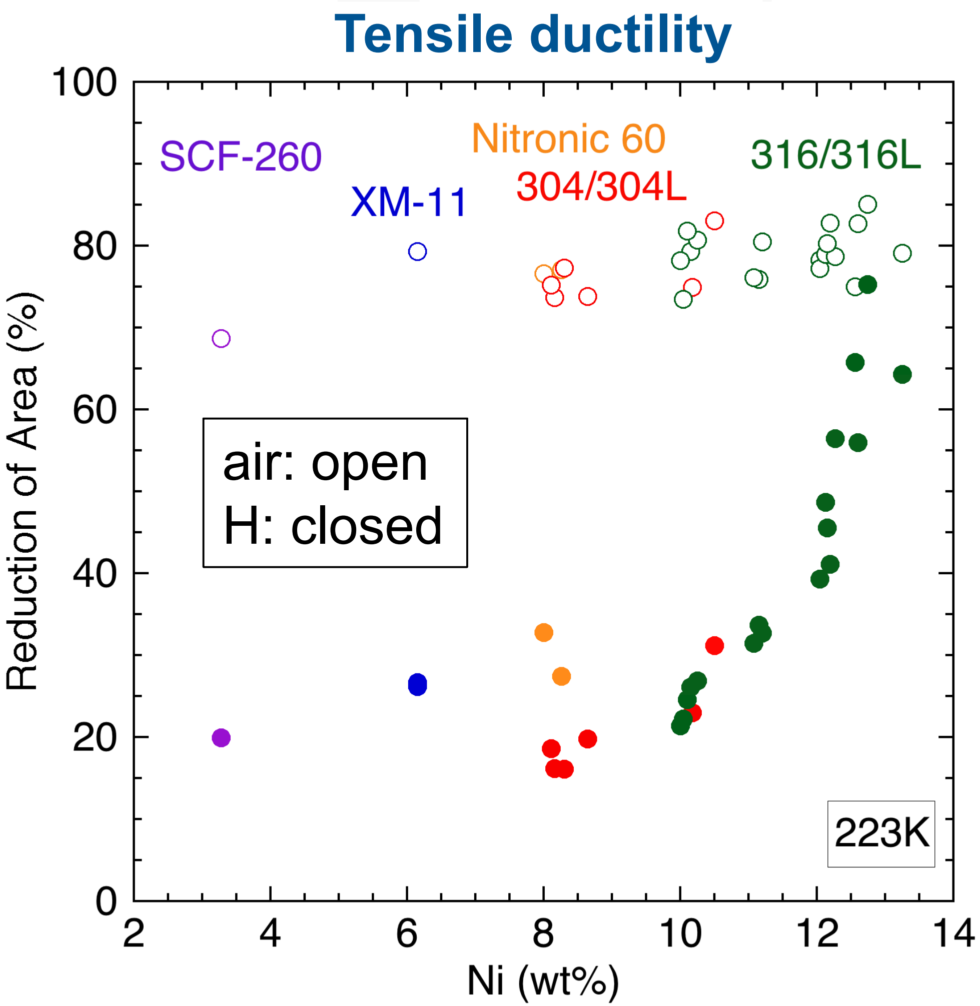




$R = S_{min} / S_{max}$

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

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

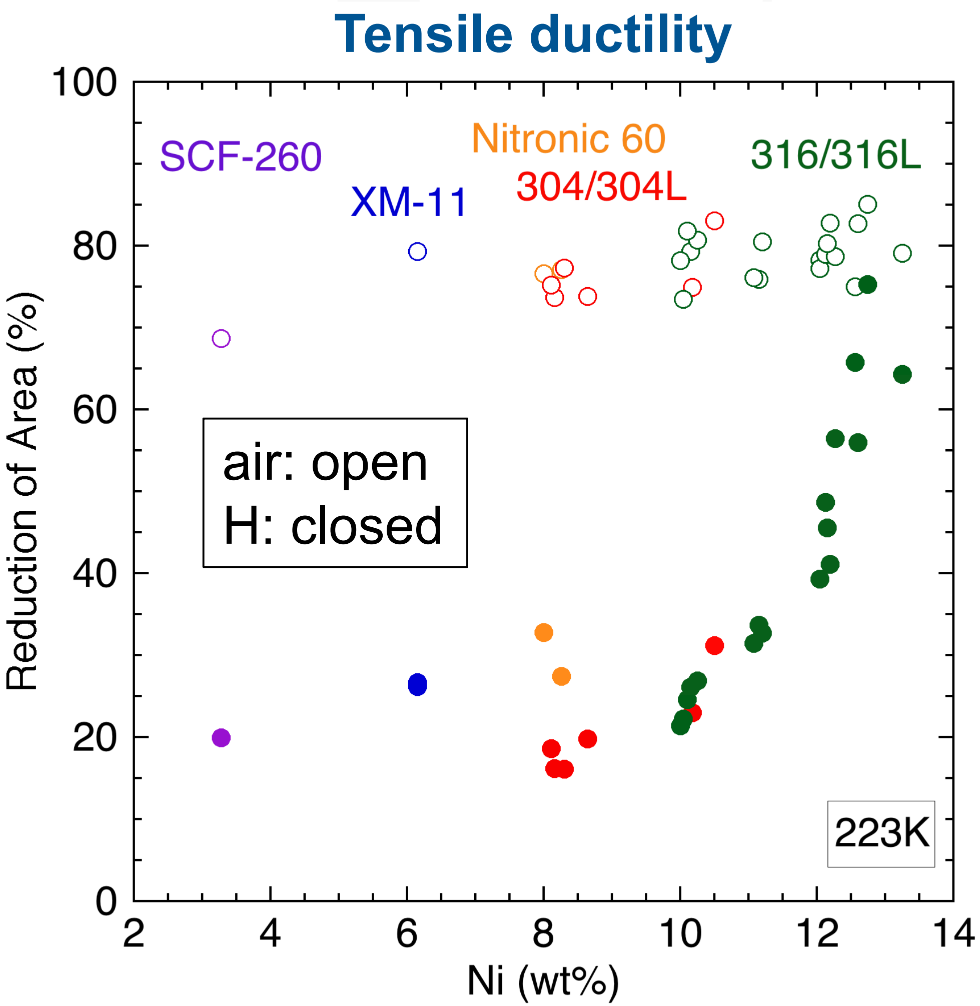


- **Strength properties are generally not affected by hydrogen**
- **Relative tensile ductility is used in the literature as a metric for performance in hydrogen**

However

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

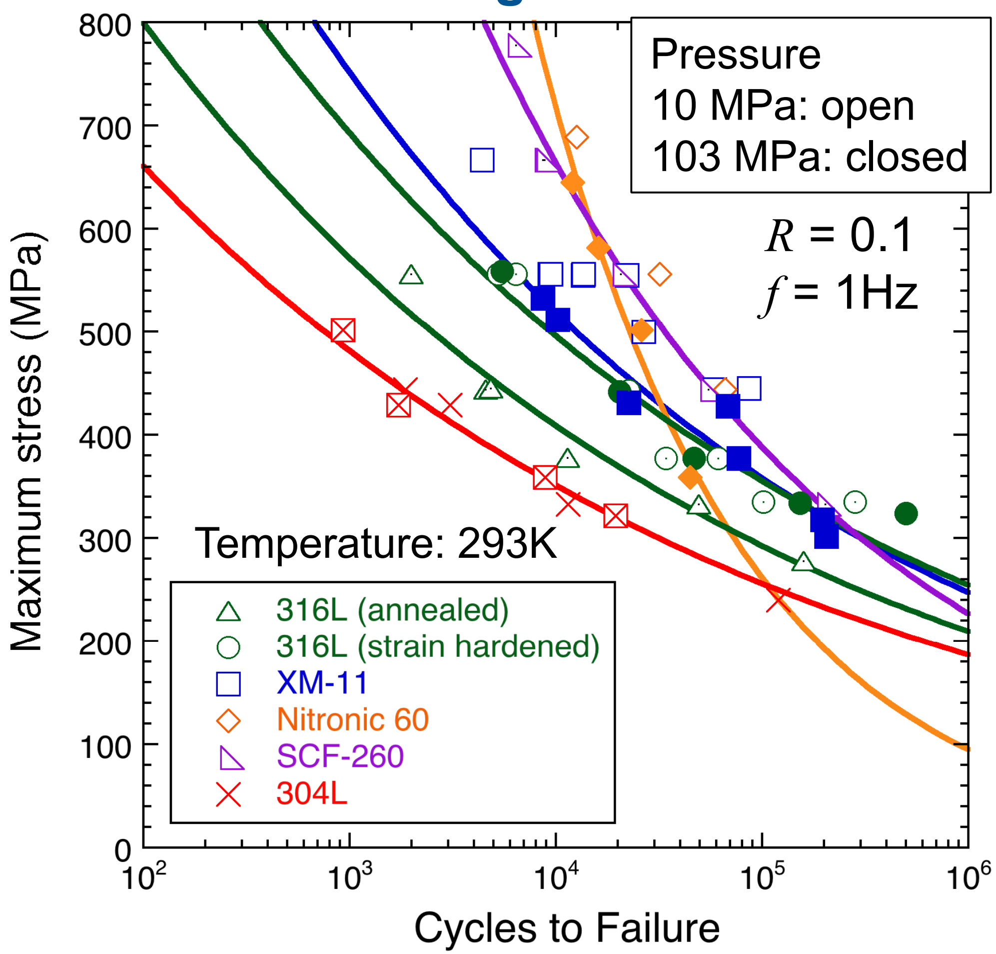
Hydrogen effects are naively correlated with nickel content or nickel equivalent in tensile tests



- 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

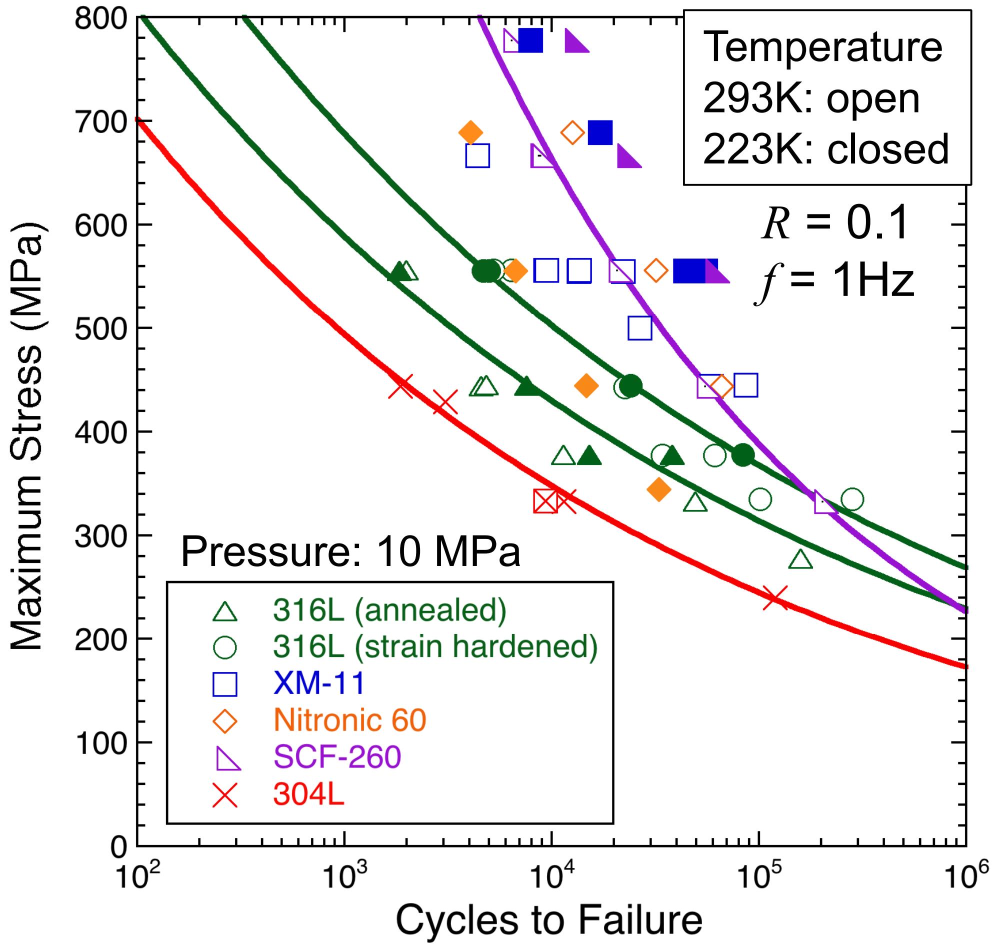
Fatigue life



- **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 most austenitic stainless steels**
- **Nitronic 60 may be an exception**

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

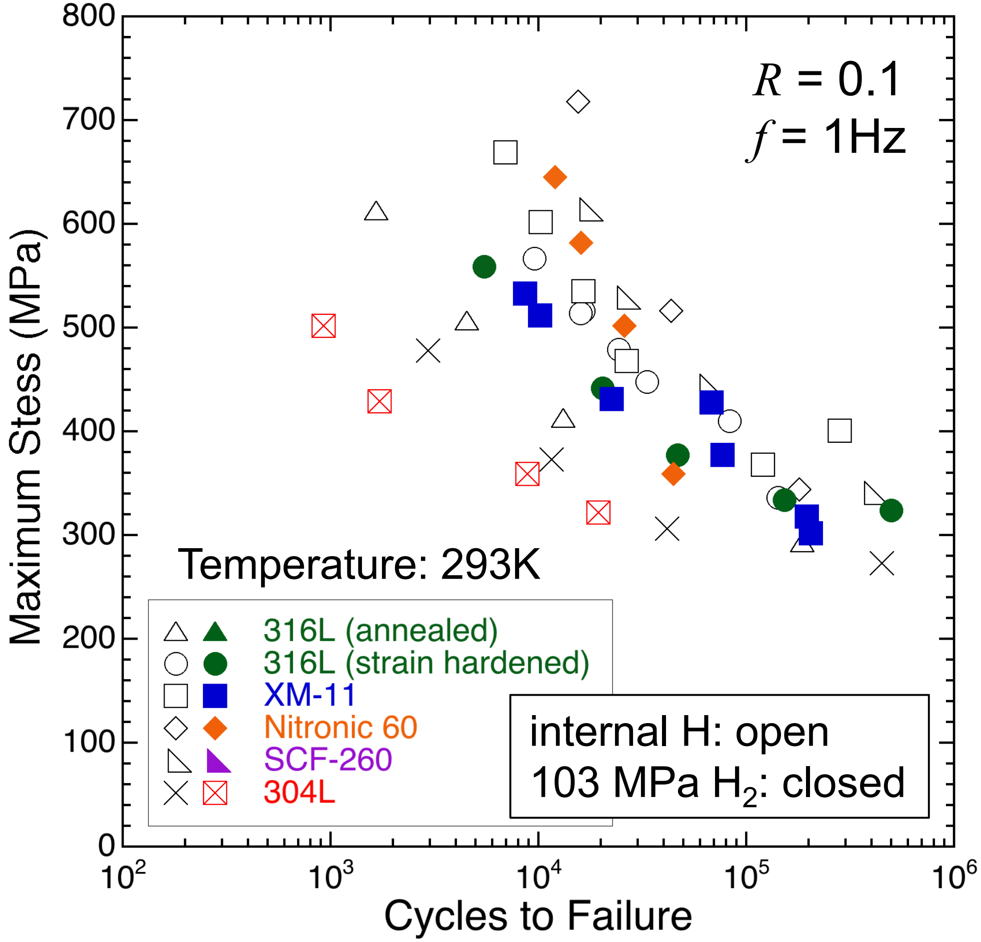
Fatigue life



- **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



- **Superficially internal H improves fatigue life**

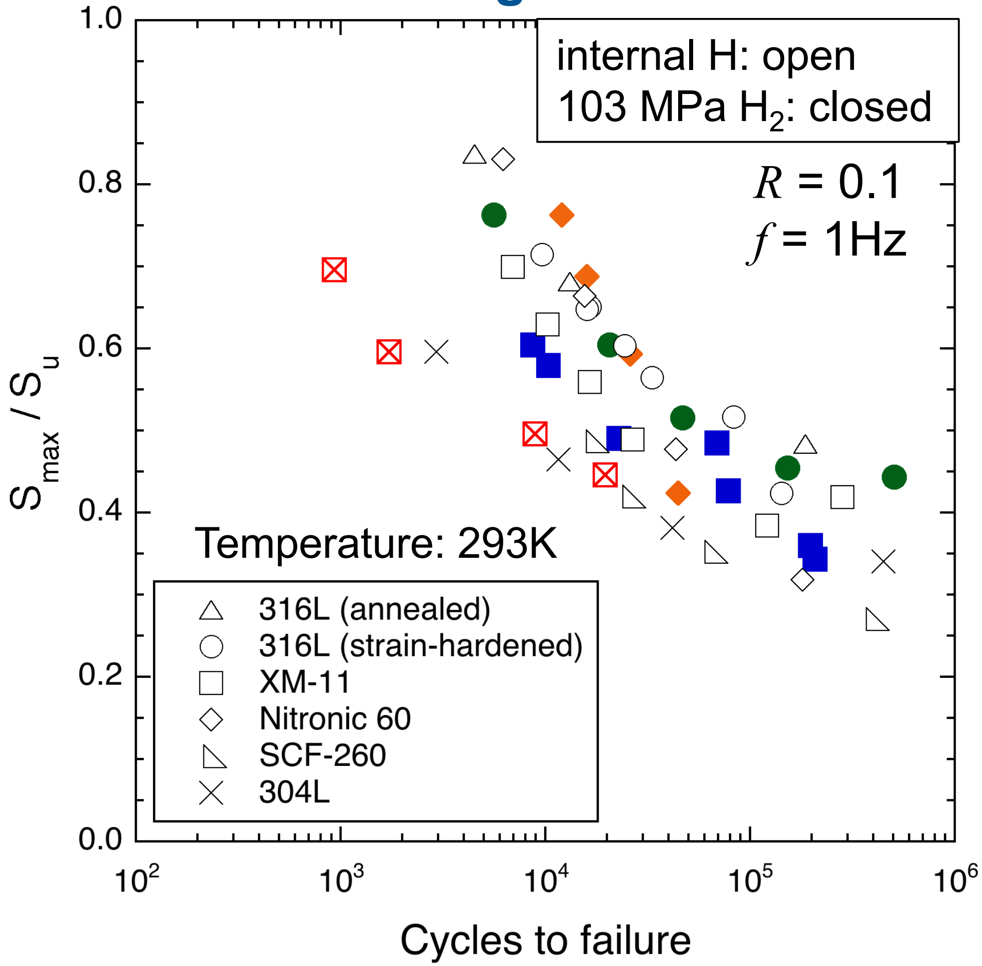
However

- **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

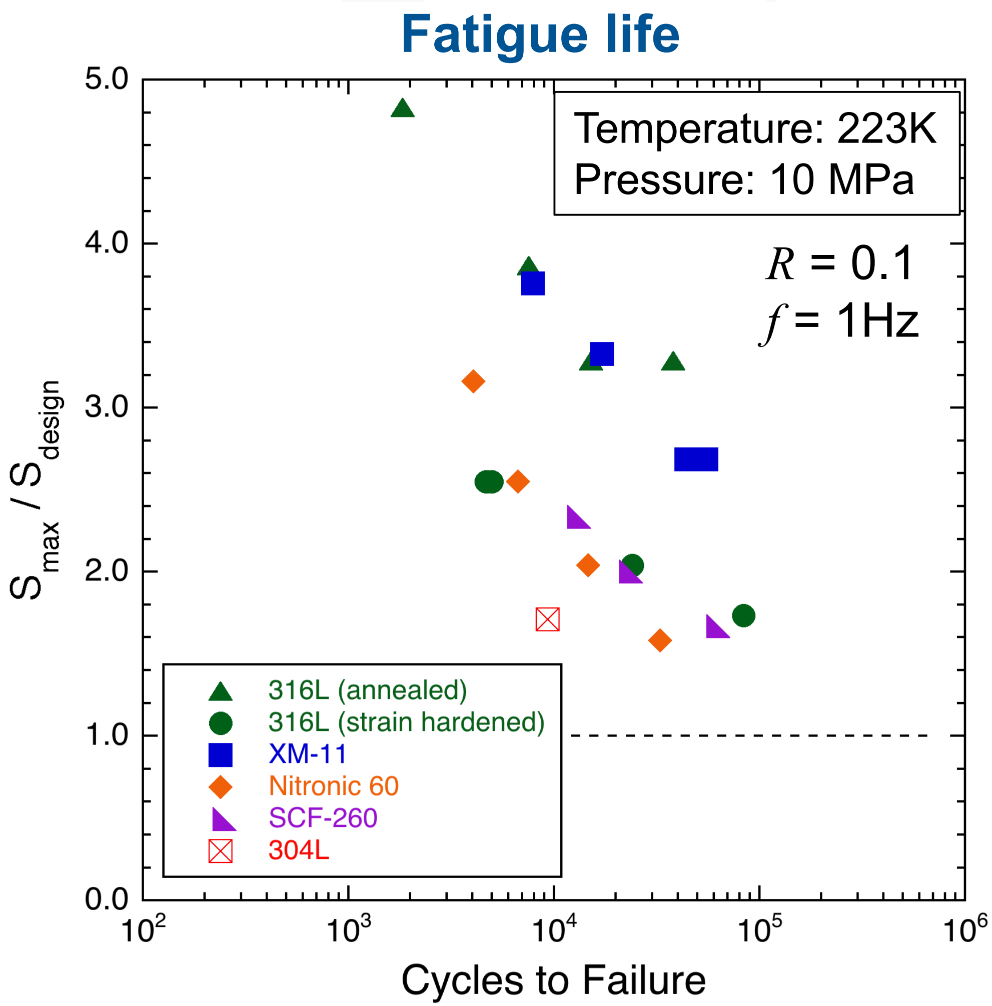
Fatigue life



- **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

Normalization of fatigue stress by allowable stress enables comparison of alloys

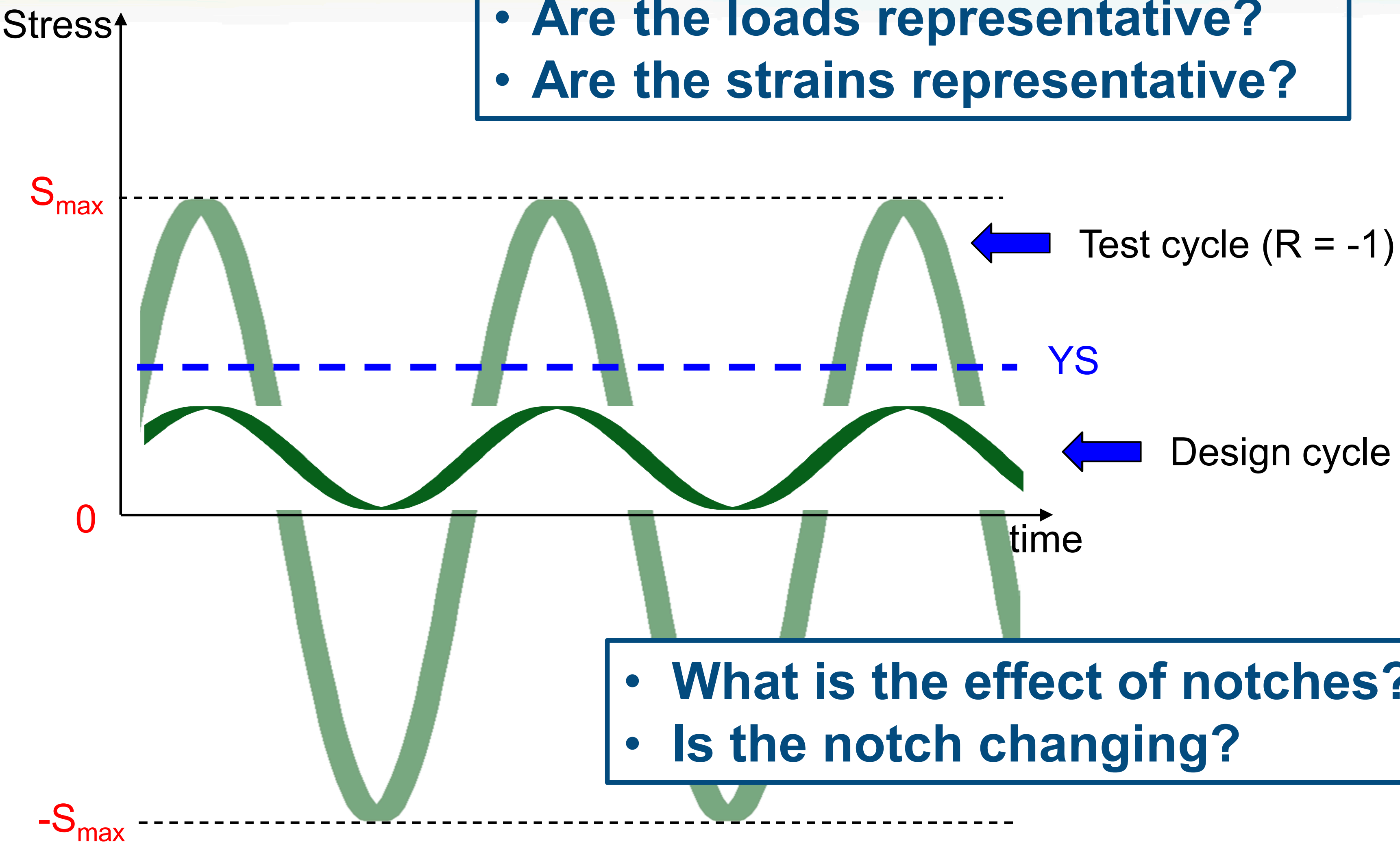


material	Typical allowable stress (MPa)
316L	115
CW 316L	218
304L	195
XM-11	207
Nitronic 60	218
SCF-260	333

For exceptional vehicle lifetimes (10,000 cycles), large safety factors exist

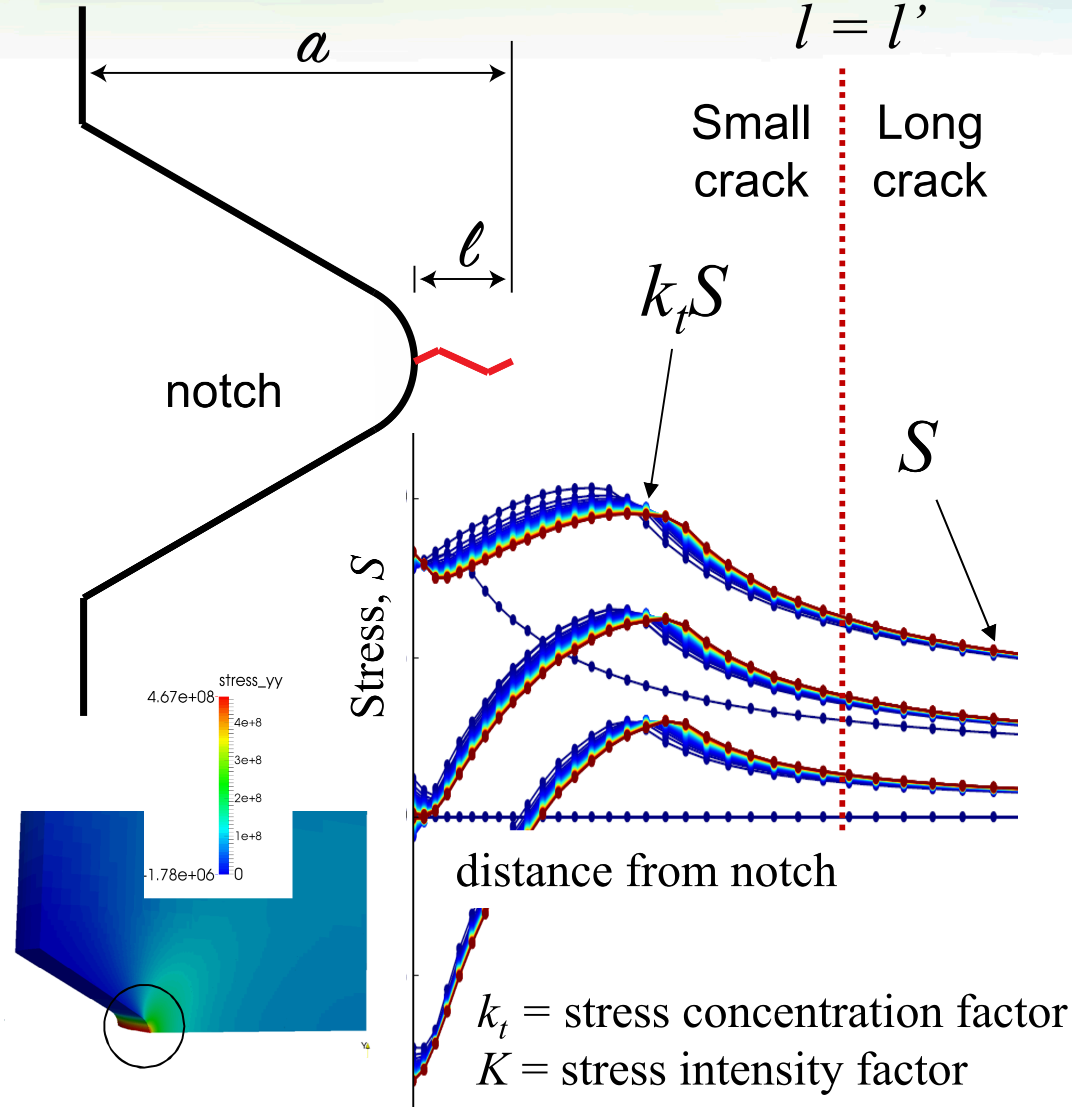
How does the test cycle compare to the design cycle?

- Are the loads representative?
- Are the strains representative?



- What is the effect of notches?
- Is the notch changing?

Notch has important implications on the cracking process



Small crack behavior

- Small ***l***
- $K \propto (k_t S)\, l^{1/2}$
- **Dominated by stress concentration**
- **Dominates total life**

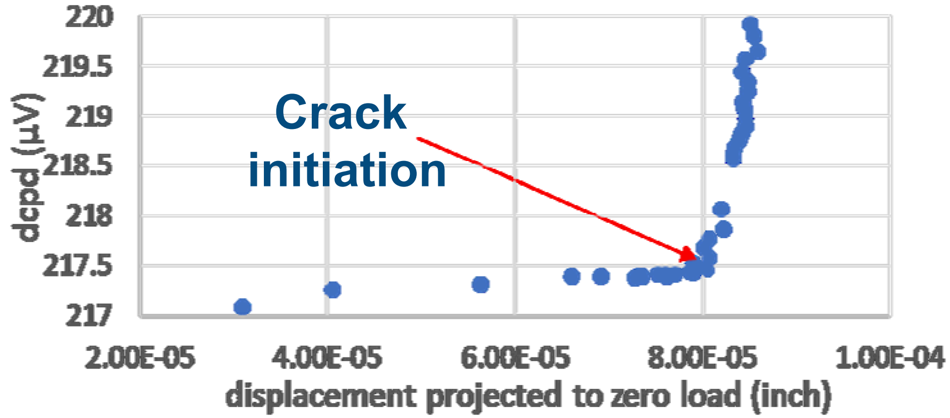
Long crack behavior

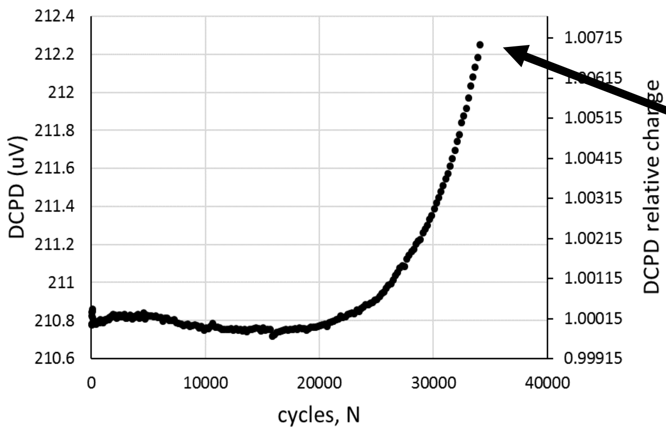
- Large ***l***
- $K \propto S\, a^{1/2}$
- **Dominated by crack length**

Small crack behavior is difficult to characterize and to generalize

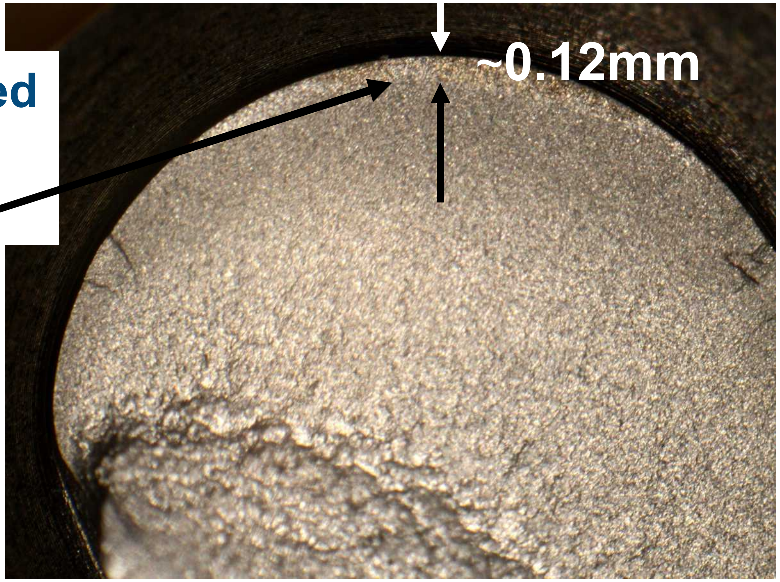
Crack initiation and growth during fatigue is identified using direct current potential difference (DCPD)

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



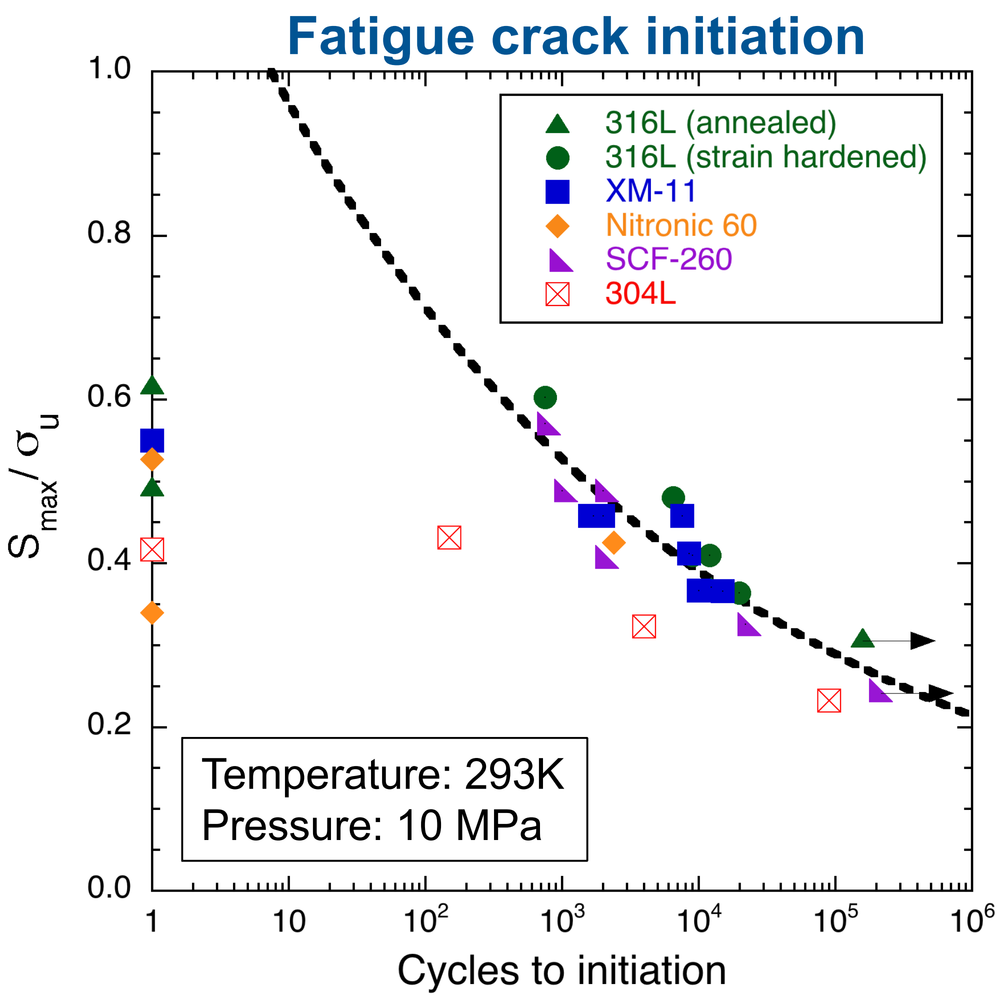


Test interrupted and then heat tinted



Crack lengths <10μm can be resolved with DCPD

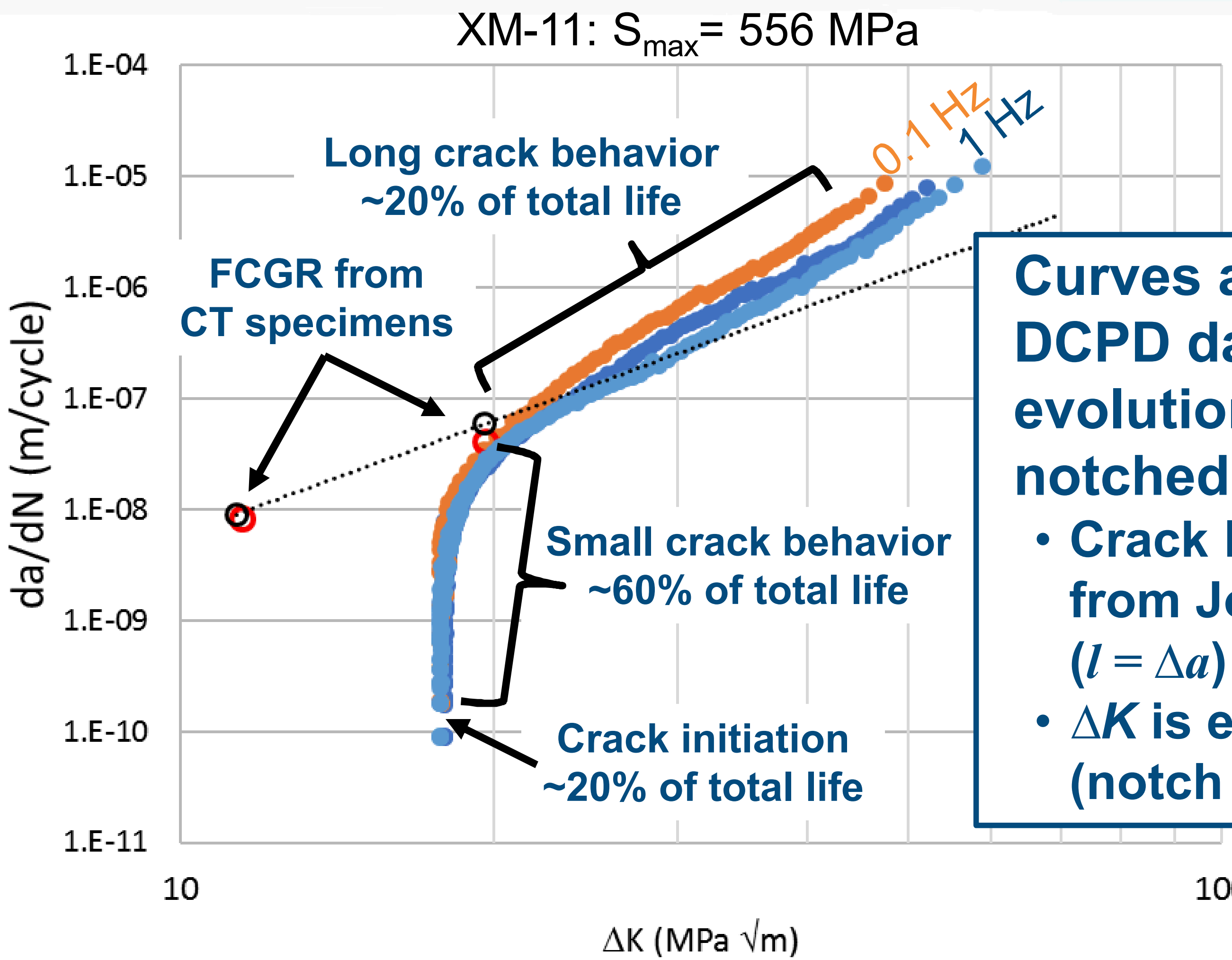
Crack initiation is relatively reproducible and consistent among materials



- **For evaluating crack initiation stress is normalized by the true tensile strength (stress at tensile instability)**
  - **Incorporates both stress and strain-hardening characteristics**
- **With the exception of 304L, data collapses to signal curve**
- **Critical stress where cracks initiate at first cycle**

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

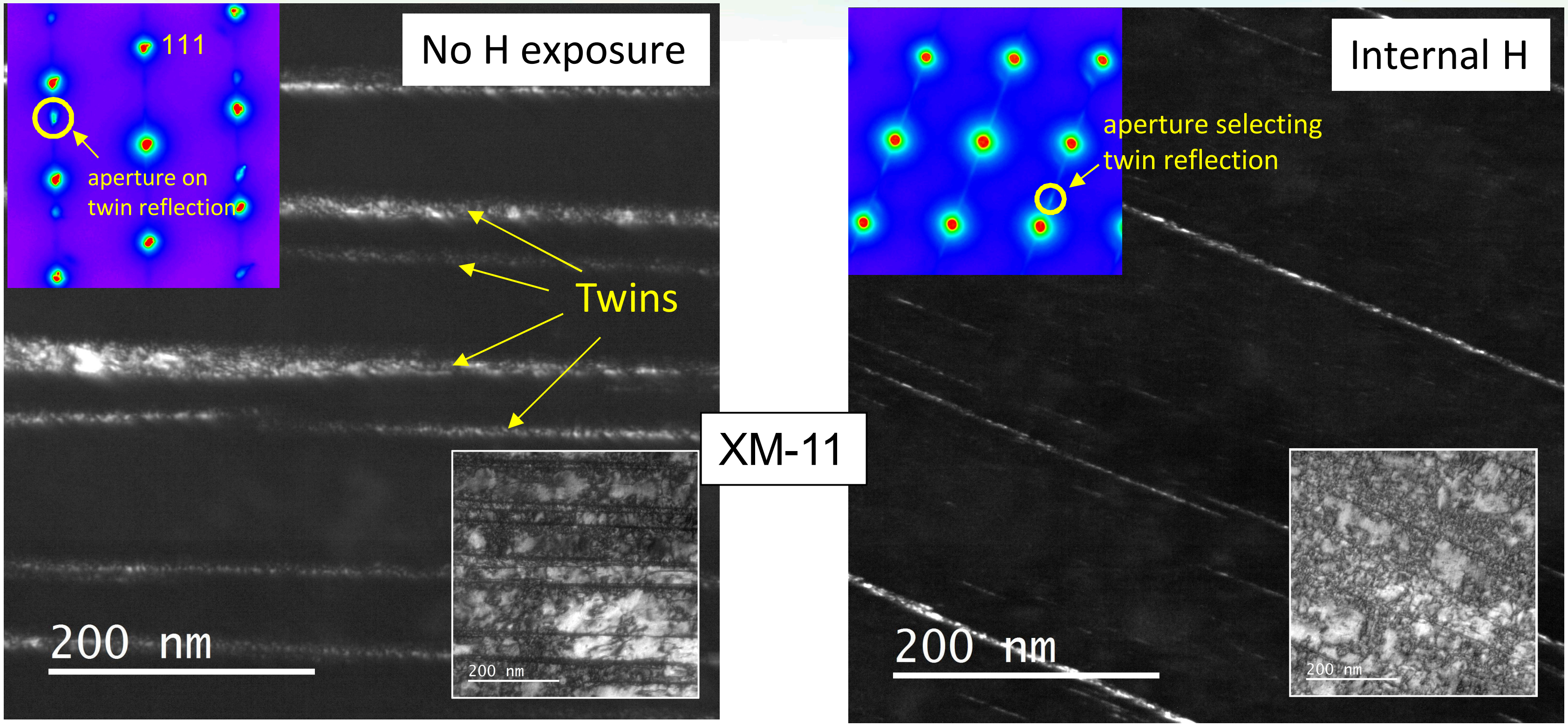
Fatigue crack growth rate can be determined from notched specimens



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

- Crack length is estimated from Johnson's equation ($l = \Delta a$)
- ΔK is estimated based on a (notch depth + crack length)

Mechanistic understanding of microstructural evolution is needed to develop micromechanical models of fatigue



- Preliminary evaluation suggests hydrogen “sharpens” twins, which may have significant effects on crack initiation
- No evidence of strain-induced martensite

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
  - Fatigue crack in notch interacts with stress field
  - DCPD can be used to monitor cracking process and shows stabilization of small cracks