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Fatigue crack initiation and fatigue life testing of high-strength austenitic stainless steel tubing with internal hydrogen (PVP2023-106413)

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he national interest

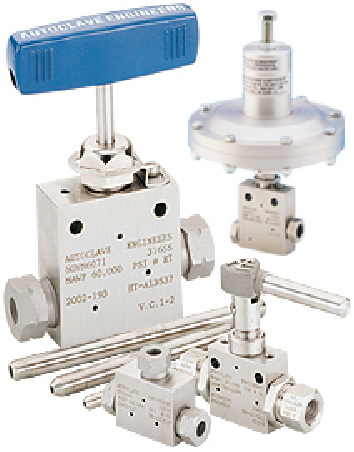
Hydrogen technologies include diverse range of operations

Hydrogen delivery

- **hydrogen pipelines: carbon steels**
- **Challenge: cyclic pressure**

Hydrogen storage

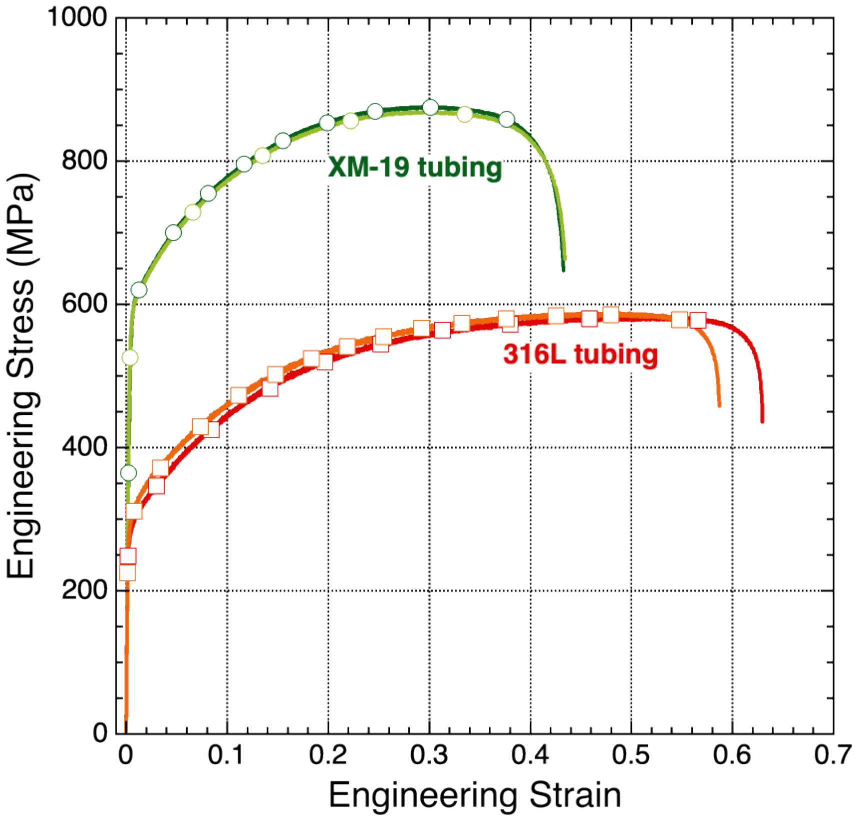
- **hydrogen forklifts: Cr-Mo ferritic steels**
- **Challenge: filling ~6/day**



Pressure manifold components

- **Valves, tubing, and other devices: *<u>austenitic stainless steels</u>***
- **Challenges: low temperature, lower-cost alternatives (e.g., aluminum or *<u>higher strength</u>*), alloy content, welding**

High-strength austenitic stainless steel tubing: XM-19



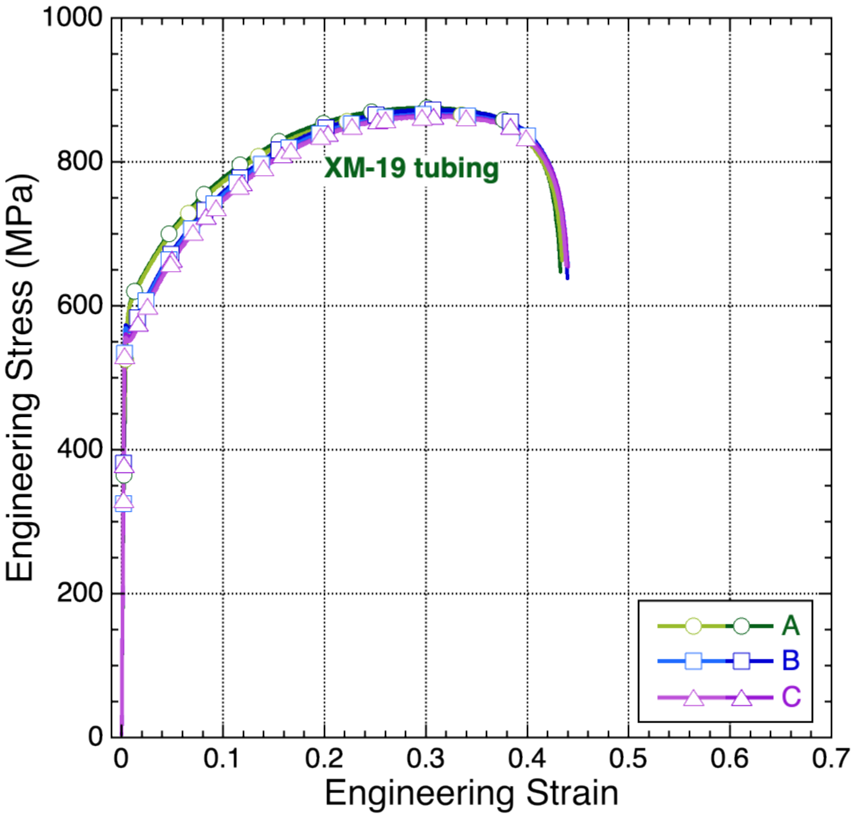
XM-19 / Nitronic 50 / 22 Cr – 13 Ni – 5 Mn						
Fe	Cr	Ni	Mn	Mo	C	N
Bal	22.0	13.1	5.3	2.1	0.015	0.32

XM-19 tubing

- 6 mm OD
- 3.6 mm ID
- Yield strength: 566 MPa
- Elongation to failure: >40%

Annealed XM-19 tubing displays yield strength almost 2X of annealed 316L tubing

XM-19 tubing has a stable microstructure



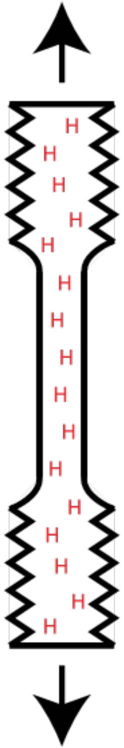
Consider the potential effects of processing-driven thermal cycles on XM-19 tubing

1. **Condition A –** as received (solution-annealed condition)
2. **Condition B –** 1050˚C exposure
3. **Condition C –** condition B + second 1050˚C exposure

Thermal exposure (1050˚C) does not significantly change the strength of the XM-19 tubing: <1% change of yield strength

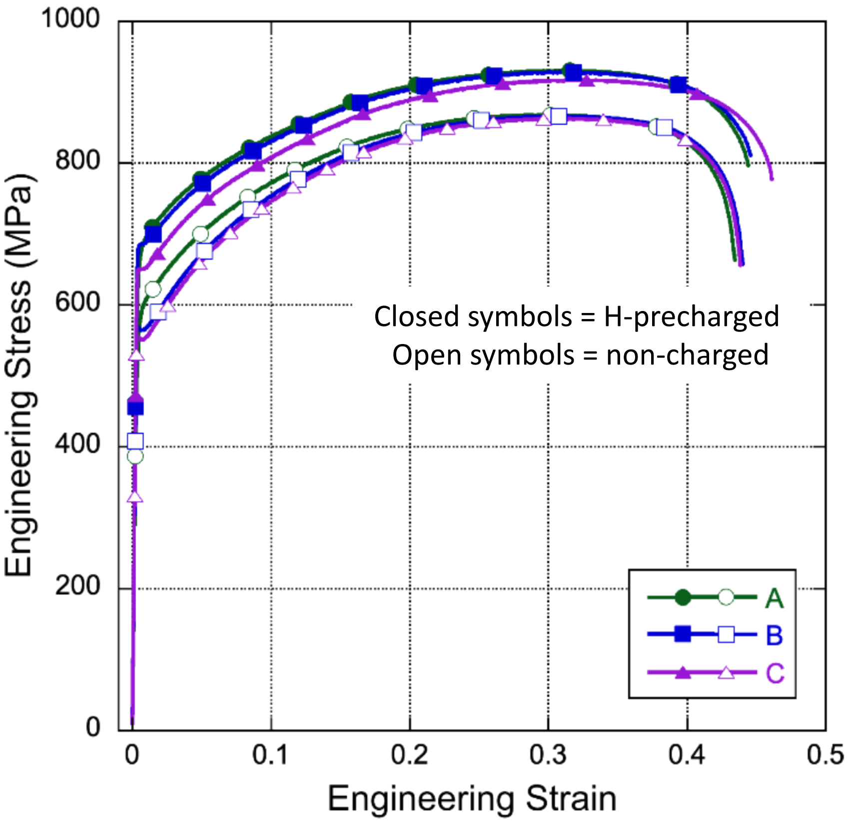
Thermal hydrogen-precharging is an effective way to simulate hydrogen-assisted fracture

- **Thermal H-precharging**
  - **Exposure to gaseous H_2 until saturated with H**
    - **Time = ~10 days**
    - **Pressure = 1,380 bar (20,000 psi)**
    - **Temperature = 300˚C**
  - **Hydrogen content ~ 210 to 220 wt ppm**
    - ***Note*: concentration is alloy dependent (304/316 = ~140 wt ppm for same conditions)**
- **Testing is conducted in air after H-precharging**



See PVP2023-106086 for more details and comparison between testing with internal H and testing in external H_2 (in situ)

Internal hydrogen provides strengthening (10-20%)



Internal H has modest effect on tensile properties

- **H concentration:** 210-220 wt ppm
- **Yield strength:** ~20% increase
- **Tensile strength:** ~10% increase
- **Elongation:** effectively unchanged

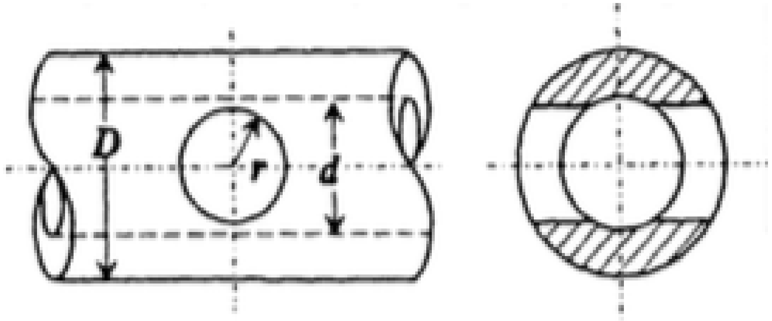
Internal H does not degrade tensile properties for the conditions considered in this study

Previous work on forged XM-19 shows some degradation of properties:

- *J Pressure Vessel Technol* **130** (2008) 041401
- *Metall Mater Trans* **41A** (2010) 3348

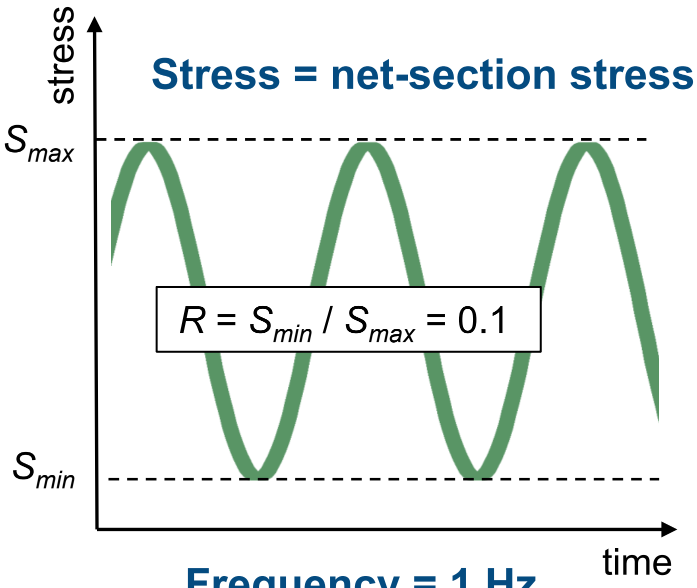
Stress concentration is used to facilitate fatigue life testing

Transverse circular hole in tube

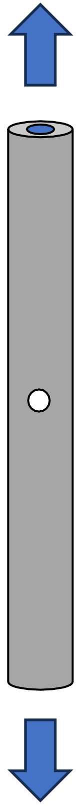


XM-19 tubing

- 6 mm OD
- 3.6 mm ID
- 1.7 mm hole diameter
- $K_t = 4$
  (relative to net section)

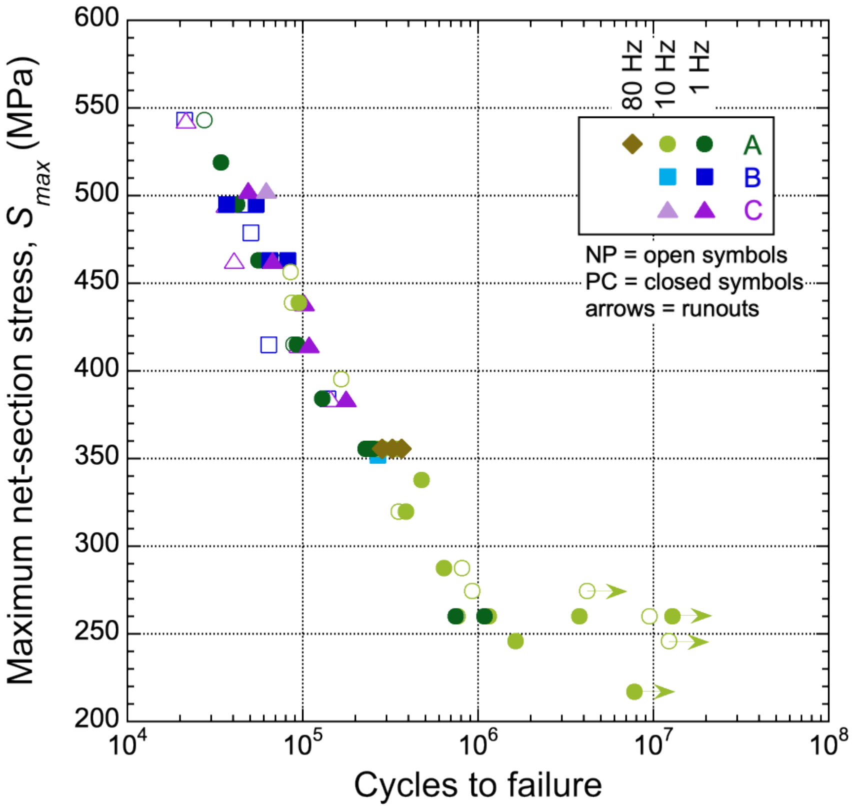


Frequency = 1 Hz
(a few tests at 10 & 80 Hz)



Test configuration is intended to be analogous to fatigue testing of circumferentially notched round bar

Fatigue life of XM-19 tubing shows consistent trends

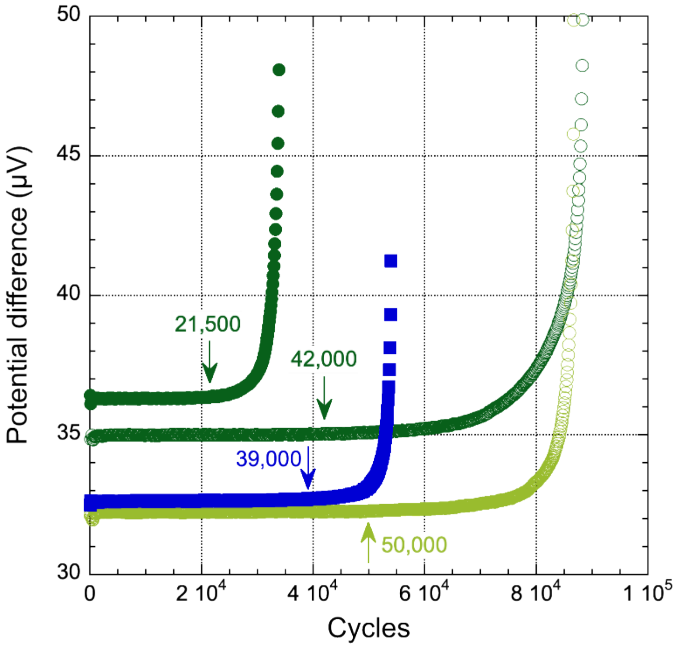


- **Cycles to failure of XM-19 tubing is essentially unchanged by the incorporation of internal H**
  - **Can be represented by simple power law**

$$N_f = 1.29x10^{18}(S_{max})^{-5}$$

- **Although data is limited, higher frequency did not change fatigue life with or without internal H**
  - **Higher frequency (up to 80 Hz) may aid acceleration of future testing**
  - **It remains unclear if frequency will be effective for materials that are more susceptible to hydrogen-assisted fatigue**

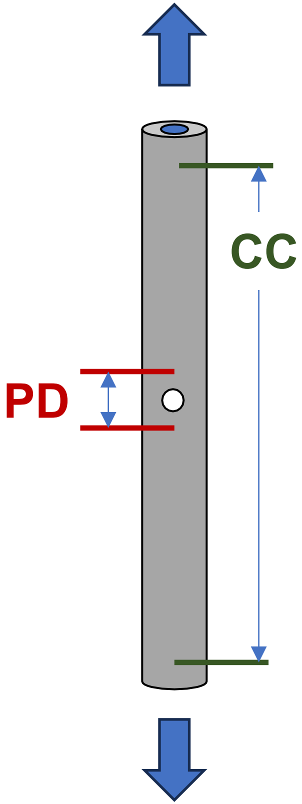
Crack initiation is monitored by DCPD



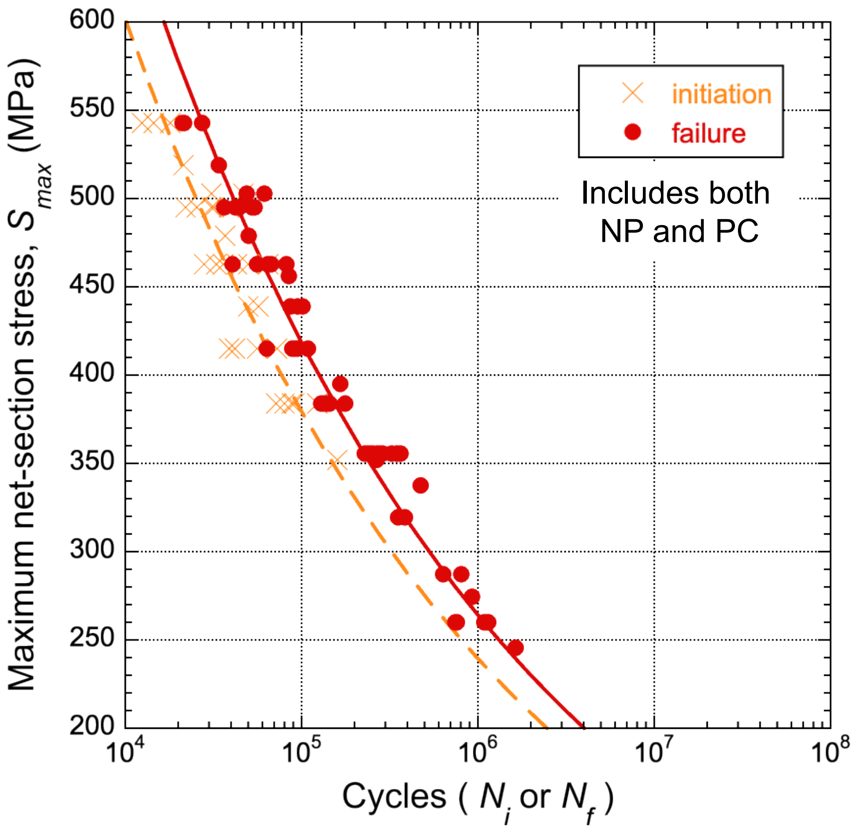
Crack initiation determined at inflection in PD-N curve

Direct current potential difference (DCPD) method

- Constant current (CC) applied near ends
  - Wire leads welded to cotter pins
  - Typically 1 A
- Potential difference (PD) monitored near stress concentration
  - Wire leads spot welded either side of hole but 180˚ apart
  - Measured in μV range



Crack initiation nominally follows stress response of failure



- **Crack initiation both with and without internal H can be represented by a simple power law**

$$N_i = 7.91x10^{17}(S_{max})^{-5}$$

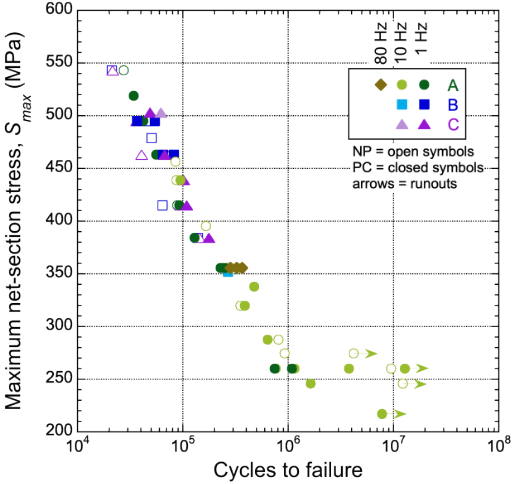
- **No obvious effective of frequency (although limited data)**
- **Since the power-law exponent is the same for initiation and failure, cycles to crack <u>initiation</u> can be idealized as a constant fraction of cycles to <u>failure:</u>**

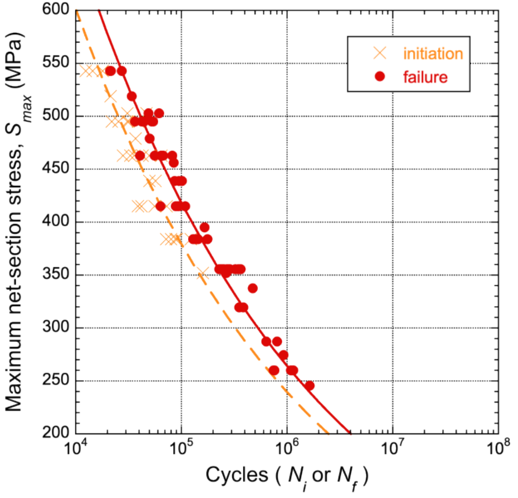
$$N_i = 0.613\, N_f$$

Summary

- **The transverse circular hole geometry and hydrogen precharging enabled evaluation of hydrogen effects on fatigue life of XM-19 tubing**
  - **Tension-tension, notched fatigue**
- **Crack initiation was also evaluated by instrumenting specimens for DCPD measurements**

Results:
- **Internal H had virtually no effect on fatigue life for tested conditions**
- **Cracks initiated at transverse hole at a constant fraction of cycles to failure**





Thank You!

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https://h-mat.org/

https://www.sandia.gov/matlsTechRef/

https://granta-mi.sandia.gov/

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