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Comparison of Stainless Steels for High-Pressure Hydrogen Service

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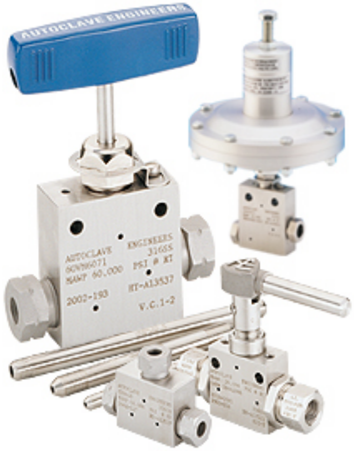
Motivation

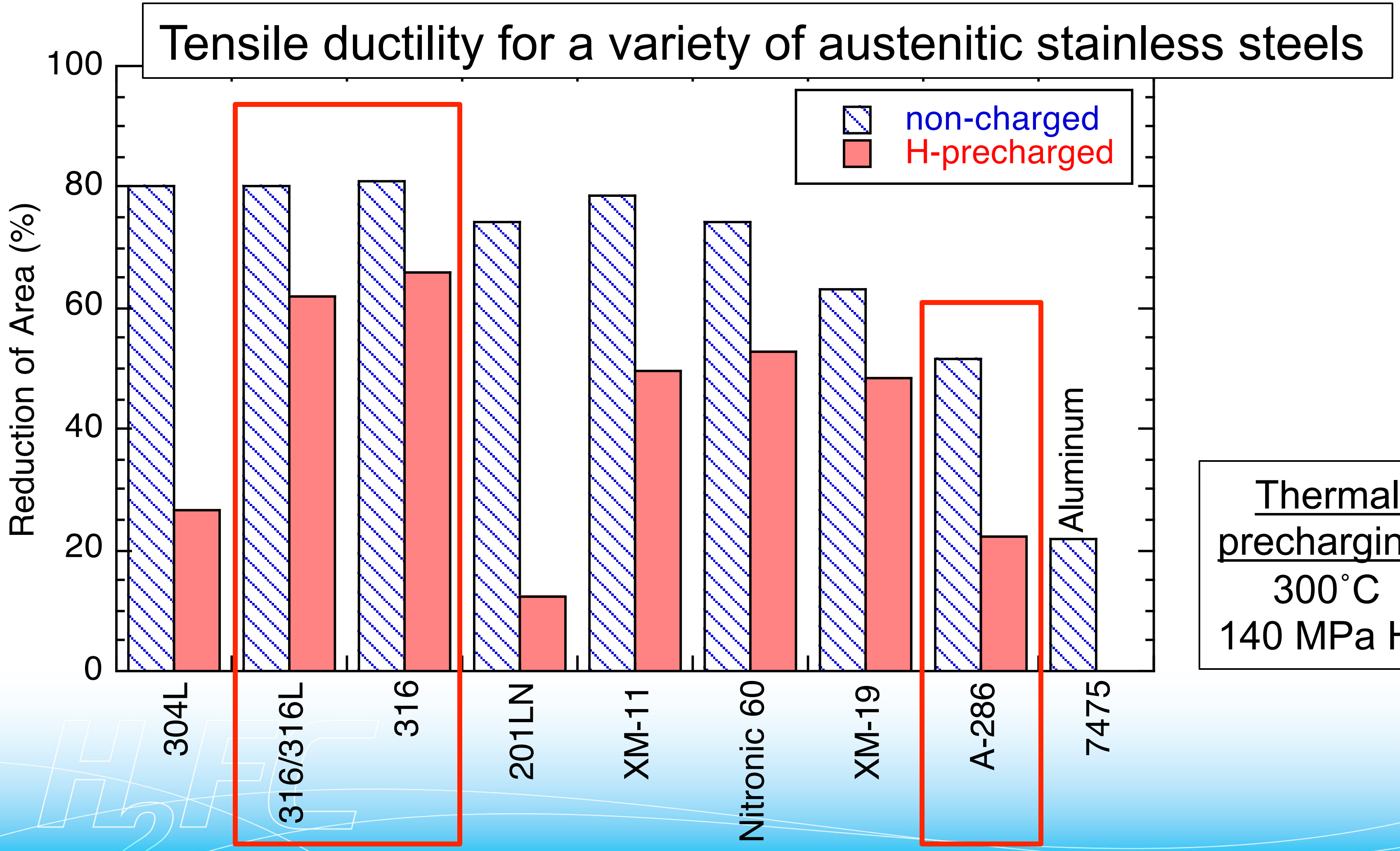


- Annealed type 316 & 316L alloys remain the primary “material of choice” for tubing, fittings and valves in hydrogen fuel applications
  - Low strength and high cost
  - *Are there opportunities to lower cost and maintain reliability?*
- There exists an extensive database of properties for austenitic stainless steels in hydrogen environments
  - *What does this data tell us?*
  - *Do other materials meet the performance needs of high-pressure hydrogen applications?*

Materials: austenitic stainless steels

alloy	Cr	Ni	Mn	Mo	C	N
304L	18.3	8.7	1.4	0.34	0.016	0.08
316/316L	16.8	11.2	1.6	2.0	0.02	0.02
316	17.8	12.1	1.2	2.1	0.046	0.02
201LN	16.2	4.1	6.6	0.34	0.024	0.14
XM-11	20.4	6.2	9.5	NR	0.033	0.26
Nitronic 60	16.5	8.0	7.4	NR	0.071	0.14
XM-19	21.0	13.5	6.0	2.1	0.01	0.33
A-286	13.9	24.3	0.11	1.2	0.04	NR

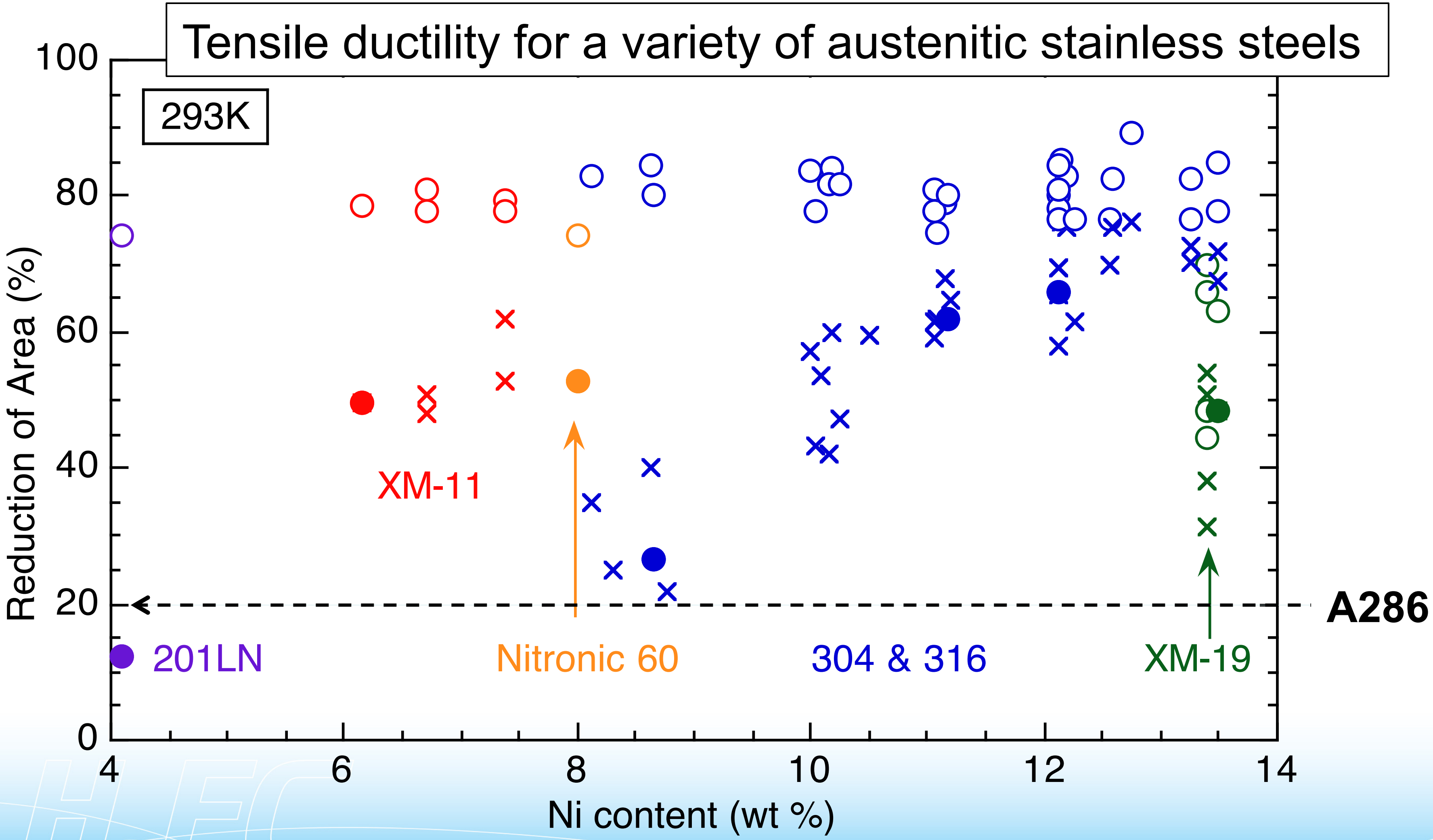
Why are materials such as 304L and XM-11 not considered for hydrogen service?



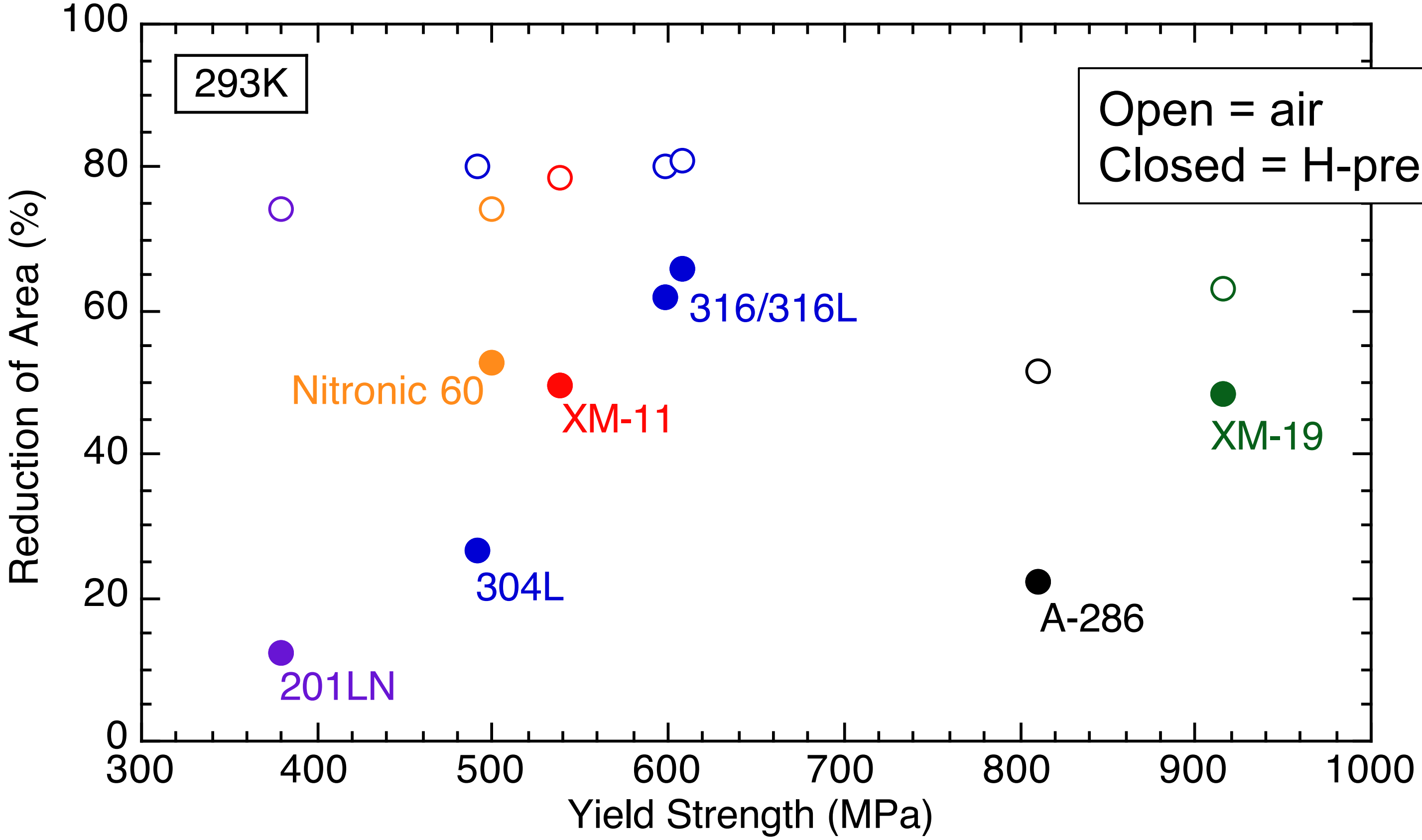
Tensile ductility for a variety of austenitic stainless steels

Thermal precharging:
300˚C
140 MPa H2

Why is A-286 considered appropriate for hydrogen service?



Tensile ductility of austenitic stainless steels do not scale with strength

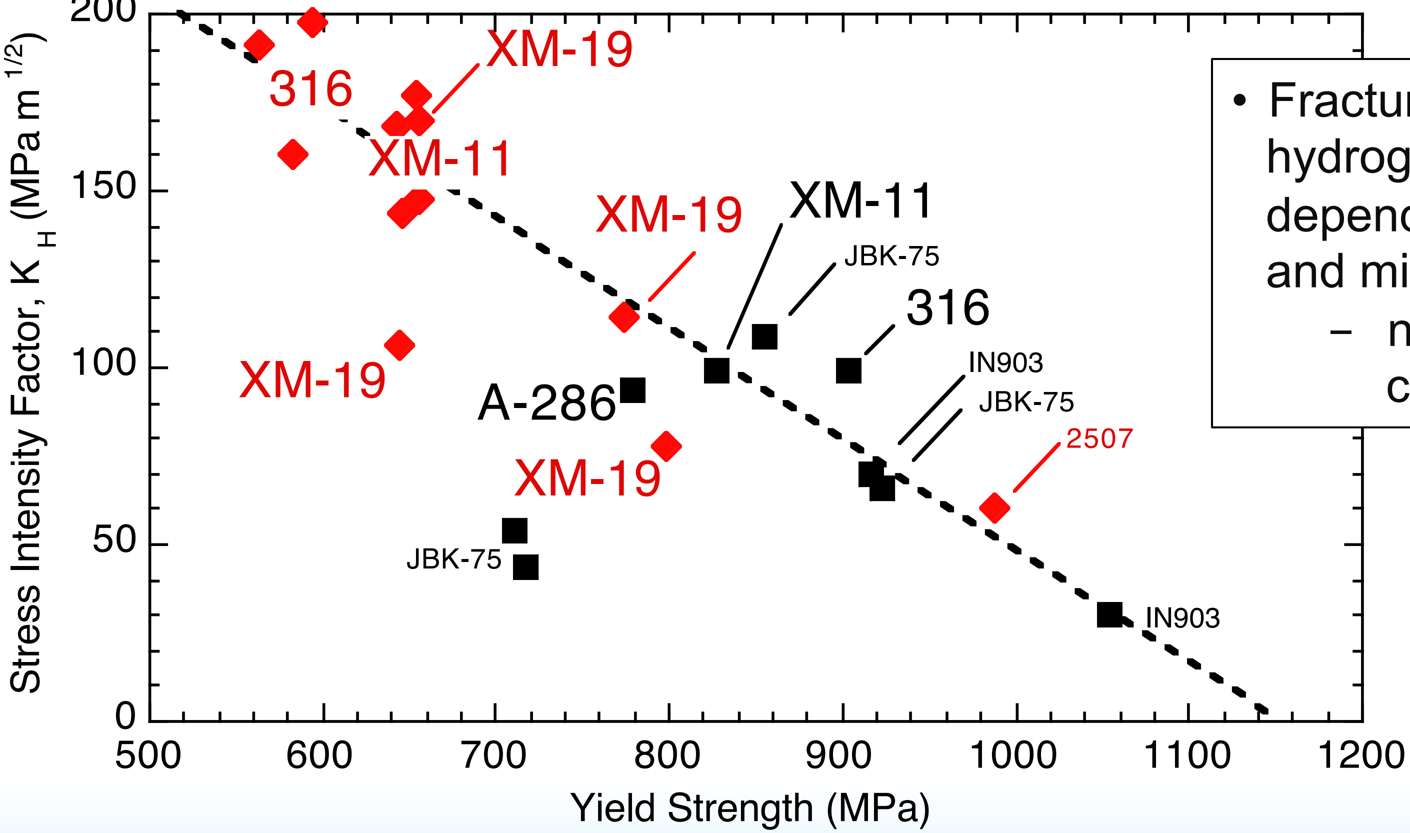


Thermal precharging:
300˚C
140 MPa H2

- Tensile ductility is not used directly in design
- If there is no design criteria associated with tensile ductility, what tensile ductility is necessary for pressure applications?

Fracture data suggests other stainless alloys perform similar to 316 alloys

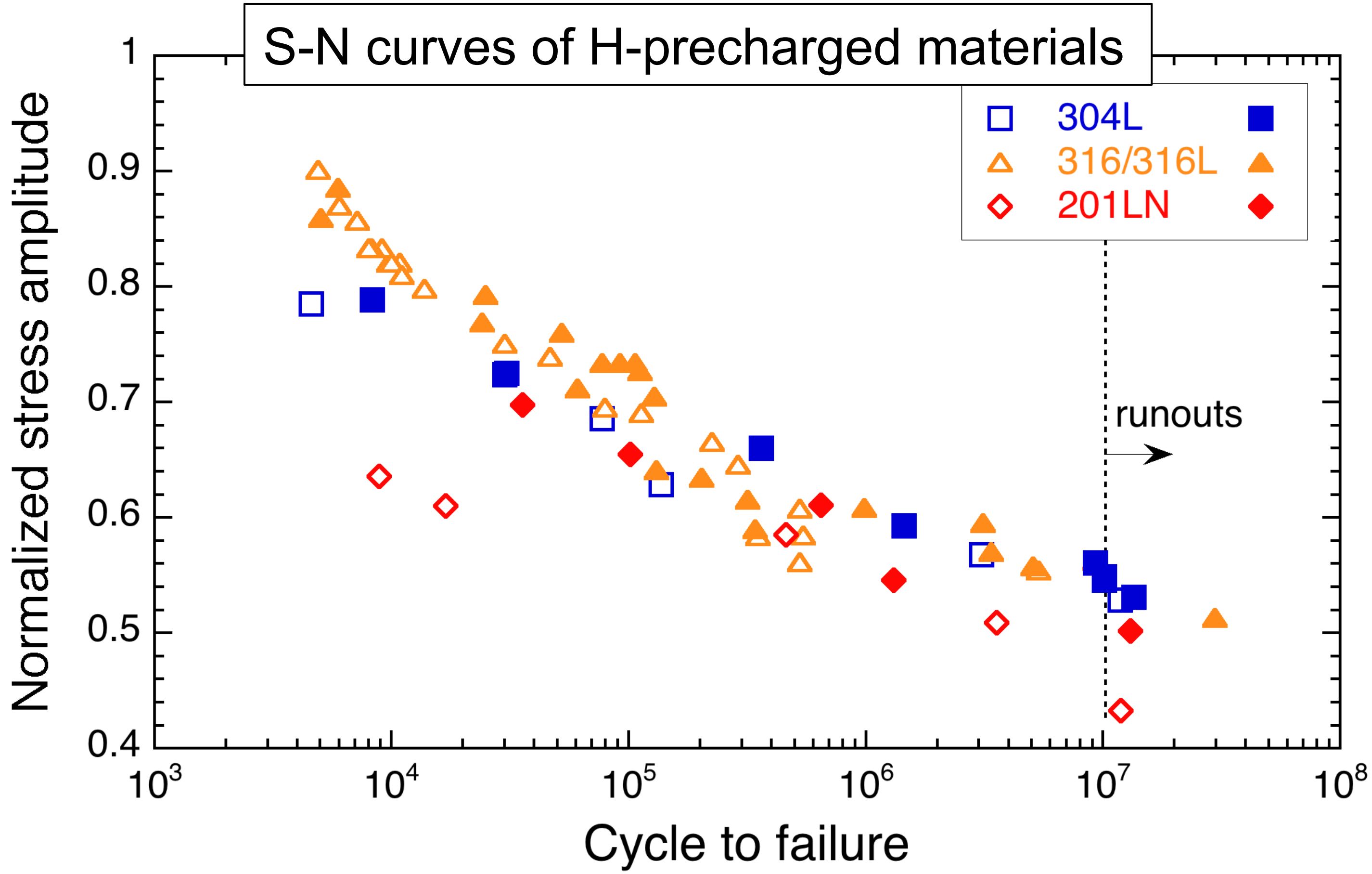
Fracture resistance measured in hydrogen environments



- Fracture resistance in hydrogen environments depends on strength and microstructure
    - not necessarily composition

Fracture mechanics (and fracture properties) can be used directly in the design of pressure components

Fatigue analysis is necessary to evaluate the performance of materials in cyclic environments



S-N curves of H-precharged materials

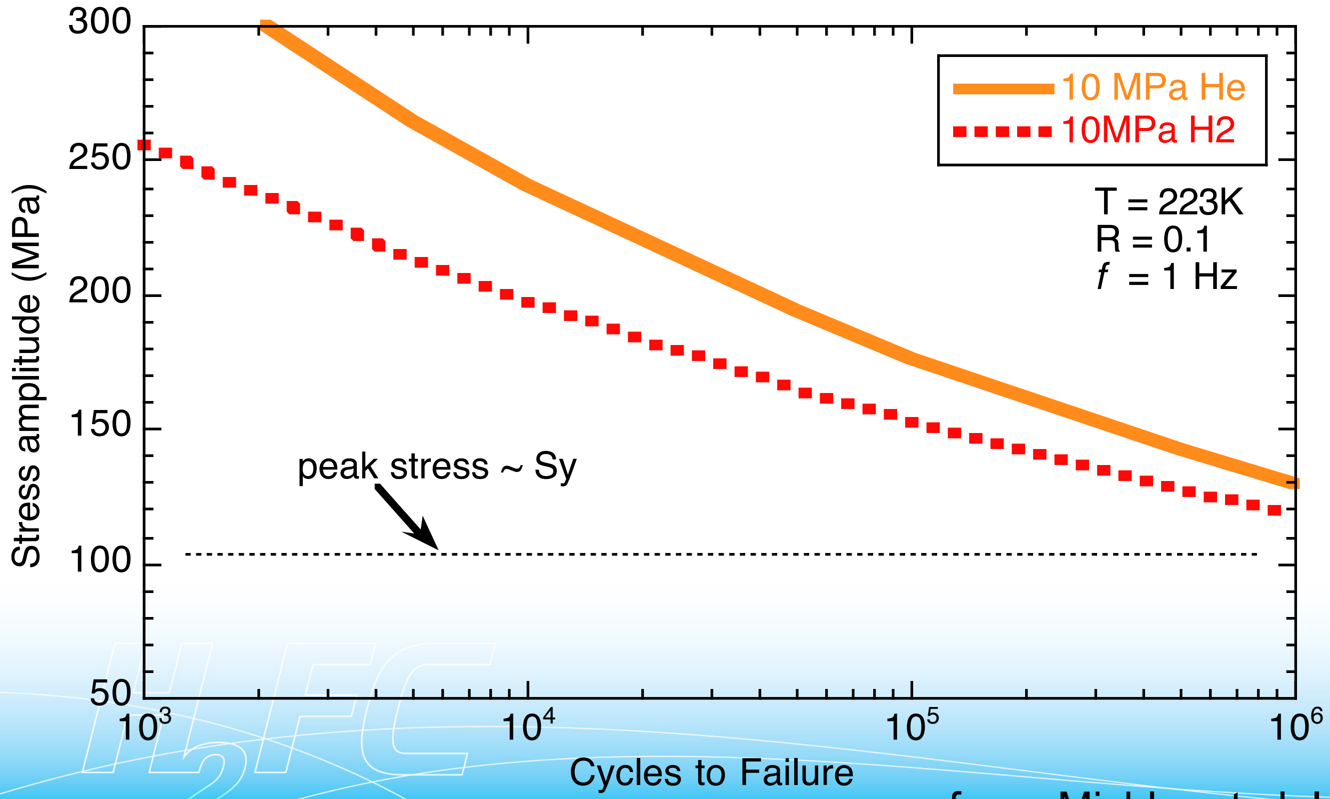
Rotating beam fatigue
R = -1
f = 50 Hz

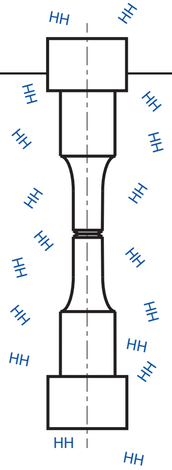
<u>Thermal precharging</u>:
300˚C
140 MPa H2

Fatigue performance of austenitic stainless steels does not appear to be affected by H-precharging

Performance-based assessment suggests that life is not limited by fatigue

- For moderate design life, the limiting fatigue stress is greater than the yield strength
- Design stresses are typically < yield strength
- Result: very conservative designs





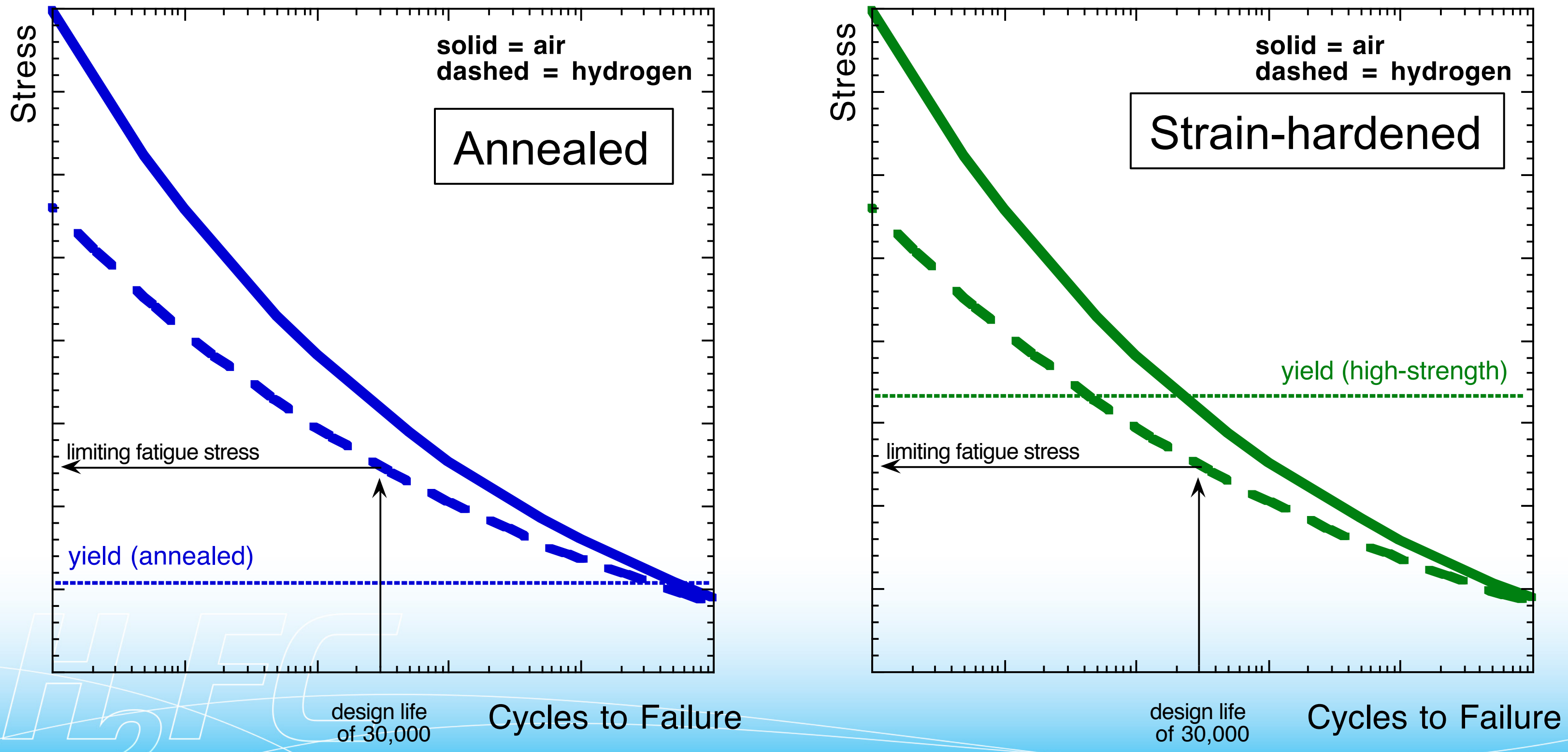
K_T~3

Tension-tension fatigue of standard notched tensile specimen (after ASTM G142)

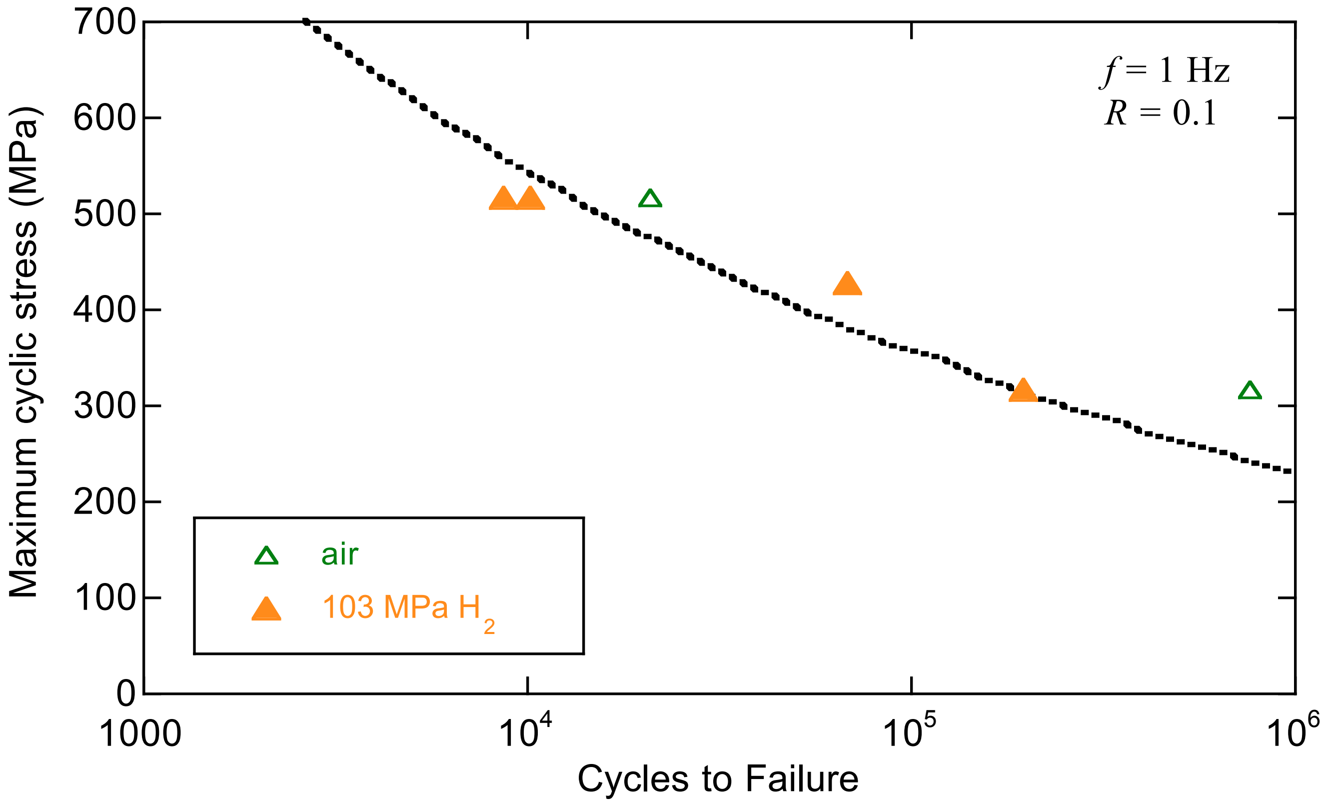
from: Michler et al. IJ Fatigue 51 (2013) 1-7.

How do we take advantage of fatigue performance?

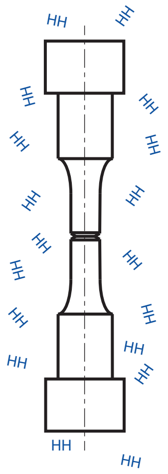
- By increasing the strength, higher fatigue stresses can be accommodated in design
  - Higher stress = less material
  - Less material = lower cost



Preliminary fatigue results

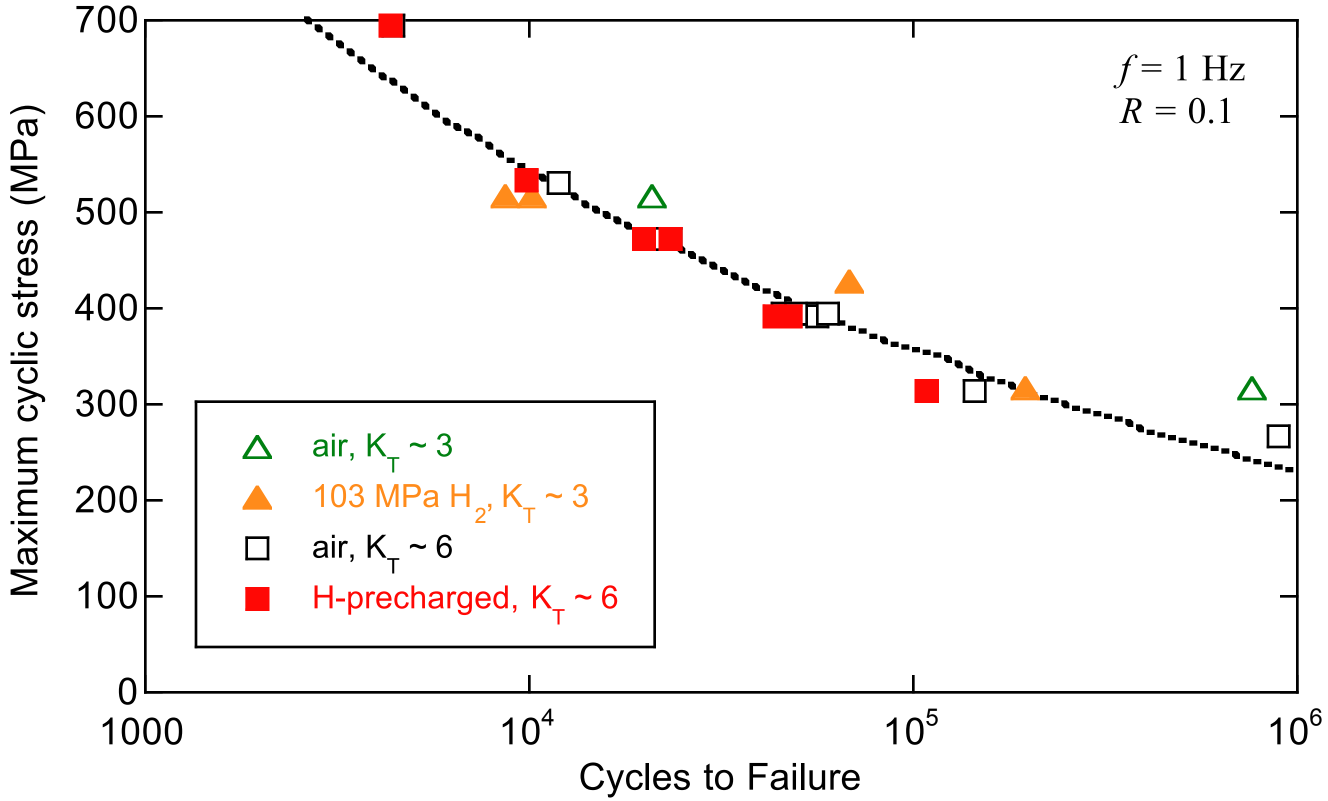


XM-11 austenitic stainless steel

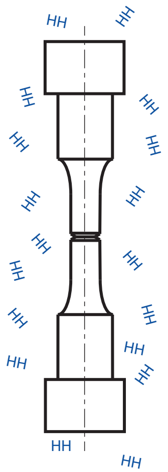


- High fatigue stress can be achieved with cycles to failure greater than 10,000 cycles
- Broader evaluation of methodology requires testing under combination of low temperature and high pressure

Preliminary results: internal versus external H



XM-11 austenitic
stainless steel



- Available data is incomplete (inconsistency of notch acuity and environments)
- Initial results suggest some correlation between internal and external H
- Data at low temperature is needed

Conclusions

- Tensile properties have limited utility for materials selection for hydrogen service
  - Results can be misleading
- Fracture properties suggest 316 alloys perform similar to other austenitic stainless steels
  - Wider range of alloys and strength conditions should be considered
- Fatigue performance in hydrogen environments suggests that some hydrogen fueling applications may not be fatigue limited
  - Higher-strength alloys/conditions may enable more efficient designs