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Materials Performance at Liquid Hydrogen Temperatures

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Sandia National Laboratories

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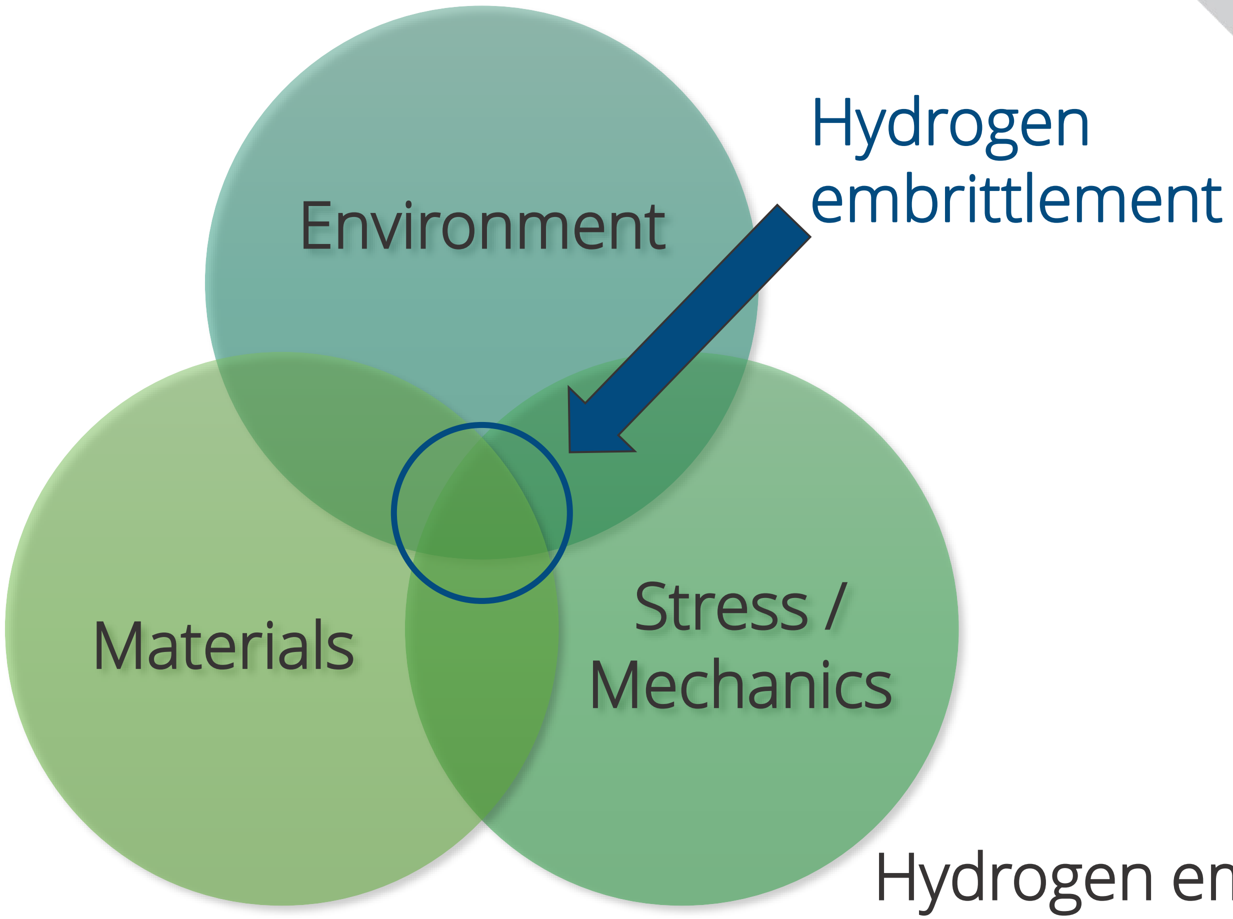
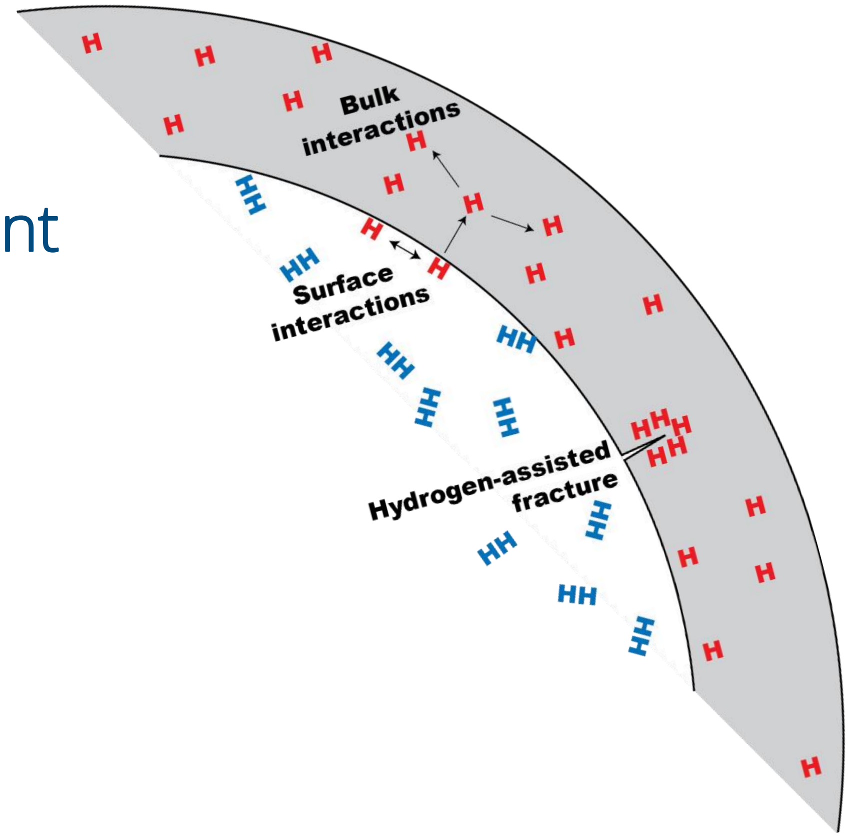
U.S. DEPARTMENT OF ENERGY

NNSA

Hydrogen embrittlement occurs in materials under the influence of stress in hydrogen environments





Hydrogen embrittlement occurs when hydrogen:

1) dissociates on metal surfaces
2) dissolves into the metal lattice
3) diffuses to regions of tensile stress

Conventional Cryogenic Materials for LH_2

3XX series austenitic stainless steel
- High toughness, high ductility, good performance in H2
- 304N for trailer applications
  - N is nitrogen strengthened to allow reduced weight

Aluminum alloys
- Low sensitivity to hydrogen
- No DBTT (ductile to brittle transition temperature)
- Good when weight reduction is critical

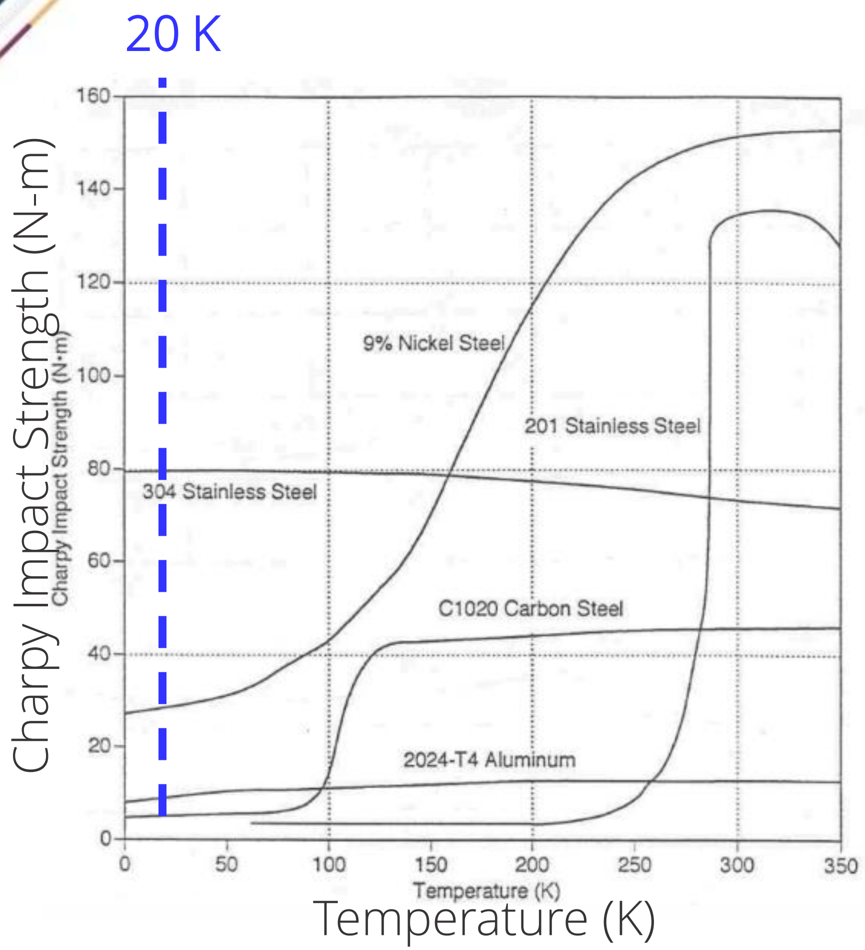
NASA 1950/1960s
Stainless steel

~~Ferritic/Martensitic alloys~~
- 3.5, 5, 9 Ni-alloys are martensitic and have minimum temperature usages of 76 K

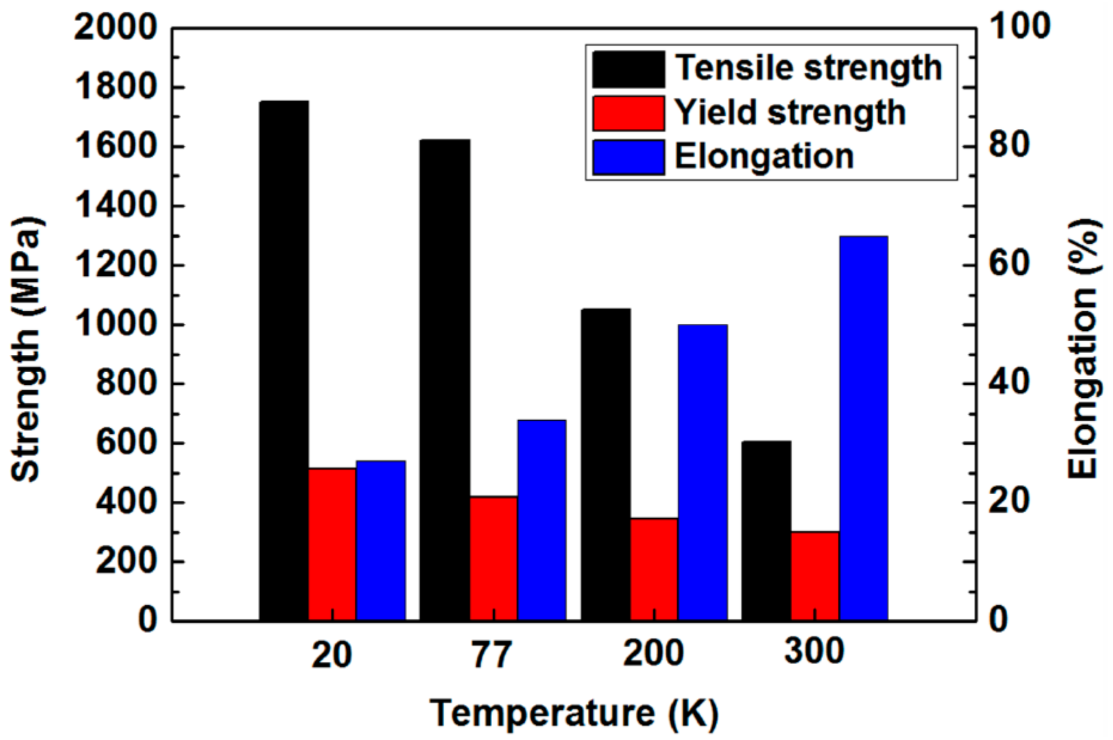
Not suitable for LH_2

Alloys used at cryogenic temperatures must exhibit good toughness
→ For LH_2 use, high toughness must extend down to 20K.

Ductility decreases at cryogenic temperatures



From: NASA, Safety Guide for Hydrogen and Hydrogen System

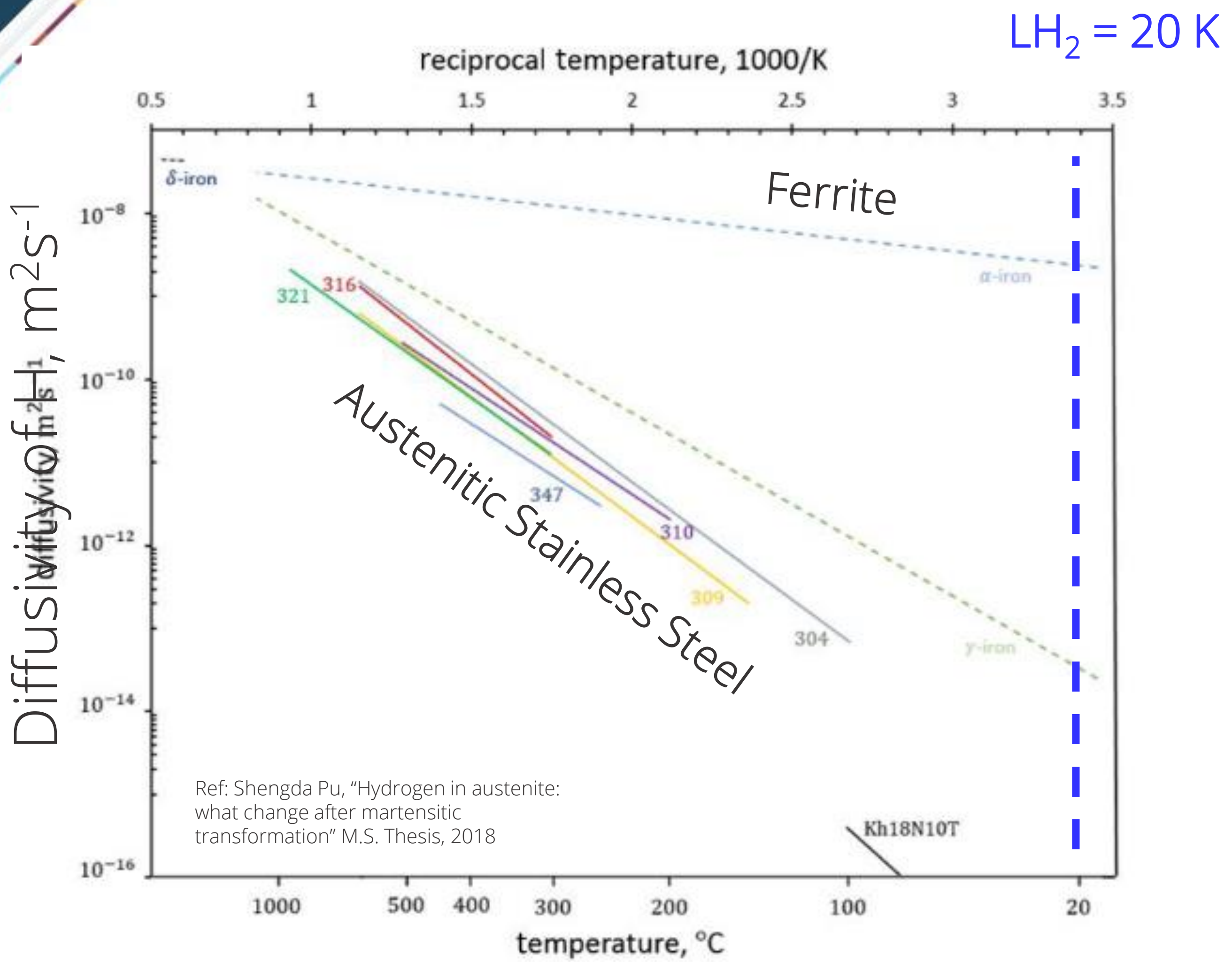


Strength increases at lower temperatures;
Elongation to failure decrease

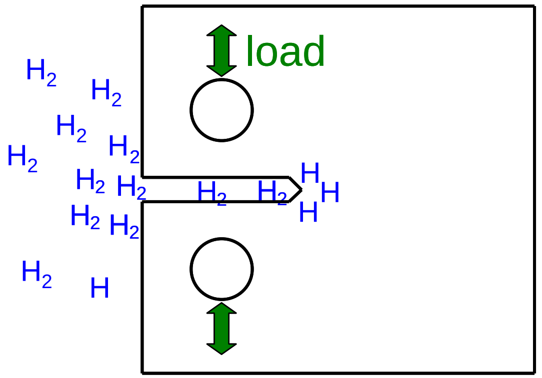
Ref: Cryogenic properties of 3XX series stainless steel at different temperatures (Qiu, *Metals* 2021)

Low-temperatures reduce ductility (elongation)
→ Hydrogen can further degrade mechanical properties

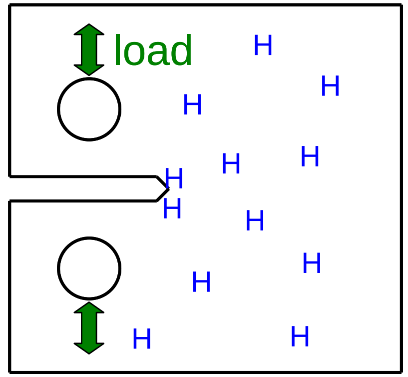
Cryogenic temperatures greatly limit hydrogen diffusion



External Hydrogen Gas

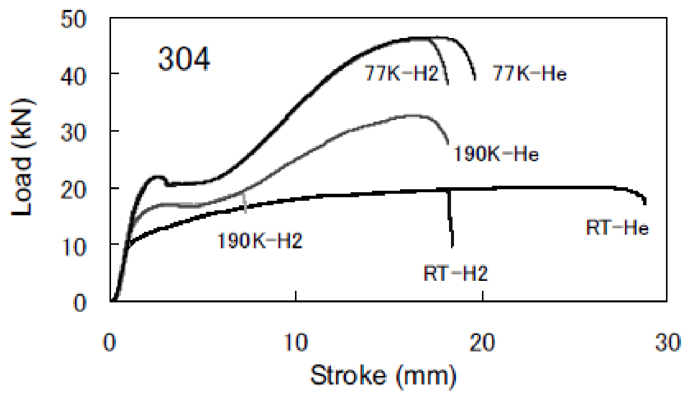


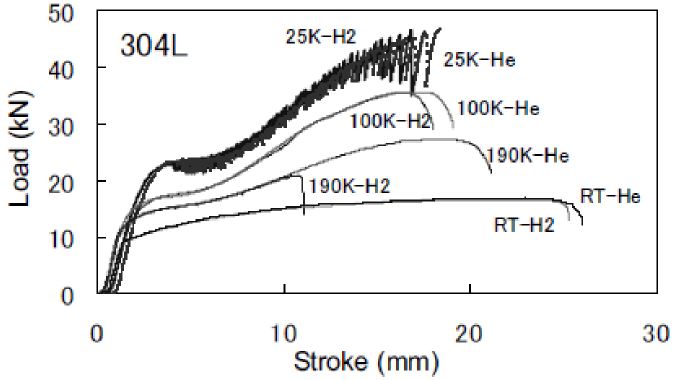
Hydrogen Precharged



Kinetics are important to consider and may influence test results
→ Experiments should try to mimic long-term exposures

Ductility loss due to external gaseous H_2 appears to diminish at <100 K

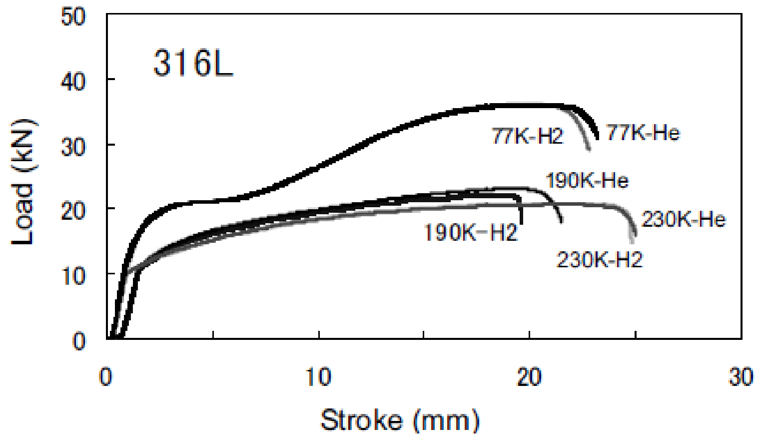


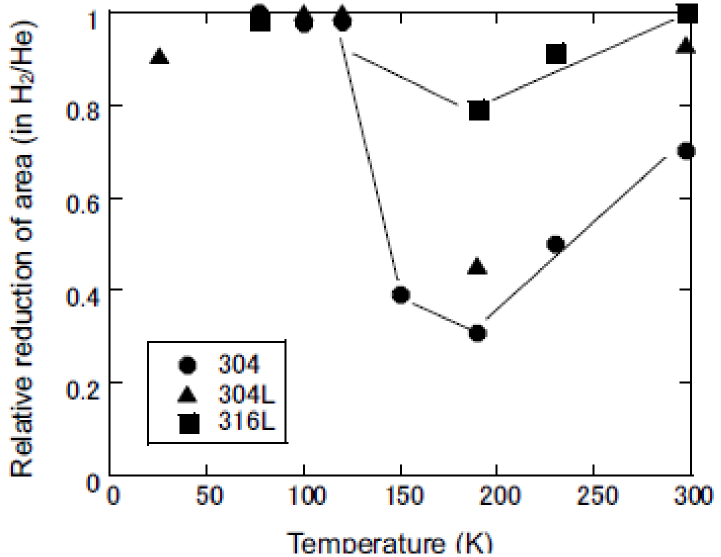


External gaseous hydrogen

H_2 = 13 MPa H_2
He = 12 MPa He

Ref: T. Ogata, “Hydrogen embrittlement evaluation in tensile properties of stainless steels at cryogenic temperatures, AIP Conference 2008)
https://doi.org/10.1063/1.2900335

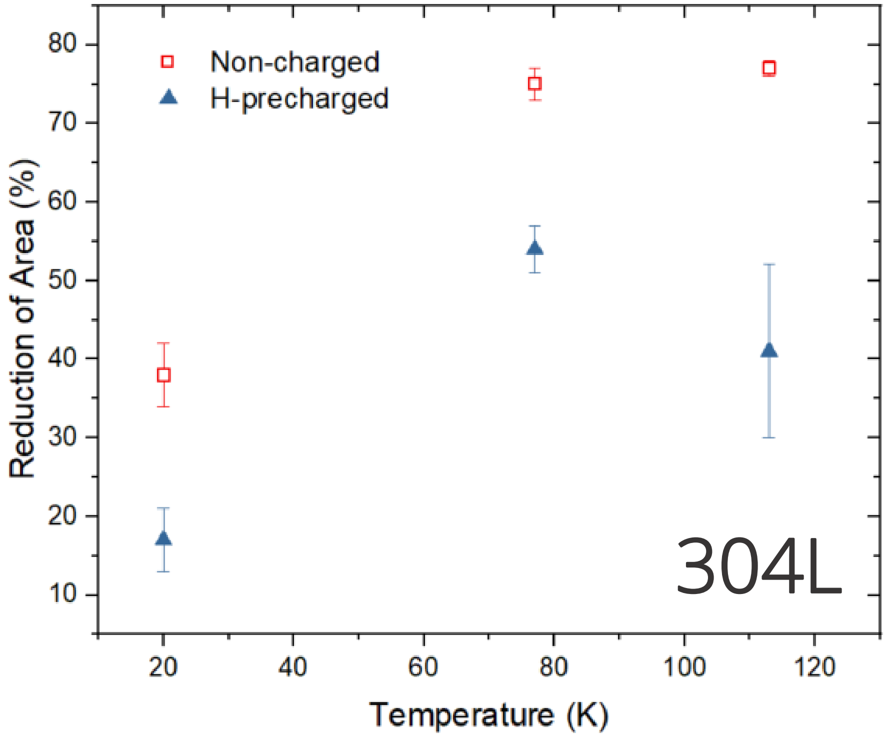




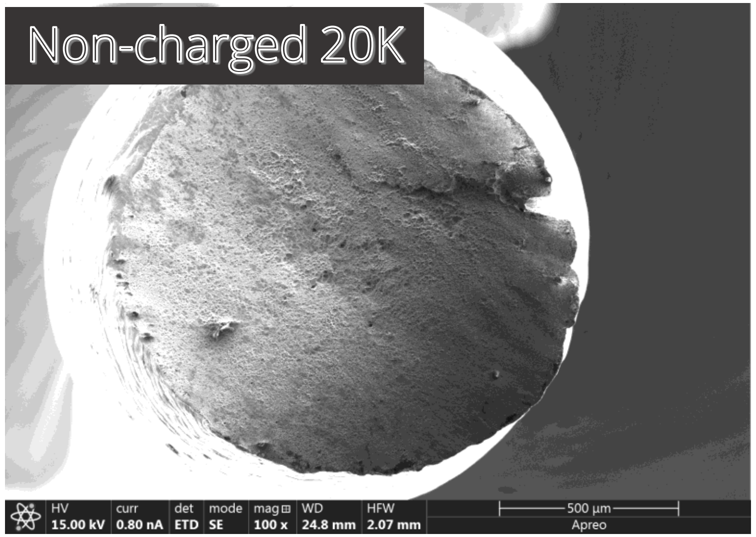
Metastable alloy (like 304) can transform to martensite due to strain and low temperatures.

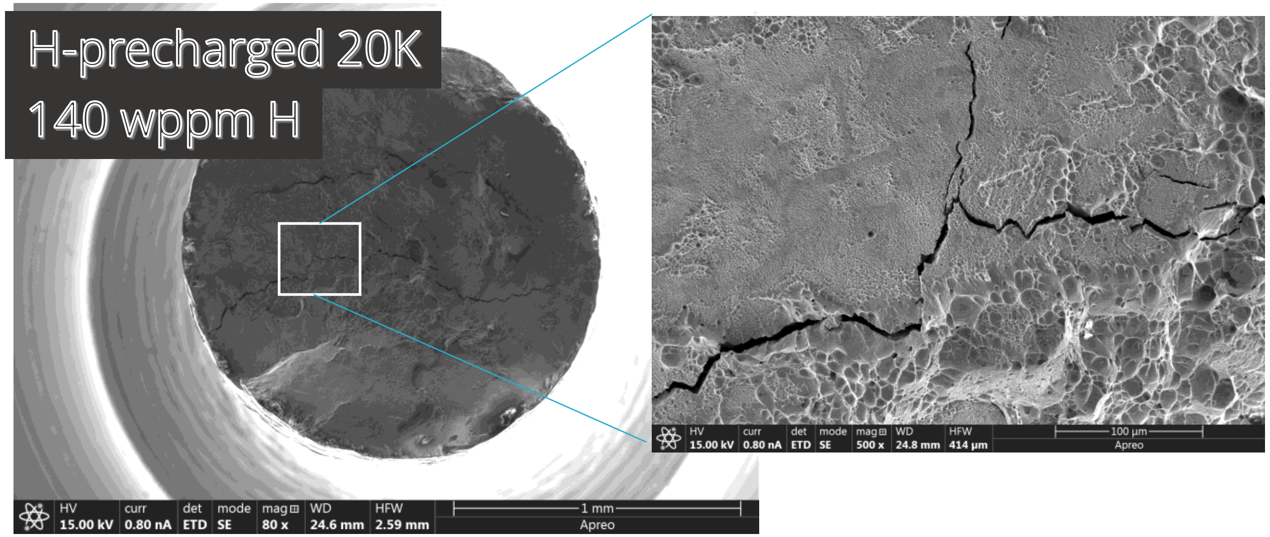
- Metastable austenitic stainless steels (304, 304L) exhibit greatest ductility losses in hydrogen gas in 150-230K range
- At <100K, negligible loss in ductility due to hydrogen – likely diffusion limited

Precharged hydrogen reduces ductility (reduction of area)



(D. Merkel, "Effect of hydrogen on tensile properties of 304L stainless steel at cryogenic temperatures, PVP2021-62436)



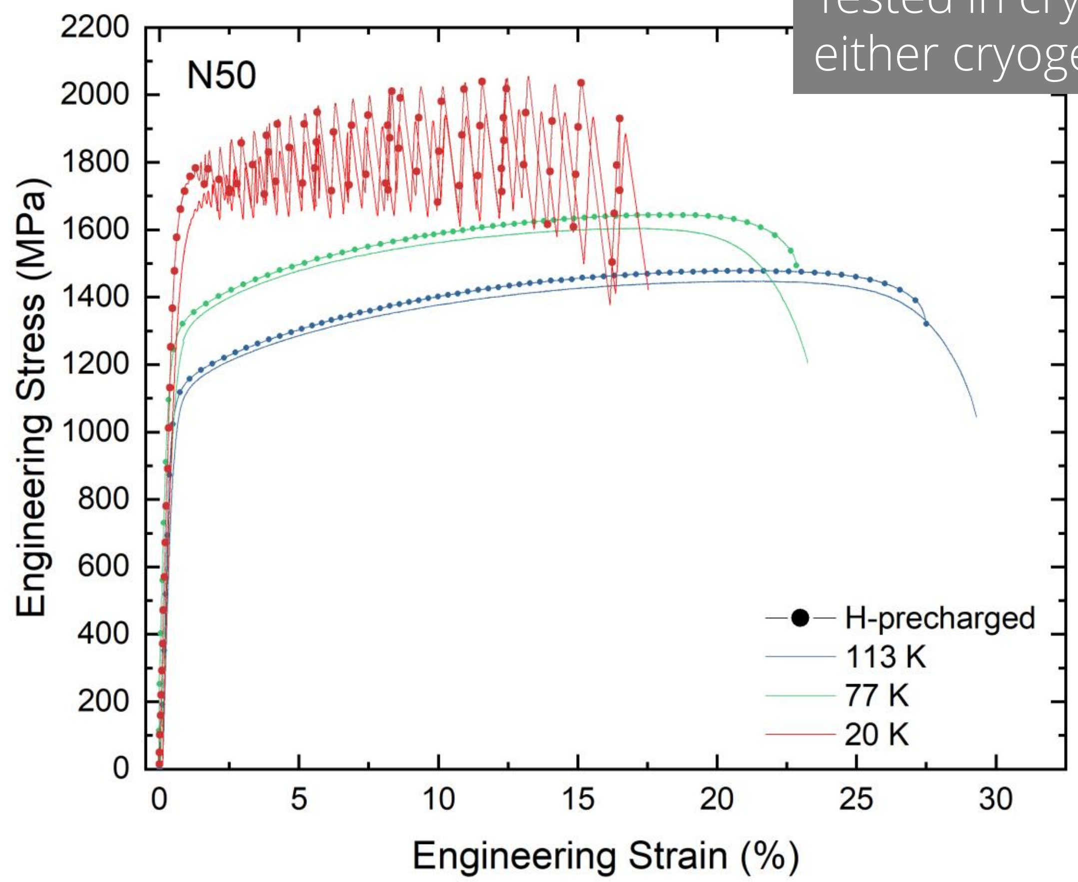


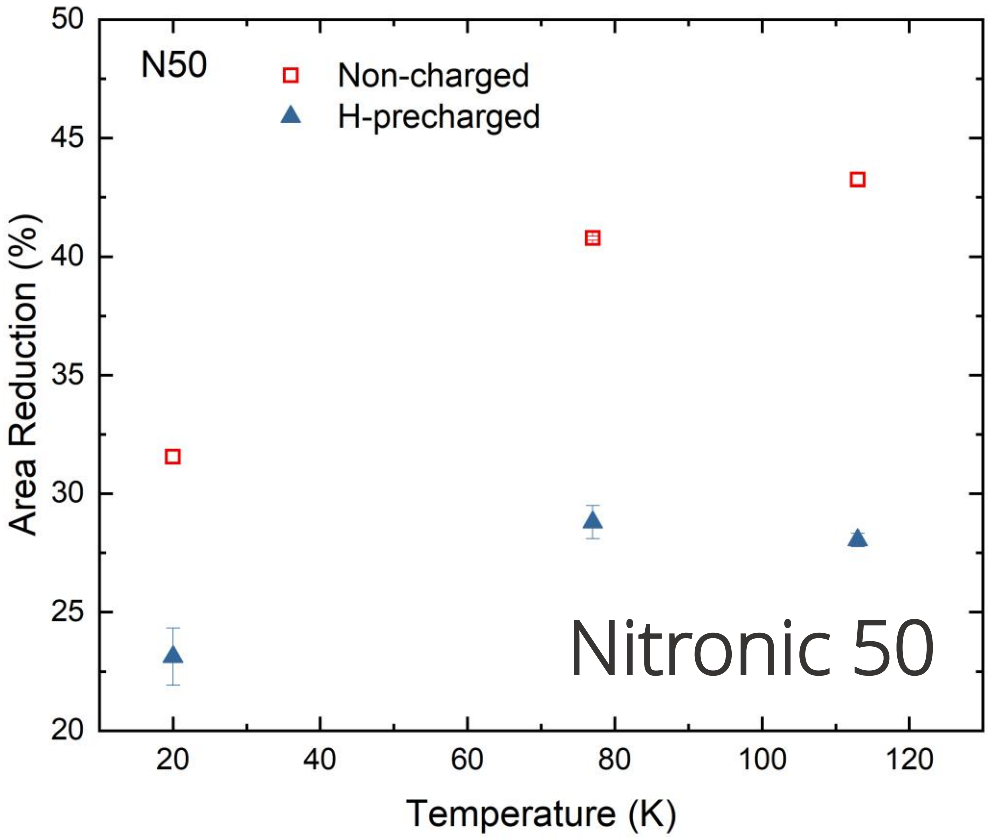
Tested in cryostat with either cryogenic N_2 or He

Reduction of area consistently lower in H-precharged samples down to 20 K
→ Hydrogen can degrade 304L even at 20 K

Alternative austenitic stainless steels Nitronic 50 (XM-19) exhibit similar behavior to 304L

Tested in cryostat with either cryogenic N_2 or He

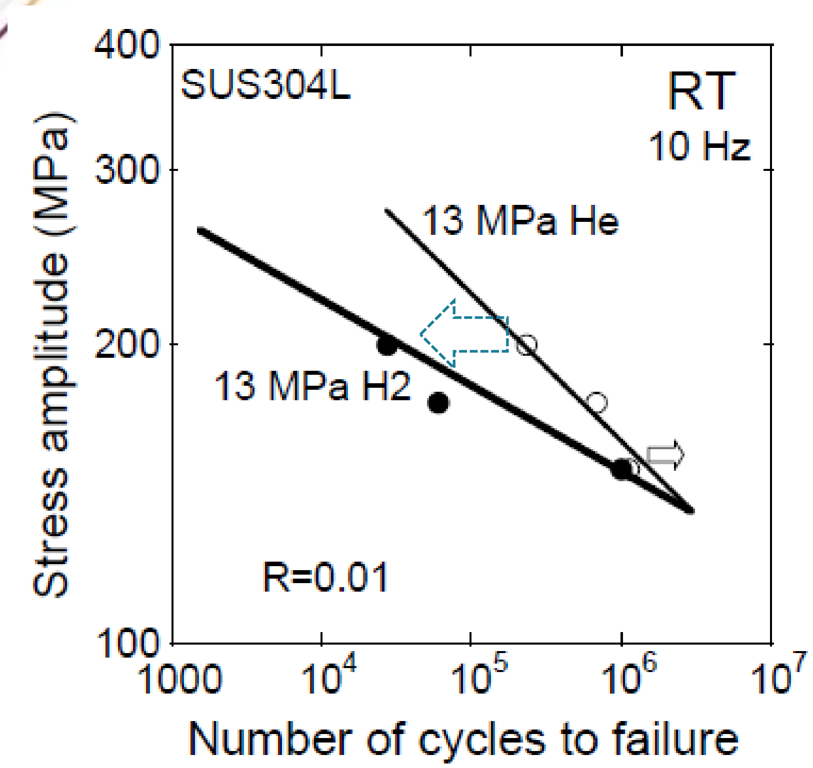




(D. Merkel, "Effect of hydrogen on tensile properties of stainless steel at cryogenic temperatures," MRS Fall 2021.

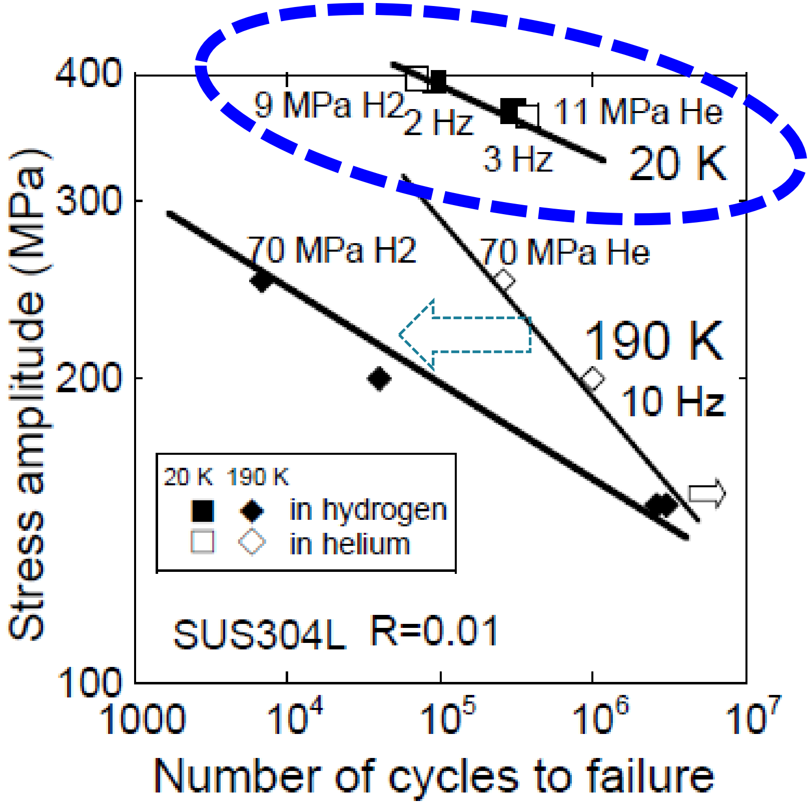
XM-19 offers higher strength alternative to 304L, but with similar effects due to H_2 at 20 K

Fatigue degradation due to H_2 diminished at 20K in lab tests



At 293K, decrease in fatigue life due to H_2

External gaseous hydrogen



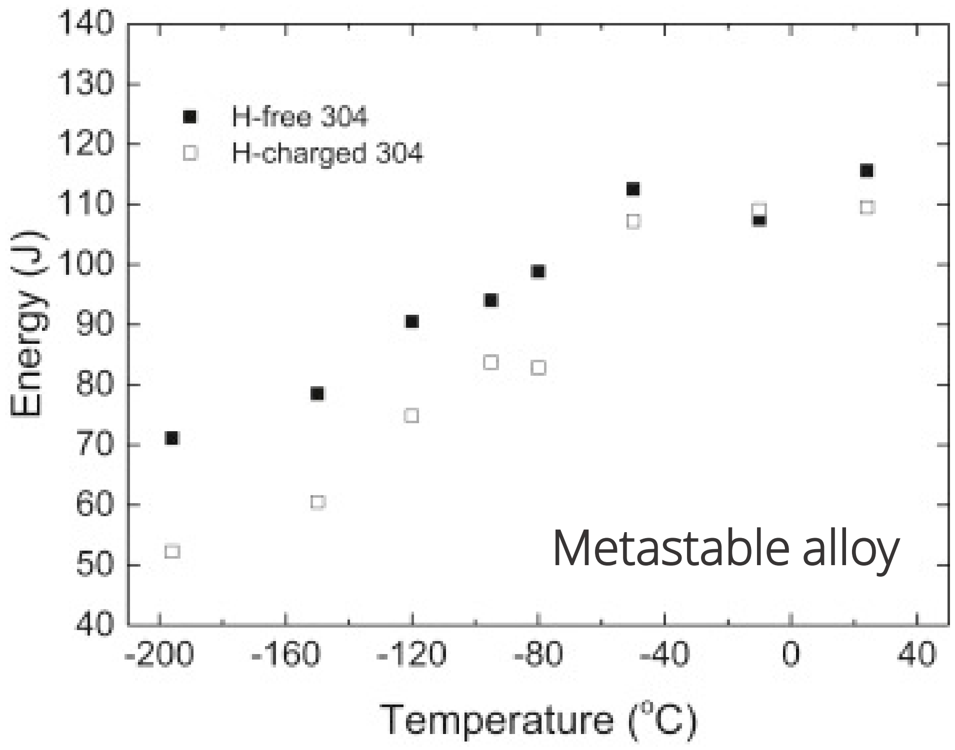
At 190K, decrease in fatigue life due to H_2
At 20K, negligible difference between He and H_2

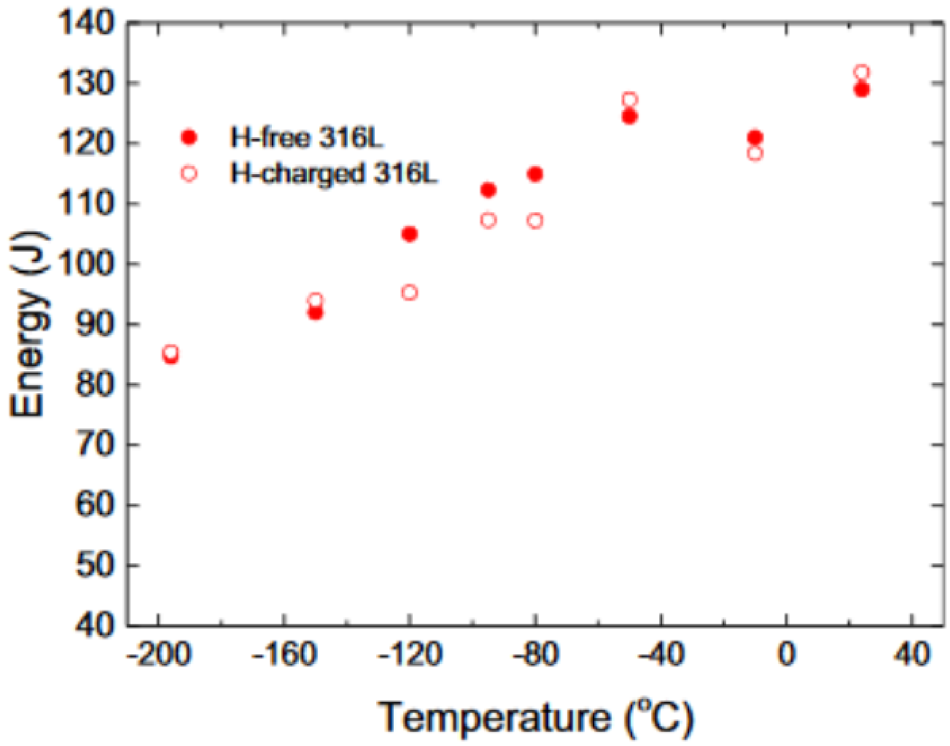
Ref: T. Ogata, "Hydrogen environment embrittlement evaluation in fatigue properties of stainless steel SUS304L at cryogenic temperatures, AIP Conference 2010) https://doi.org/10.1063/1.3402310

→ At 10 Hz, Hydrogen reduces fatigue life at 293K and 190K, no measured effect at 20K

Fatigue load frequency in application is likely less than 10 Hz allowing more time for H-diffusion.
→ May result in different behavior

Charpy impact toughness of H-precharged austenitic stainless steels decreases in metastable alloys





Charpy impact test

, Low temperature tensile and impact properties of hydrogen-charged high manganese steel, *IJHE*, 2019.

Metastable = more likely to form martensite

→ Martensite is more susceptible to low temperature embrittlement and hydrogen embrittlement

Despite fast loading rates, hydrogen still can have a measurable impact at low temperatures

Summary

- Austenitic stainless steels (304/316) are used at cryogenic temperatures due to high toughness

  → At cryogenic temperatures, strength improves but ductility and impact toughness are reduced

- Most of material degradation is due to extreme low temperatures

  → Hydrogen can further degrade mechanical properties

  → Research on Nitronic 50 (XM-19) shows comparable tensile behavior to 304L

- Hydrogen diffusion is limited at 20 K which can affect laboratory tests
  - Important to consider when assessing long-term effects in applications
  - Precharged hydrogen can overcome slow diffusion and better represent long-term exposure
  - Slow rate fracture testing at low temperature is notable gap in literature

Thank you for your attention!

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References:

- Cryogenic properties of 3XX series stainless steel at different temperatures (Qiu, *Metals* 2021)
- NASA, Safety Guide for Hydrogen and Hydrogen System
- Shengda Pu, "Hydrogen in austenite: what change after martensitic transformation" M.S. Thesis, 2018
- T. Ogata, "Hydrogen embrittlement evaluation in tensile properties of stainless steels at cryogenic temperatures, AIP Conference 2008) https://doi.org/10.1063/1.2900335
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- D. Merkel, "Effect of hydrogen on tensile properties of 304L stainless steel at cryogenic temperatures, PVP2021-62436
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- Nam, Low temperature tensile and impact properties of hydrogen-charged high-manganese steel, *IJHE*, 2019.