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Mechanical Properties of Tritium Precharged and Aged Additively Manufactured Austenitic Stainless Steel

Natalie Wieber

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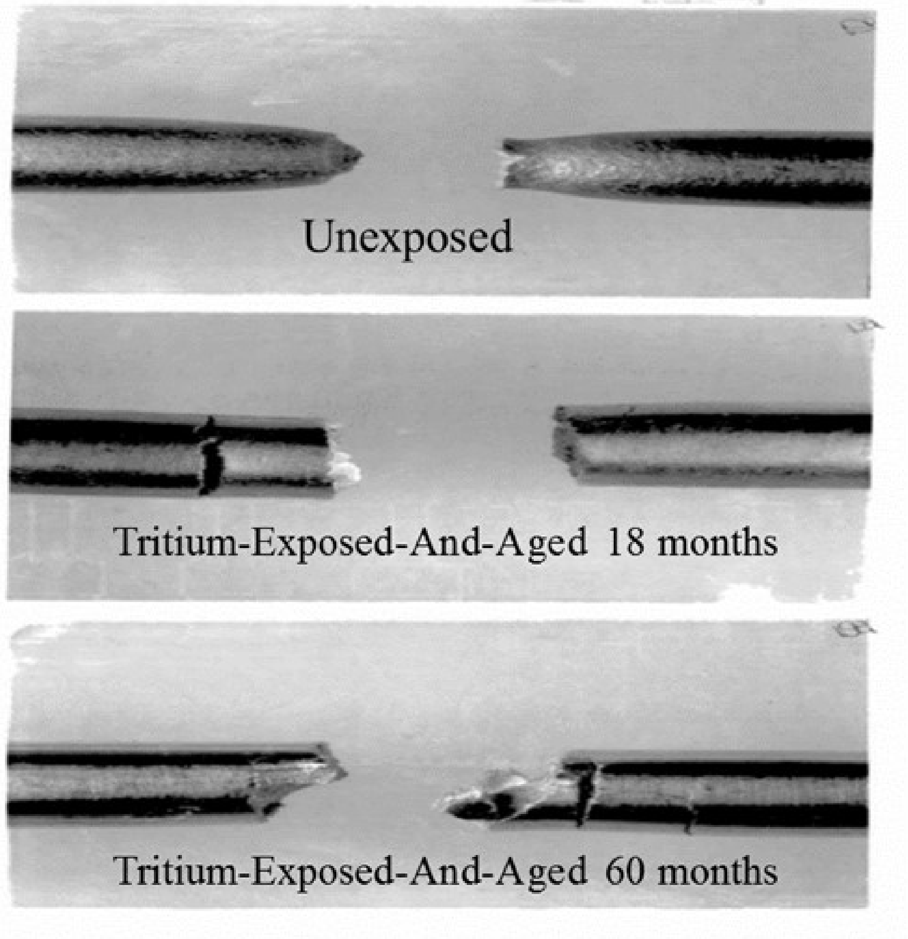
Demands for tritium-facing components

- Weapons, analytical chemistry, self powered lighting, fuel for fusion power
- Tritium compatibility
  - Functional components/materials
  - Structural components/materials

- Primary pressure boundaries
- Safety performance
- Austenitic stainless steels
  - Higher Ni, Cr, Mo, and N
  - Composition
  - Formability/weldability

Austenitic SS is relatively resistant to hydrogen isotopes embrittlement, but…



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- Internal hydrogen degrades ductility
- Decay product from hydrogen isotope, tritium, forms helium bubbles causing further embrittlement

1. D. Rawl, Notebook, November 1979.

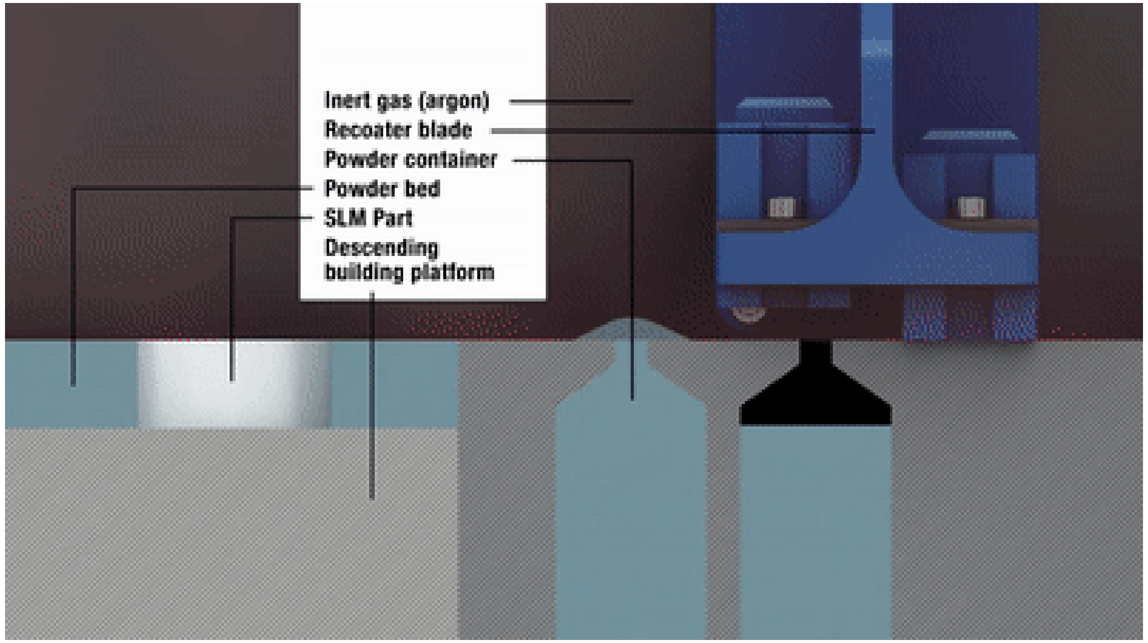
Lots of data on conventionally manufactured structural materials/steel

- What is "known" about tritium effects on austenitic steel
  - Decreased ductility and fracture resistance
  - Hardening/strengthening
  - Hydrogen is believed to interact with dislocations, grain boundaries, vacancies, and other microstructural features[2]

- But what about AM??
  - Similar behavior/trends?
  - How do we account for differences between AM and forged?
  - Can we design based on material with similar microstructure that has already been tested?

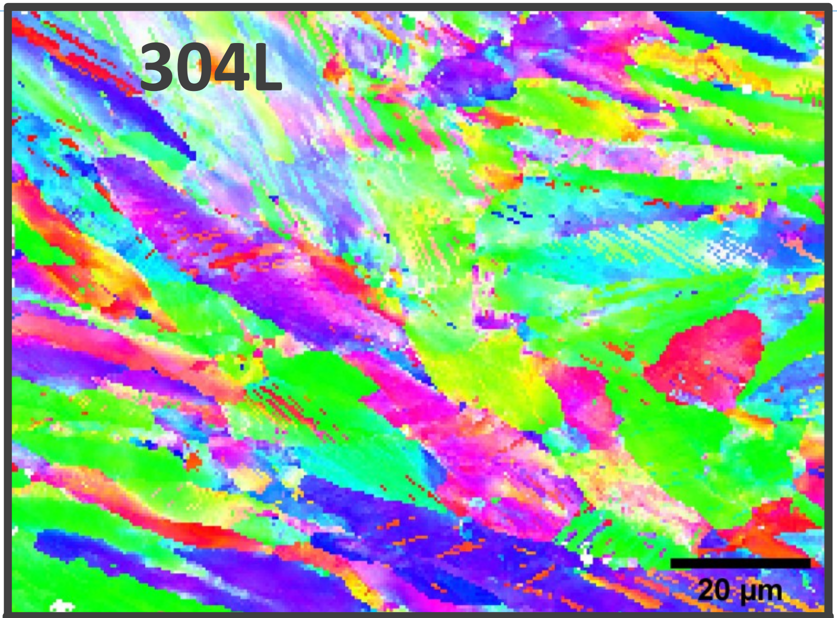
2. Lawrence, S.K., Pokharel, R., Clausen, B. *et al.* In Situ X-ray Diffraction Investigation of Hydrogen Effects on Deformation-Induced Phase Transformation in Forged and Additively Manufactured 304L Stainless Steels. *JOM* **75**, 2287–2298 (2023). https://doi.org/10.1007/s11837-023-05787-6.

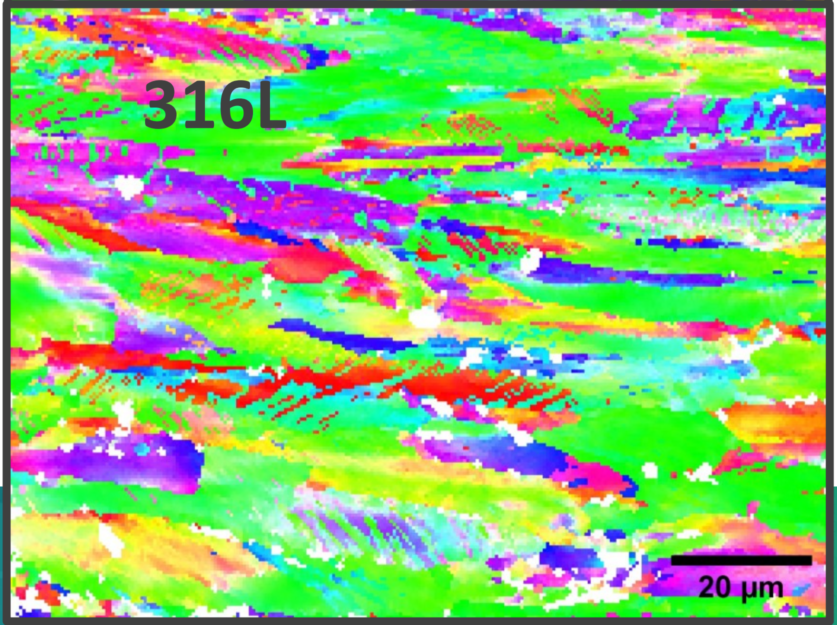
304L and 316L test samples made via laser powder bed fusion (LPBF)



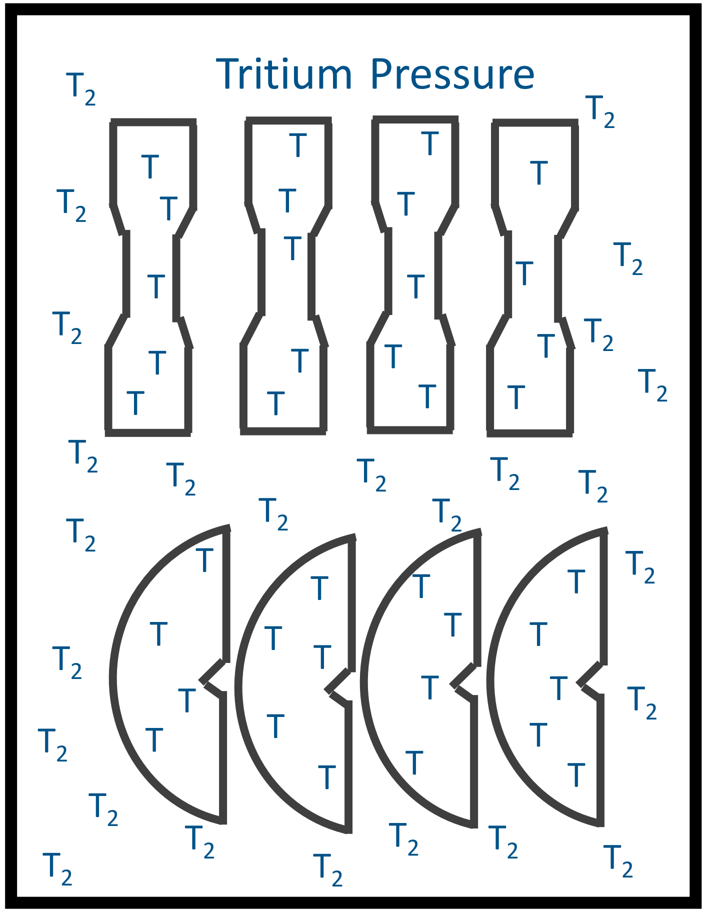
Video credit: sokolmask on https://makeagif.com/i/_1JqqM

(In MPa)	Yield Strength	Ultimate Tensile (UTS)
304L	412	513
316L	416	496

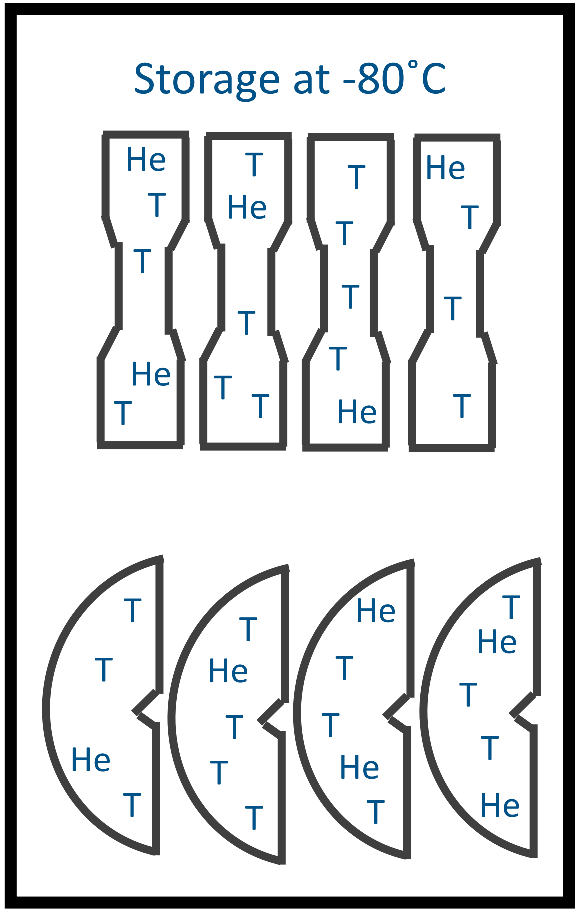




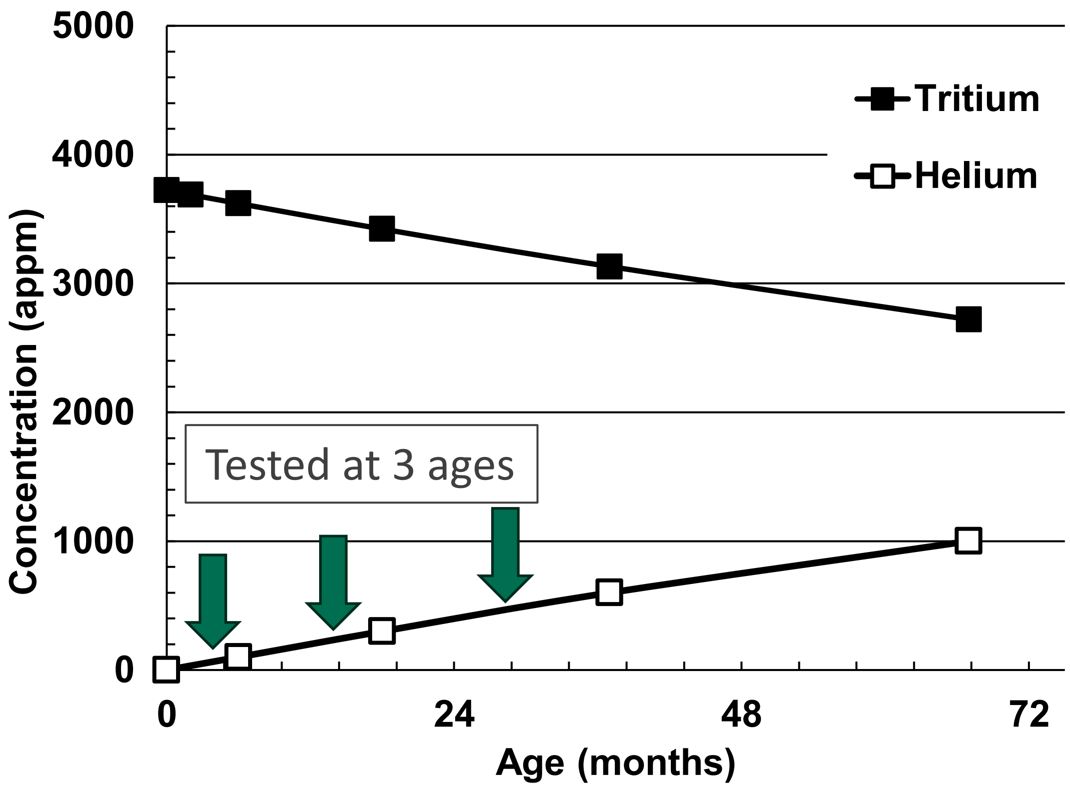
Tritium charging and aging enables control of helium content



T-charging



Low-temperature aging



Helium increases as T decays

Ductility loss due to T/He content evaluated by tensile testing

Testing conducted at 3 ages representing Tritium + 100, 200, and 375 appm He (and noncharged “NC”)

Tensile testing conditions:

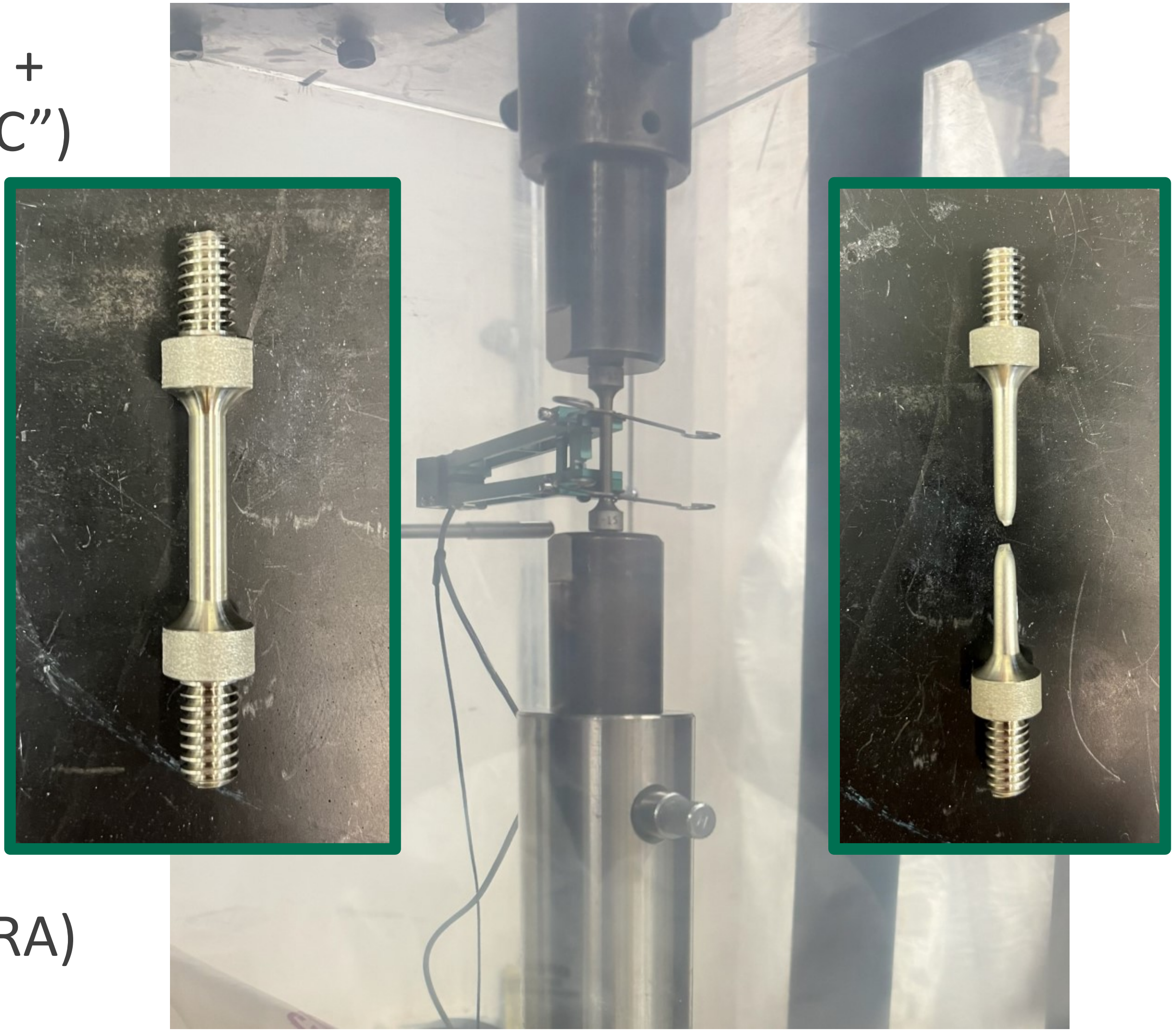
→Displacement controlled: 1.27 mm/minute

→Strain measured across 25.4 mm gauge length (extensometer)

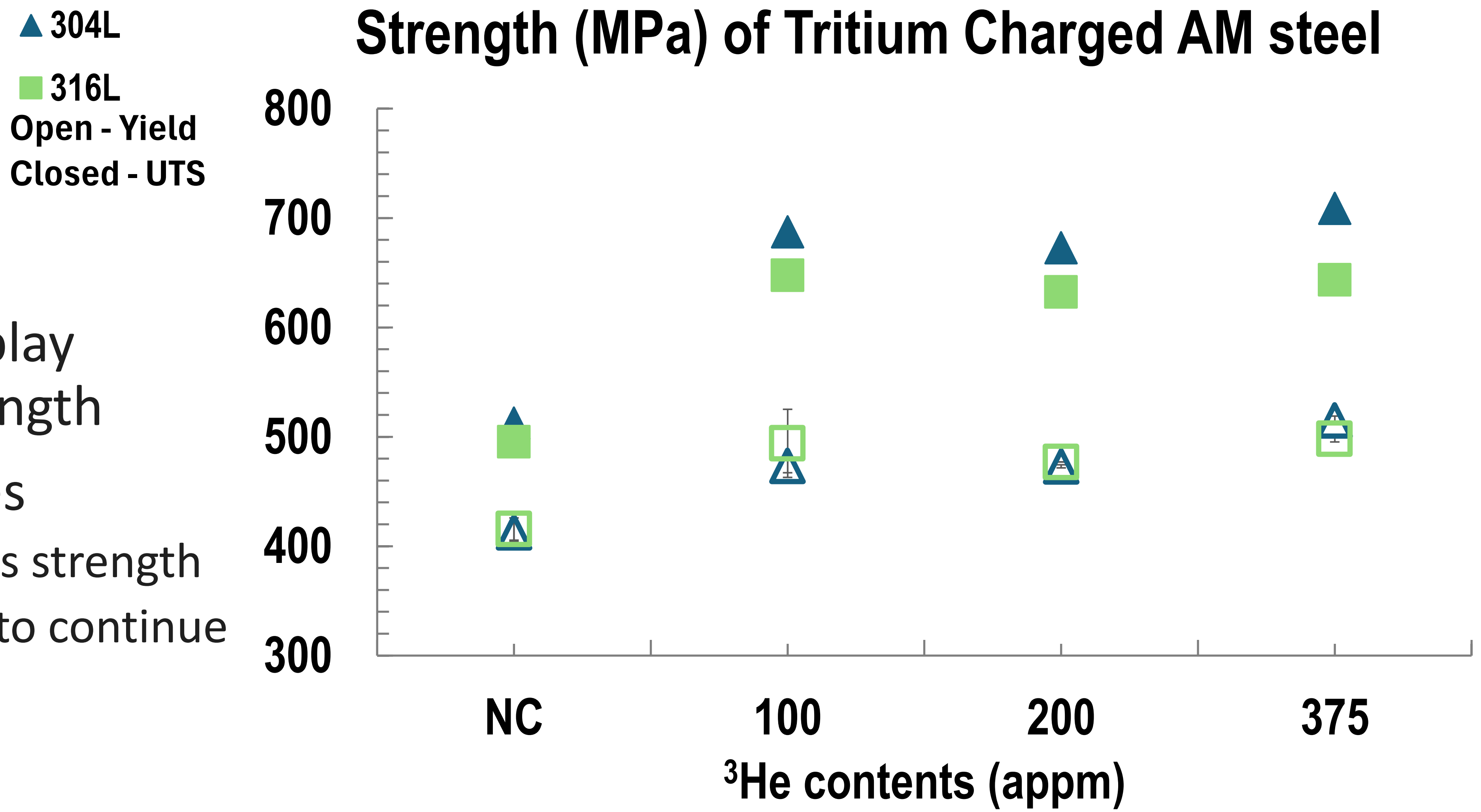
Results:

→Yield and Tensile strengths

→Ductility loss evaluated by Reduction of Area (RA) – estimated from reduction of OD

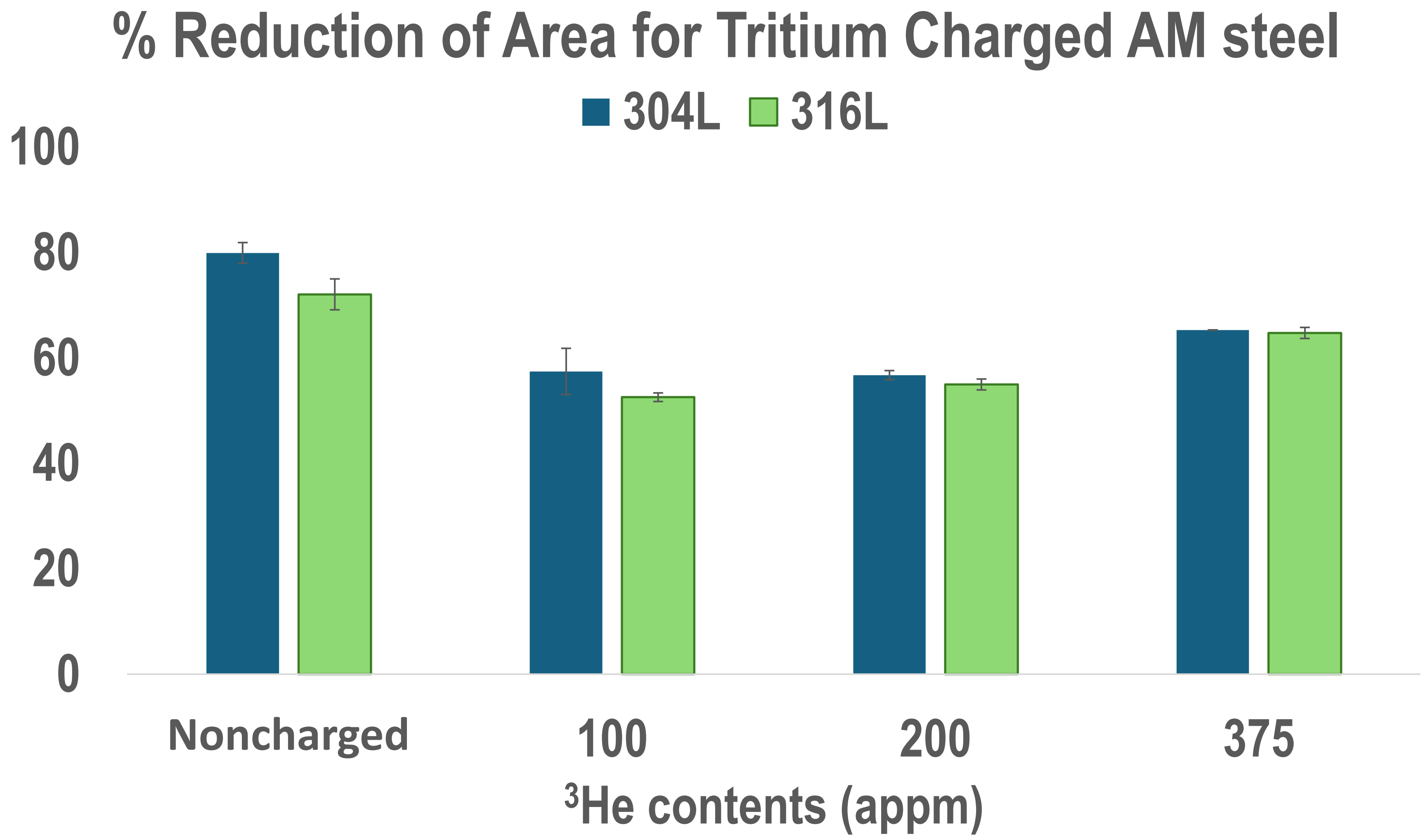


Tritium and helium-3 content leads to increased strength



- Both alloys display increase in strength
- As ^{3}He increases
  - 316L maintains strength
  - 304L appears to continue increasing

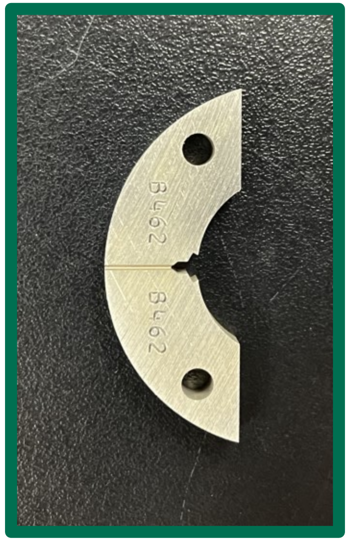
Initial loss of ductility followed by modest increase between 200 and 375 appm helium-3

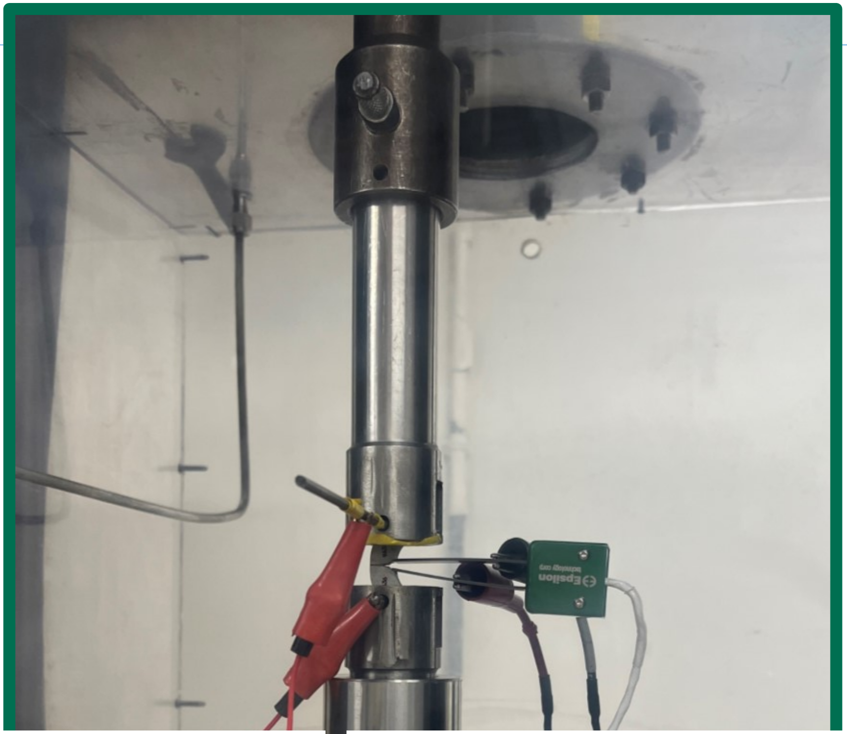


- 20% drop after charging, some increase after 200 appm He
- 304L and 316L behave and perform similarly – even less difference with more ^{3}He

"Arc" fracture testing conducted to evaluate fracture resistance

Same ages as tensile tested samples

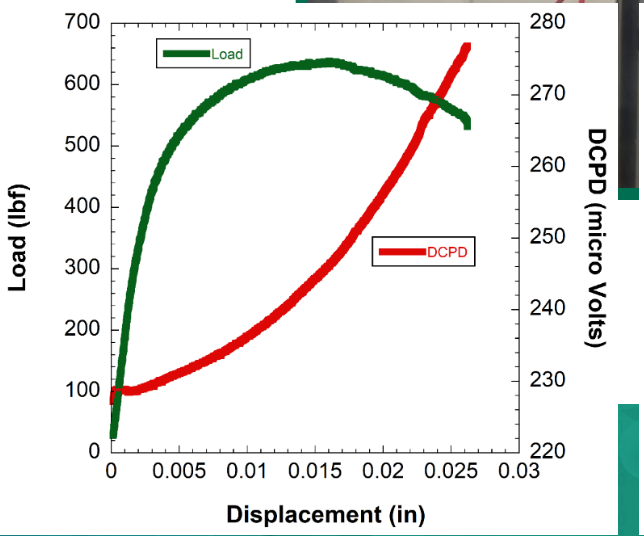


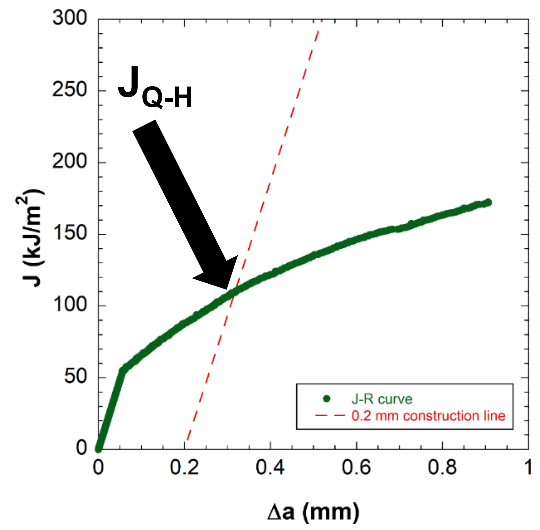


ASTM E1820 fracture test

- Precrack
- Rising displacement at 0.02 mm/min
- Direct current potential drop measured for crack extension

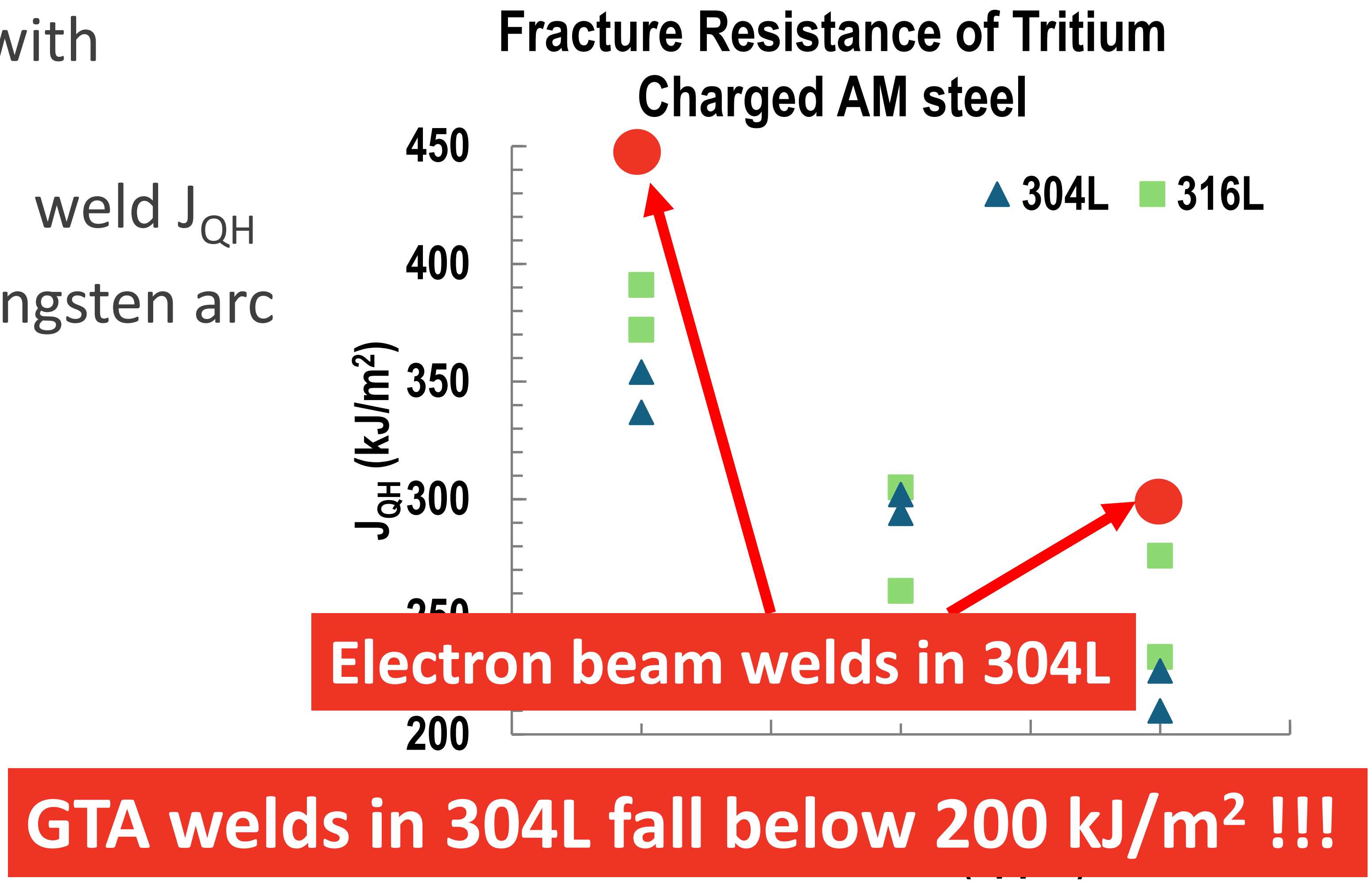
"$J_{Q\text{-}H}$" calculated from load/displacement curve and crack extension





Increased helium content further degrades fracture resistance

- J_{QH} continues to decreases with increasing ^3He
- ~75% of electron beam (EB) weld J_{QH}
- AM 304L outperform gas tungsten arc (GTA) welds



Conclusions and future work

- Both alloys display higher strength and lower ductility when tritium and helium are present
  - Increasing helium does not affect significantly
- Fracture resistance of both alloys decreases with increasing helium
  - Lower than EB welds, higher than GTA welds
- Looking forward…
  - Continue aging and testing at higher helium contents
  - Fracture testing of non charged and hydrogen charged material
  - Other relevant AM material?

Acknowledgements

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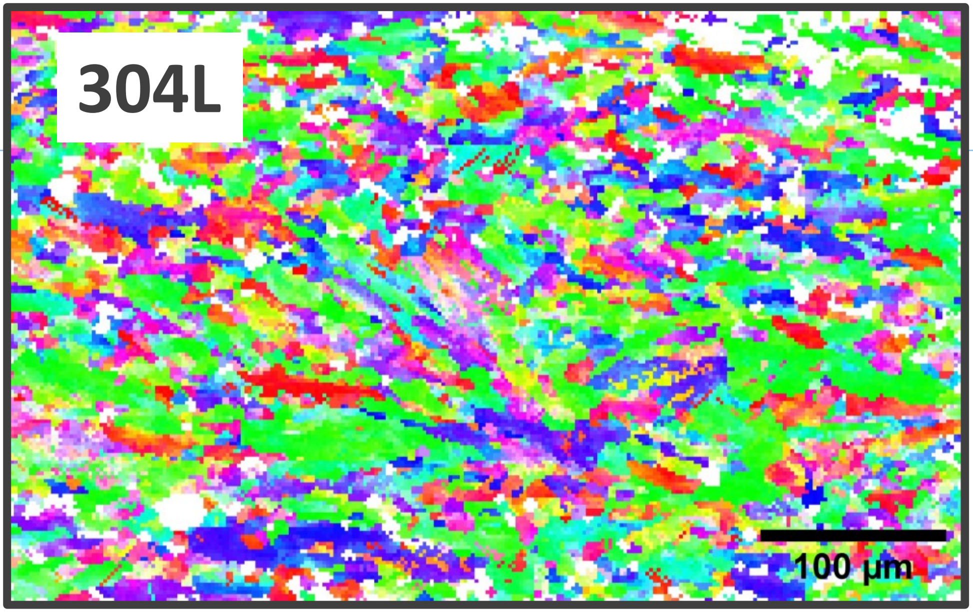
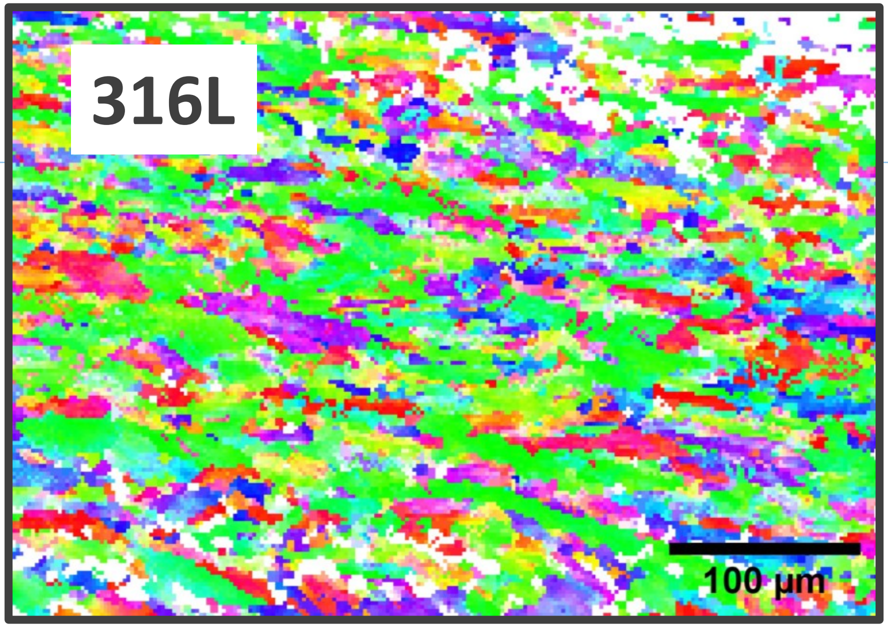
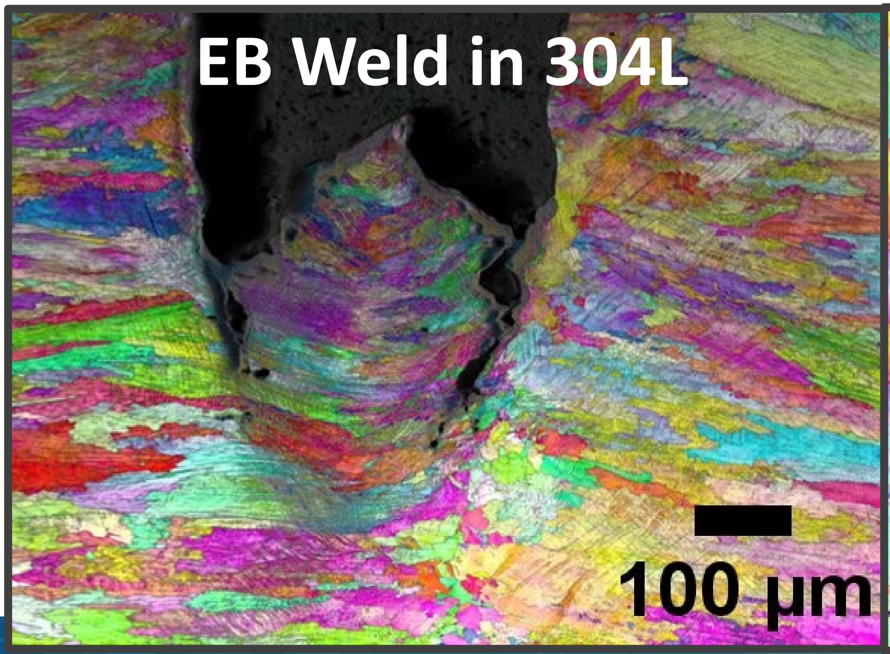
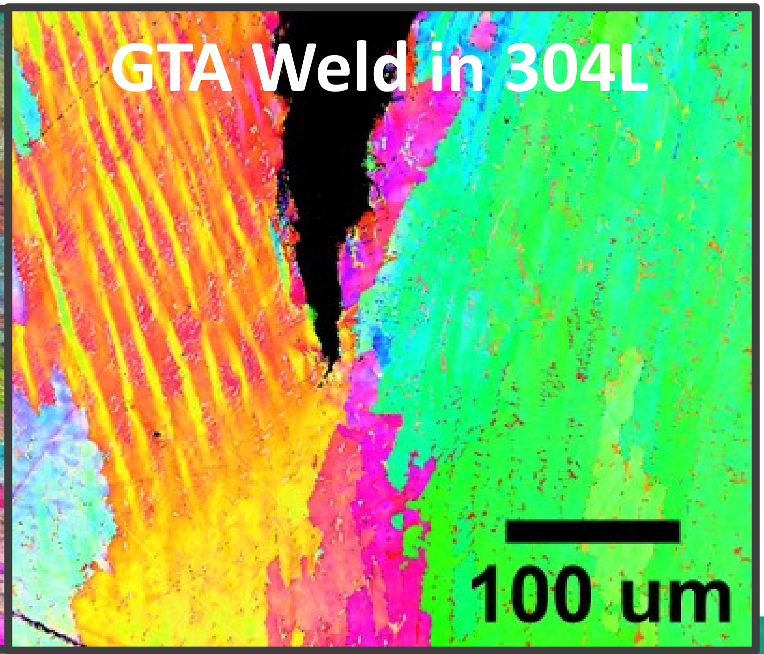
KANSAS CITY NSC National Security Campus

Sandia National Laboratories



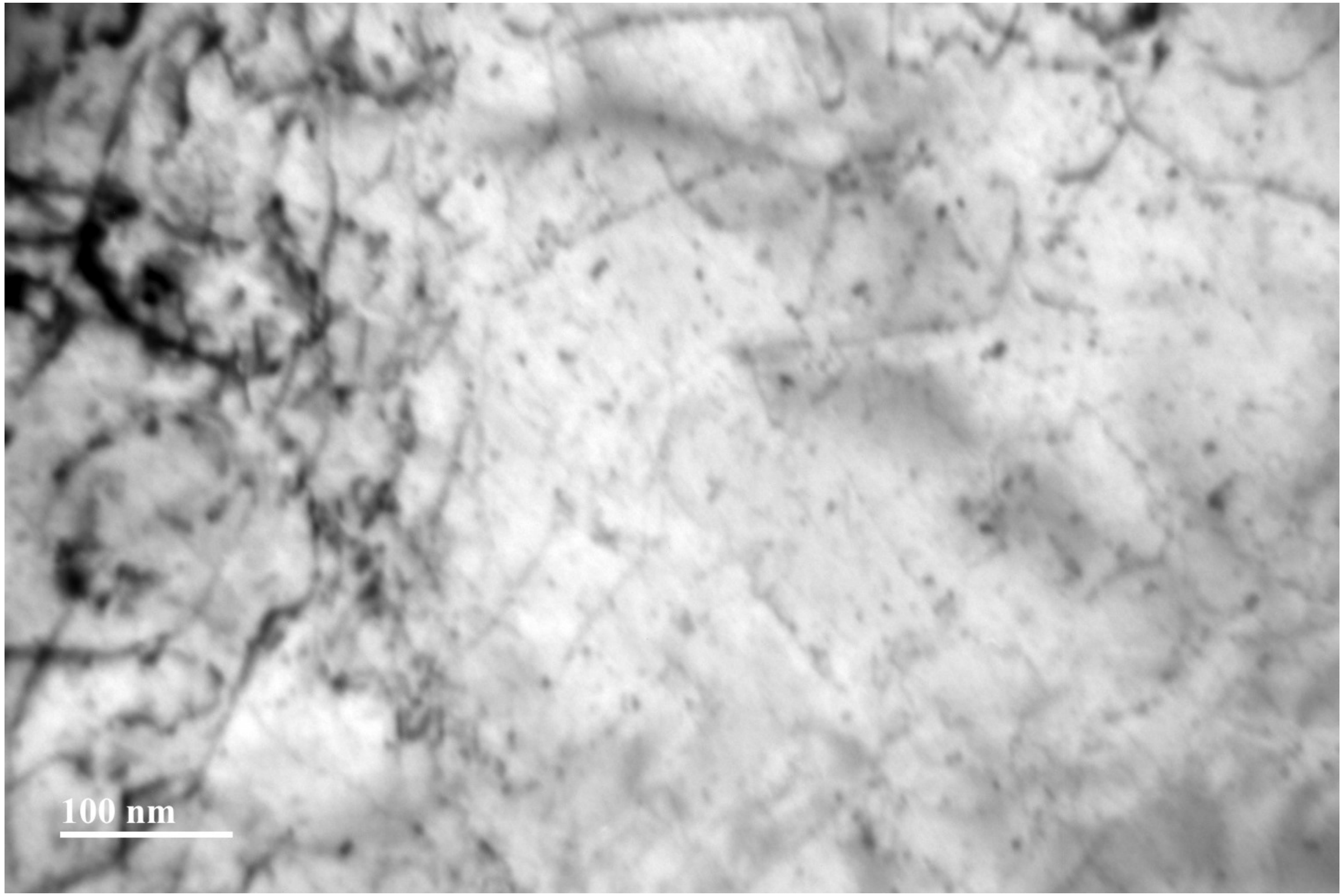




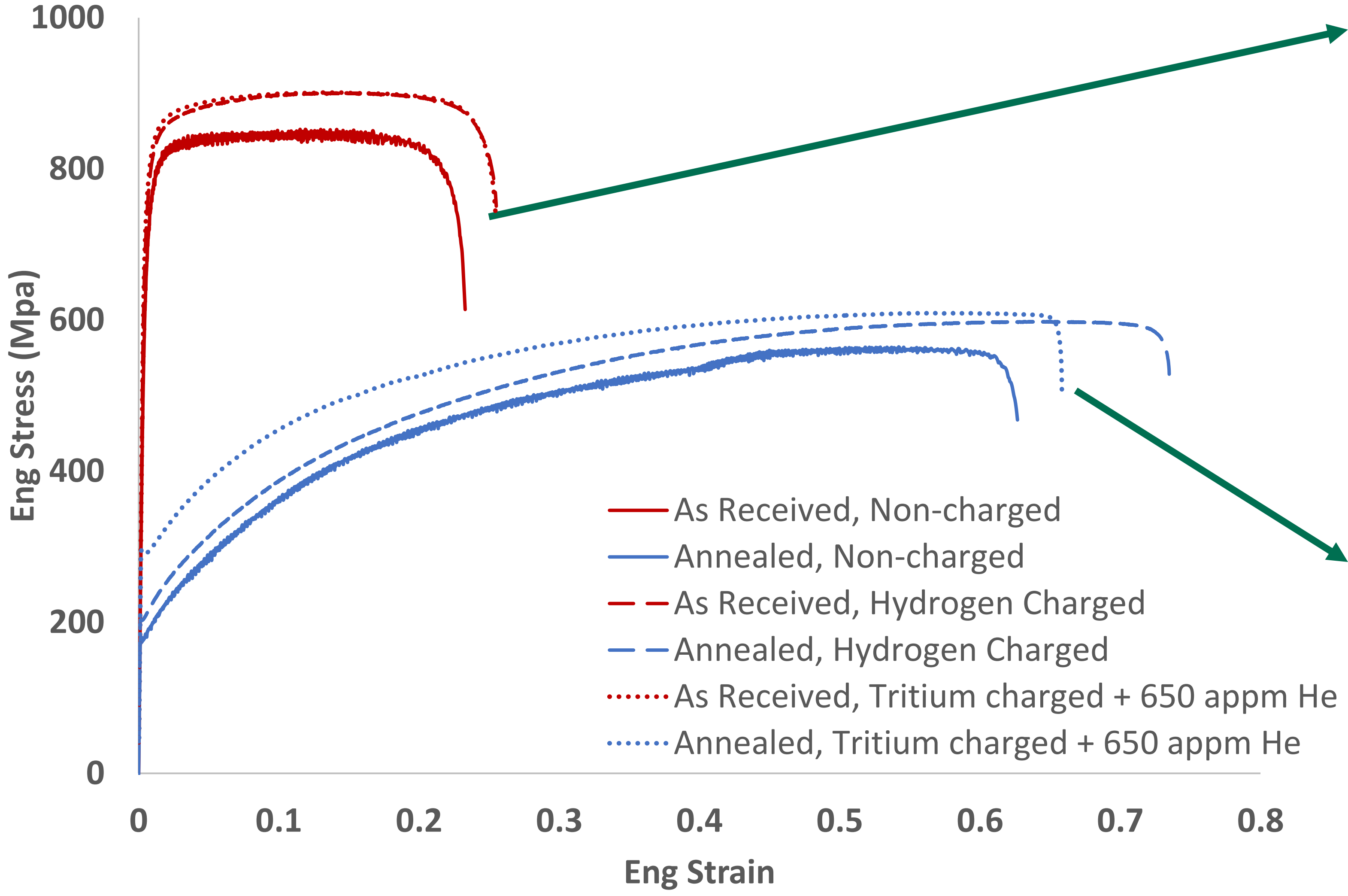


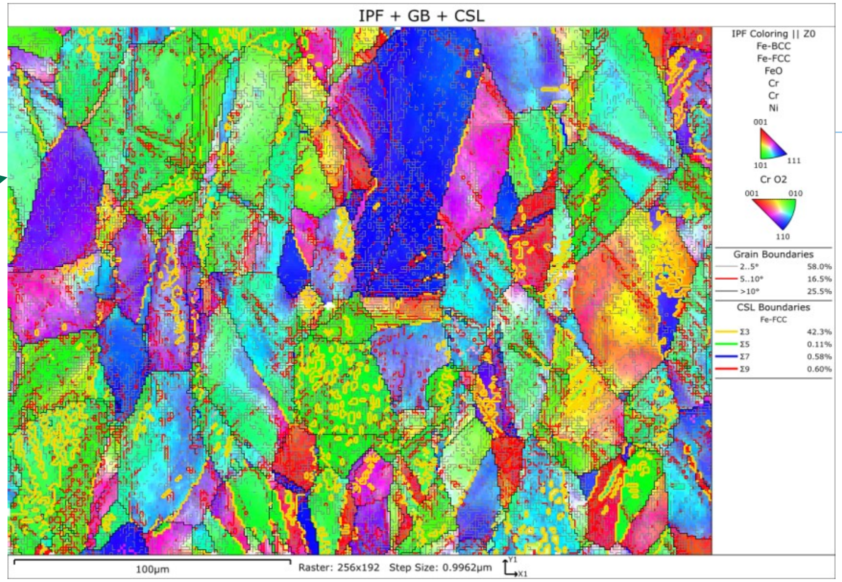
Ronevich, et al. 2025, *in draft*

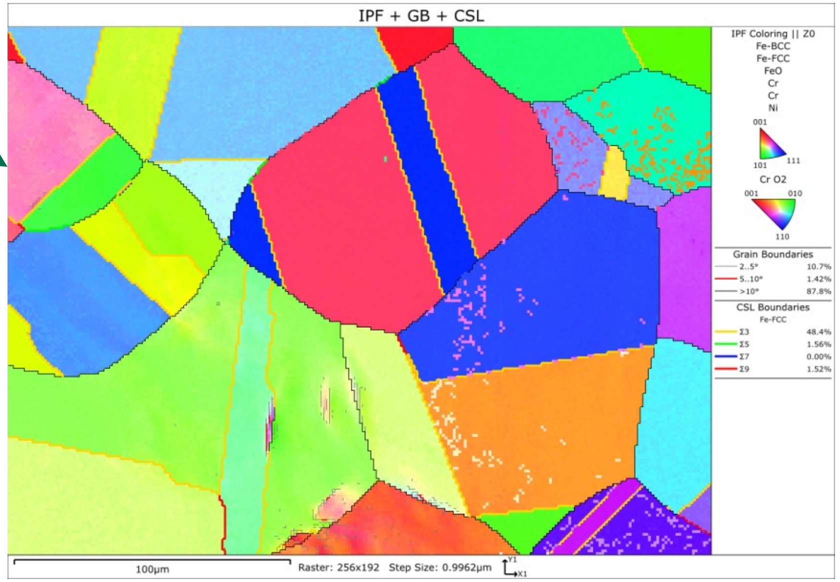
TEM reveals helium bubbles in partially recovered material



304L Tubes: Uncharged, Hydrogen Charged, and Tritium Charged + 650 appm He

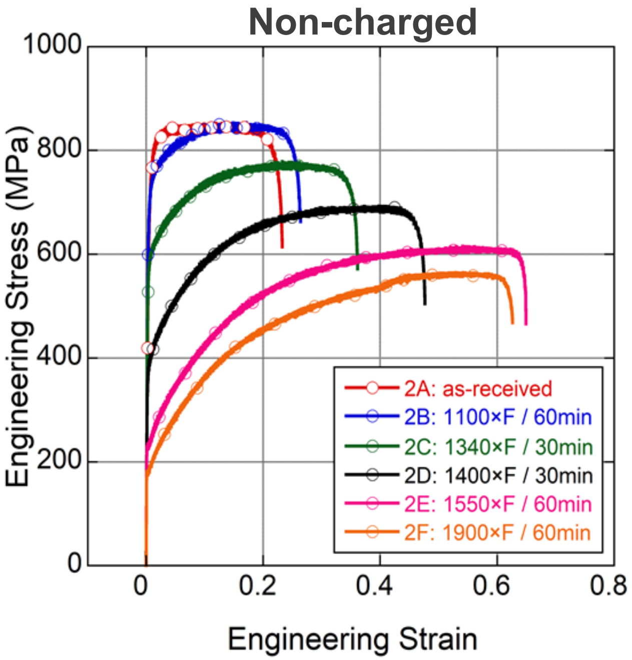


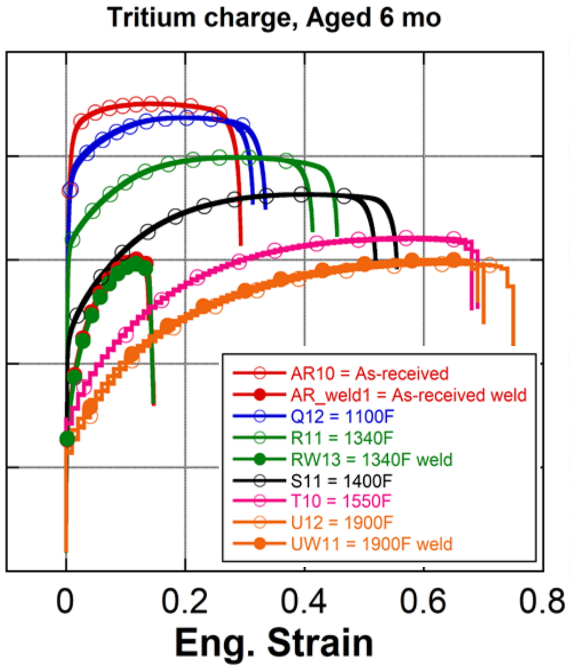


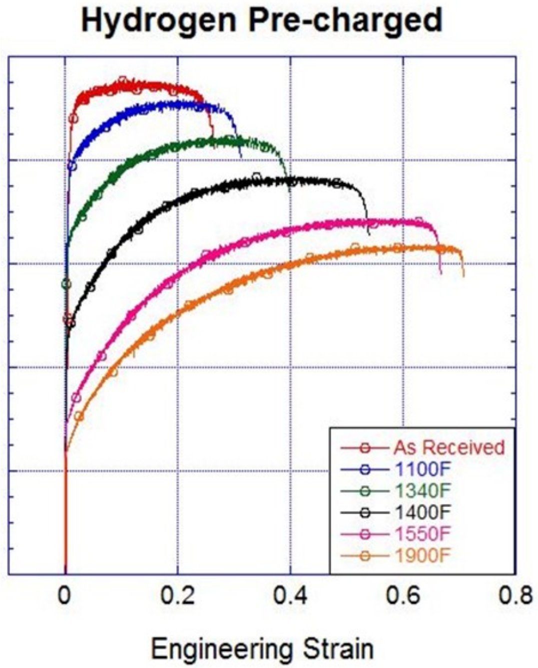


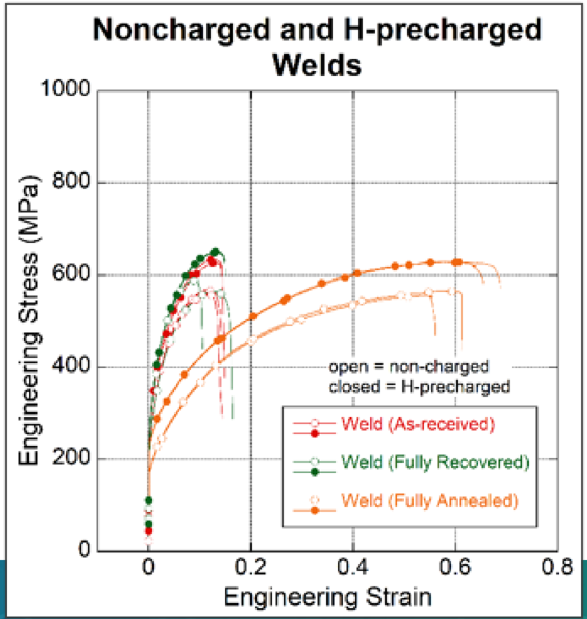
Previous Work

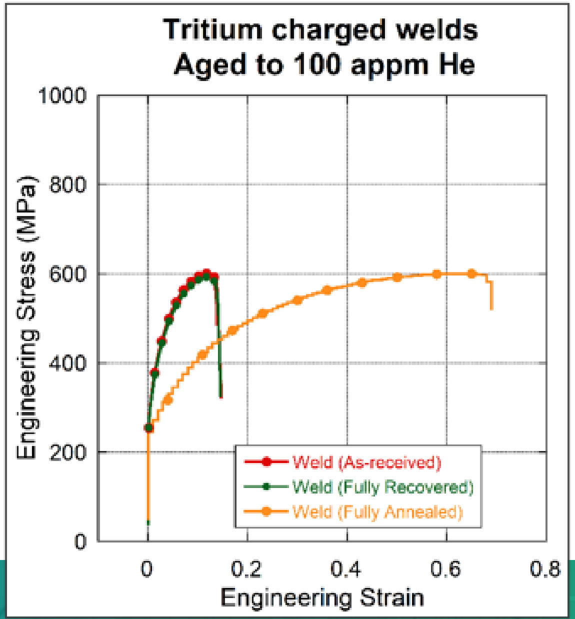
- Yield strength increases similarly for hydrogen and tritium exposed material
- Annealed 304L remains the most ductile of the microstructures, despite hydrogen isotope exposure
- Weld yield strength and UTS are between noncharged and hydrogen charged material





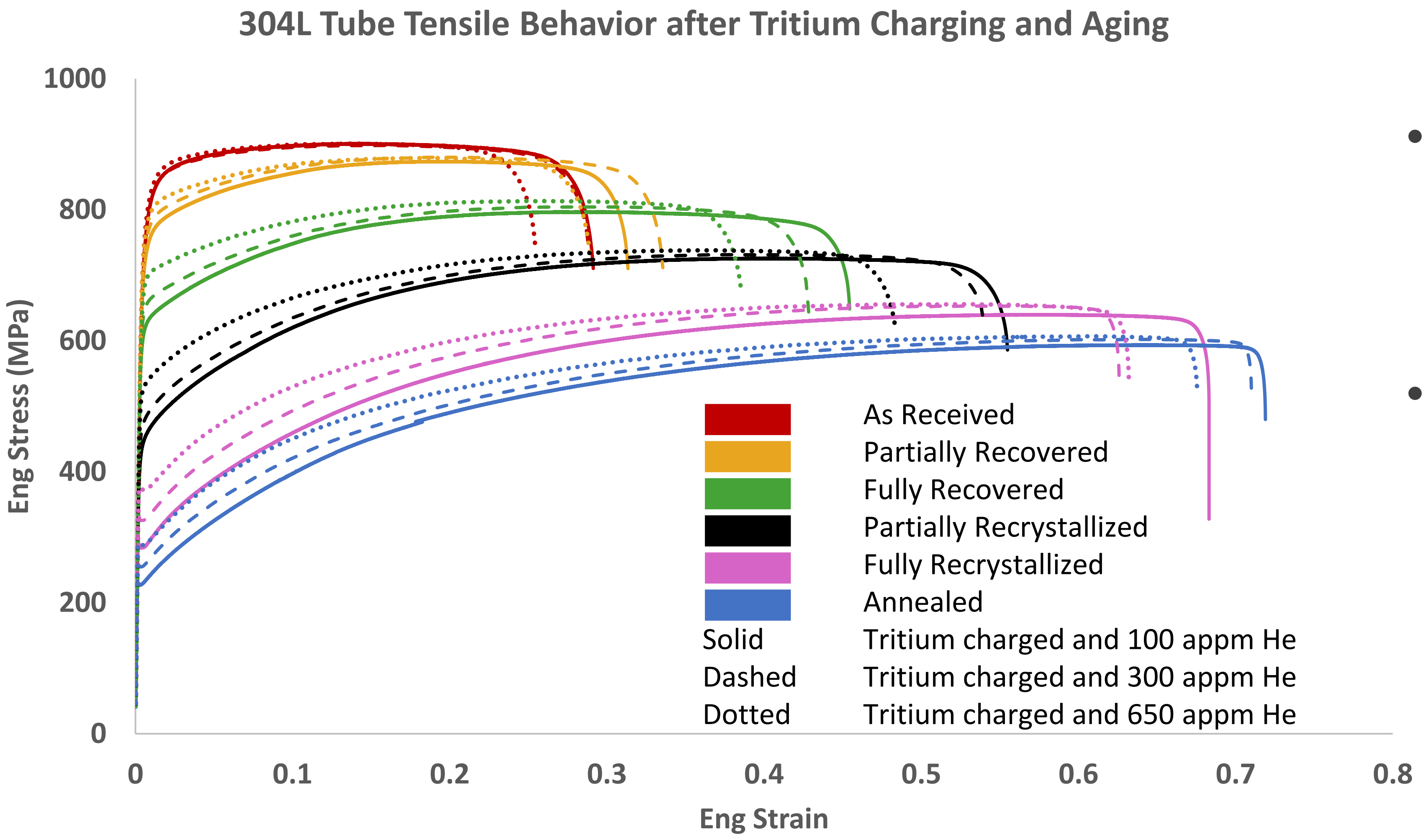






T. M. Krentz, J. A. Ronevich, D. K. Balch, C. San Marchi, Tritium embrittlement of austenitic stainless-steel tubing at low helium contents, Fusion Engineering and Design,168 (2021).

Two additional aging periods



- Recrystallized and annealed material yield and UTS most sensitive to He content
- Yield strength varies more with aging/ increasing with He content

304L Microstructure/Strength Study

- Reduction of Area (ductility)