

Hydrogen-Related Aging in Stainless Steels for GTS Applications

Brian Somerday

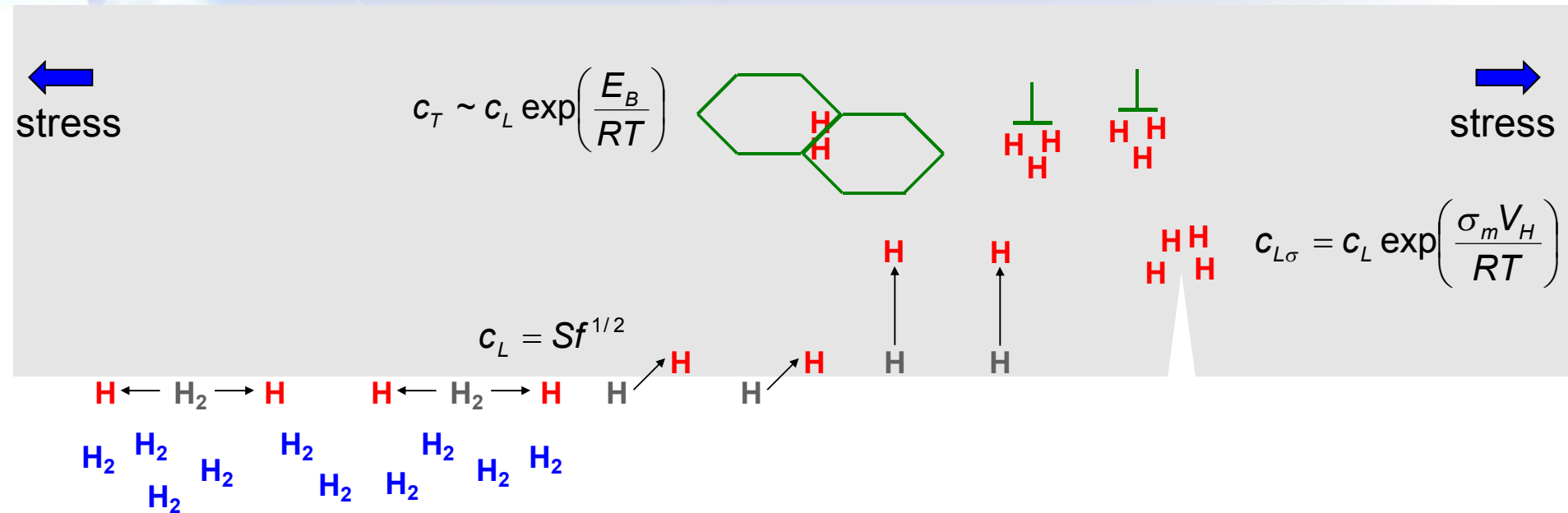
Hydrogen and Metallurgy Science, Org 8252

2013 Enhanced Surveillance (ES) Biennial Review

April 17, 2013

Sandia is a multiprogram laboratory operated by Sandia Corporation, a Lockheed Martin Company, for the United States Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000.

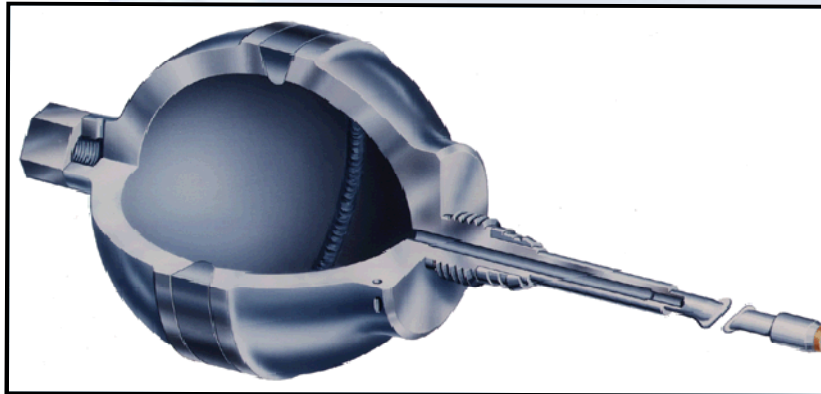
Stainless steels exposed to gaseous H₂ isotopes vulnerable to aging phenomena



H₂ gas → H₂ adsorption → H₂ dissociation →
 H absorption → H diffusion → H trapping

Subcritical crack extension enabled by *mobility* of hydrogen at near-ambient temperature

Safety issue for GTS reservoirs: hydrogen isotope-assisted subcritical cracking

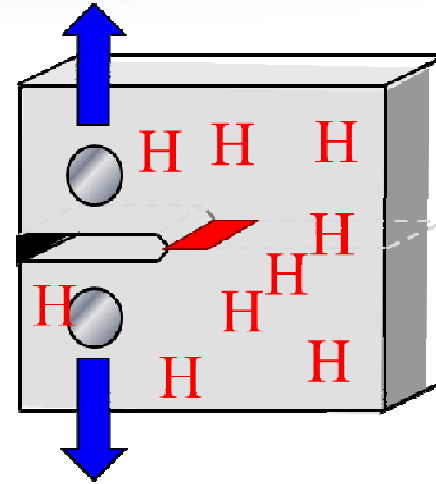


- Despite extensive study of H₂-assisted fracture in stainless steels, several issues require attention:
 - Quantifying H₂-assisted crack extension susceptibility and establishing fracture mechanisms in *welds*
 - Evaluating effects of *sub-ambient temperature* on H₂-assisted crack extension in forged base metal *and* welds
 - Detailed link between deformation and H₂-assisted crack extension

Approach

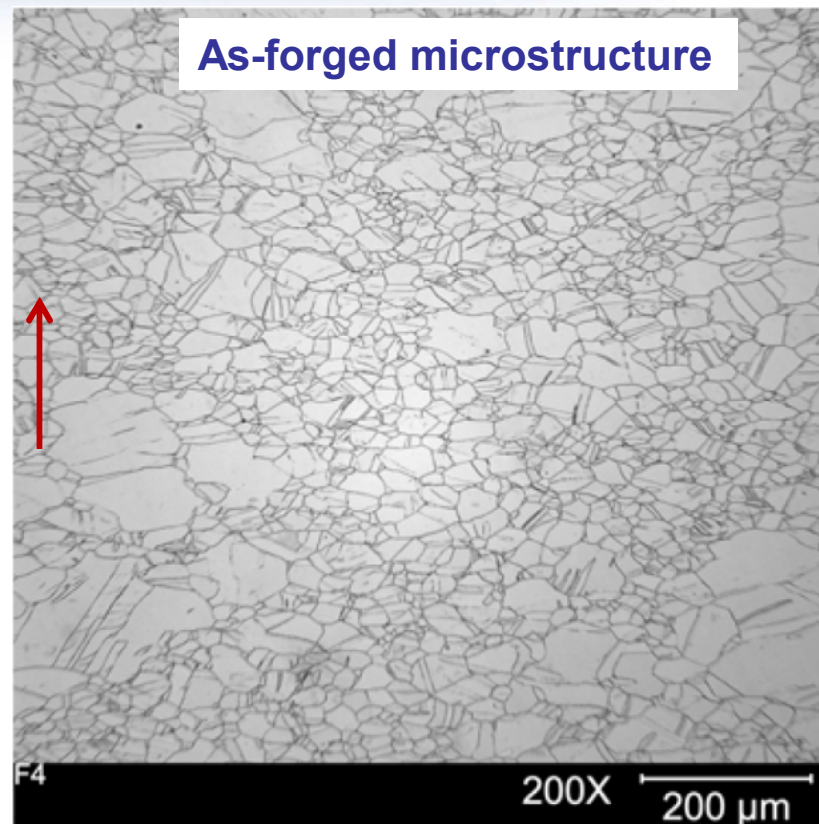
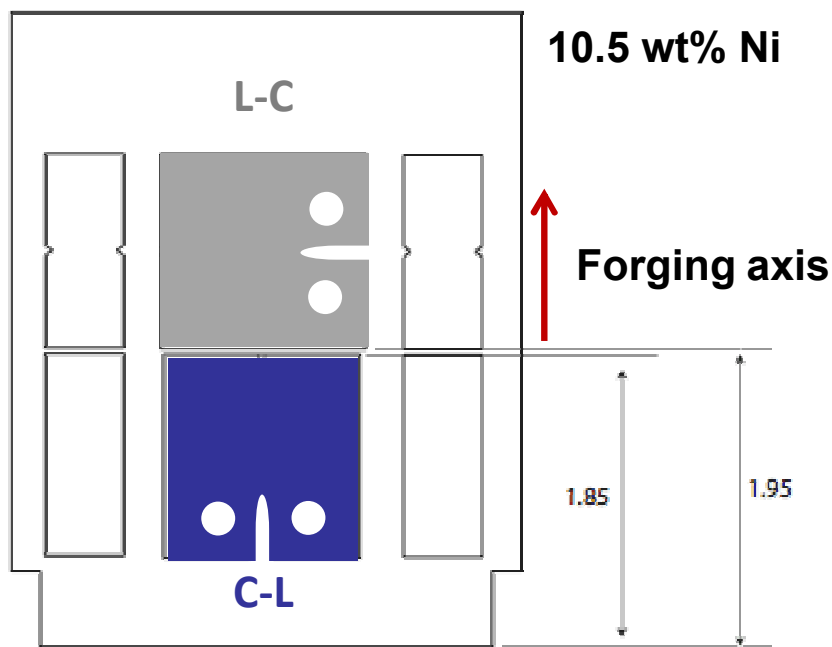
- Measure hydrogen-assisted crack extension resistance of stainless steels using fracture mechanics methods
- Employ electron microscopy and other analytical tools to identify deformation and fracture mechanisms
- Establish physical models of H₂-assisted crack propagation, emphasizing relationship between deformation and fracture
- Based on physical model foundation, develop finite-element framework for modeling crack propagation
- Conduct critical experiments to quantify model parameters

SNL/CA core capability: Hydrogen Effects on Materials Laboratory



- Hydrogen thermal charging facility
 - Expose stainless steel mechanical test specimens to H_2 up to 20,000 psi (138 MPa) and temperature up to 300 °C
 - Measure crack extension resistance of H_2 -exposed specimens at ambient and sub-ambient temperatures

Measure fracture resistance of forged 304L at 293 K and 223 K, with or without H₂

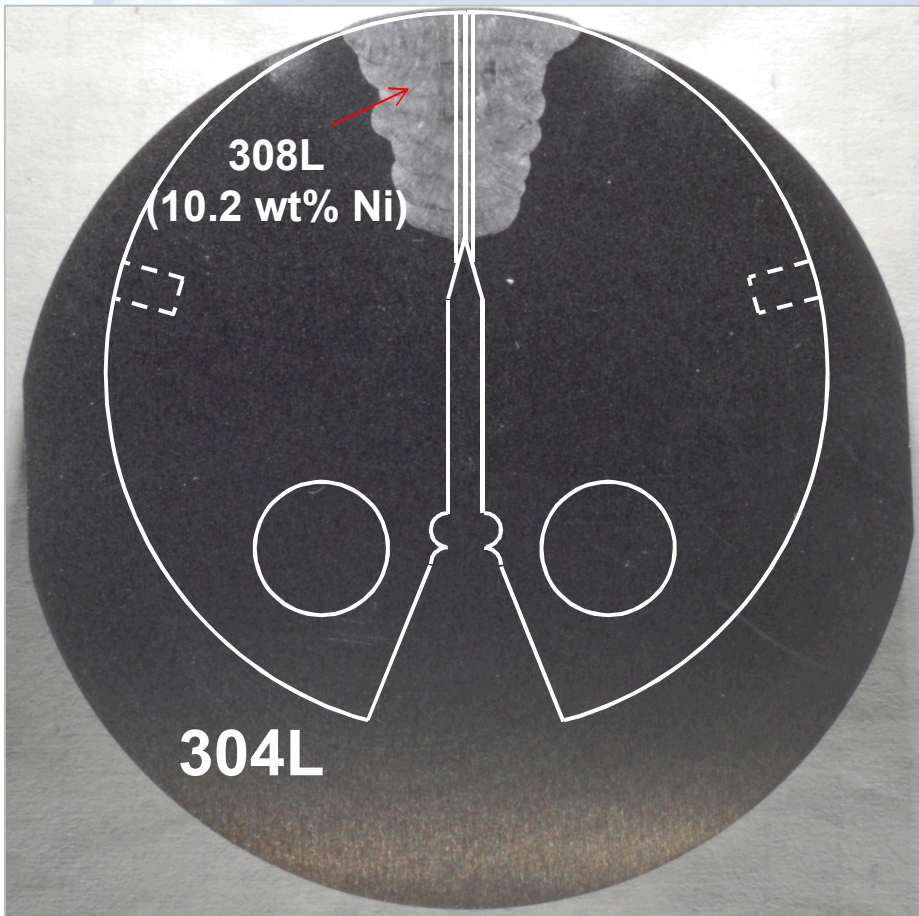


421 MPa yield strength
4-stage qualification lot
1116 K (1550°F)

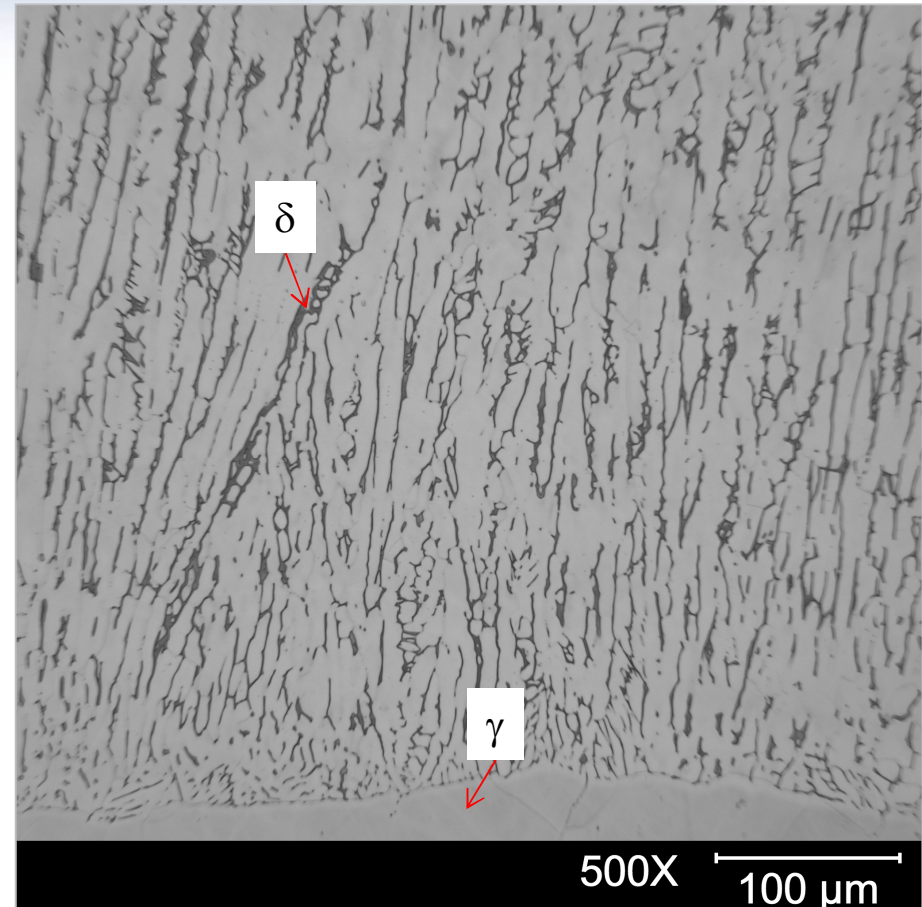
469 MPa yield strength
3-stage, higher-strength lot
1116 K (1550°F)



Measure fracture resistance of 304L/308L GTA welds at 293 K and 223 K, with or without H₂



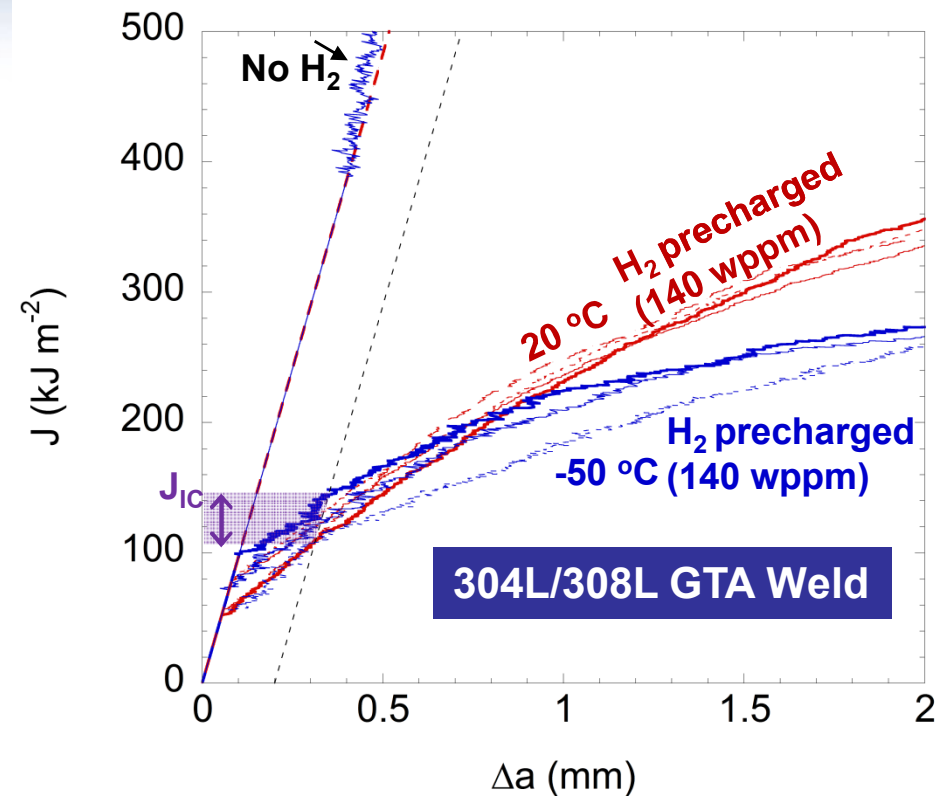
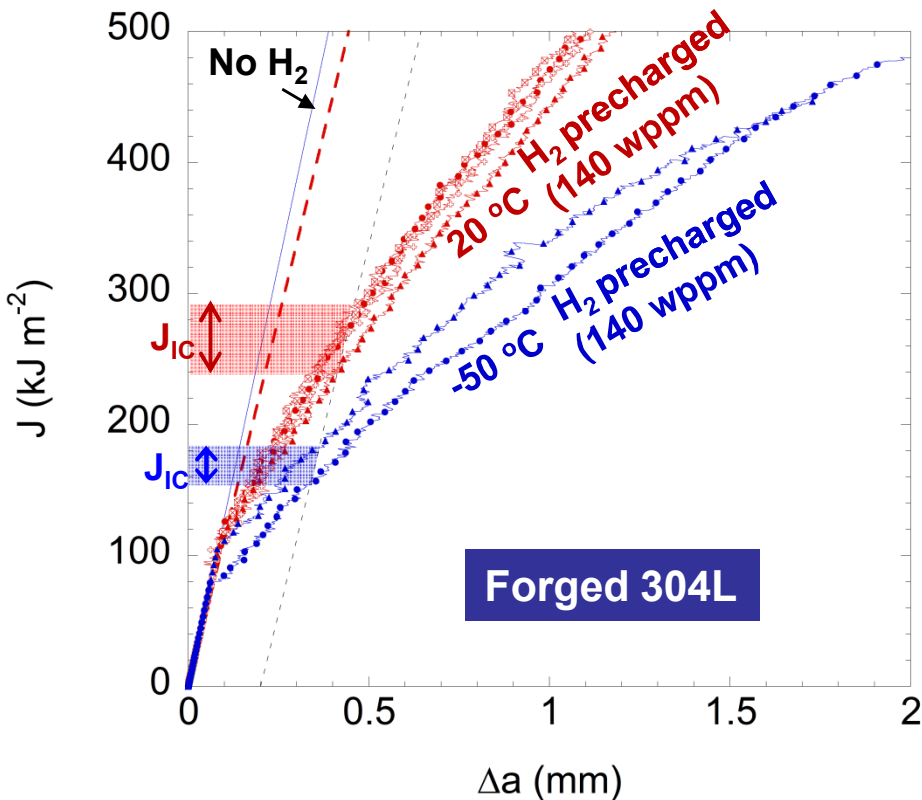
Crack growth direction ↑



Solidification direction ↑

$Cr_{eq}/Ni_{eq} \sim 1.75$
Ferrite number (FN) ~ 10

Temperature effects different in forged base metal compared to GTA weld



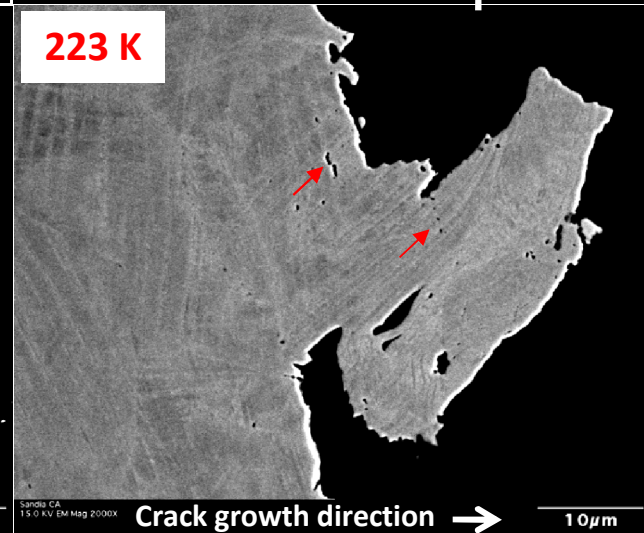
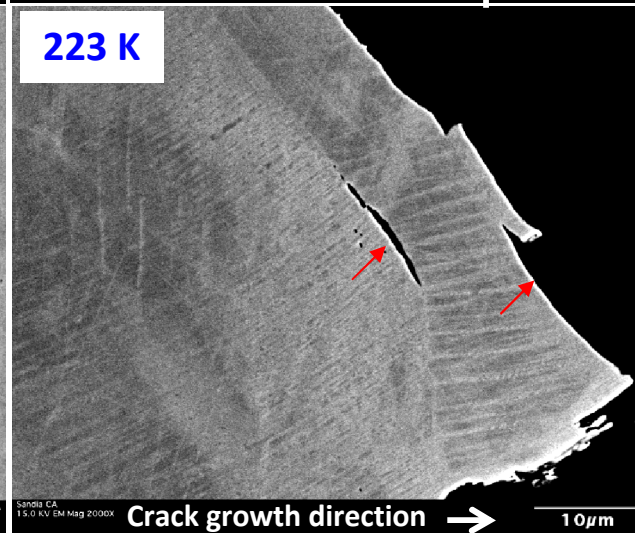
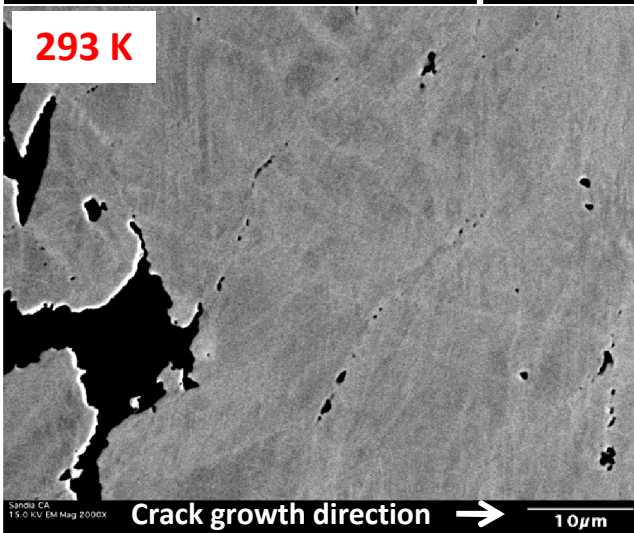
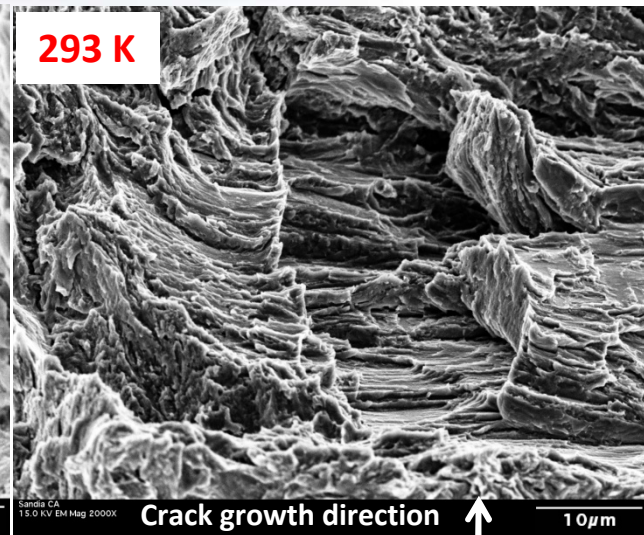
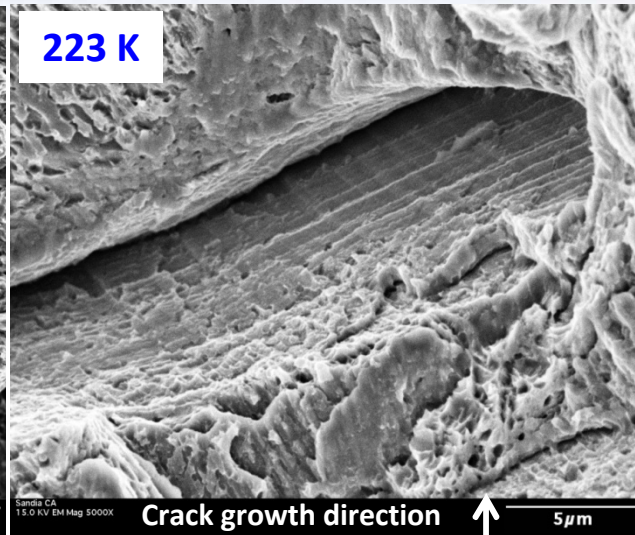
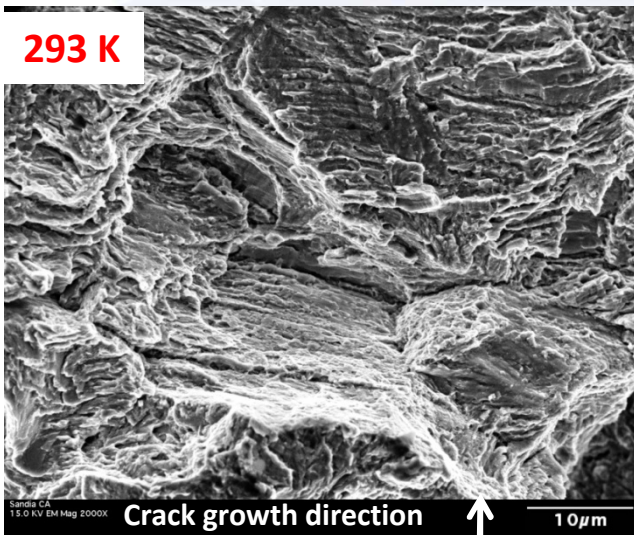
- In H_2 -exposed materials, sub-ambient temperature lowers fracture resistance in forging but not in weld
 - At either temperature, weld more susceptible to hydrogen-assisted crack extension than base metal

Forging: cracks nucleate at intersection of deformation bands with obstacles

At grain boundaries

At twin boundaries (223 K only)

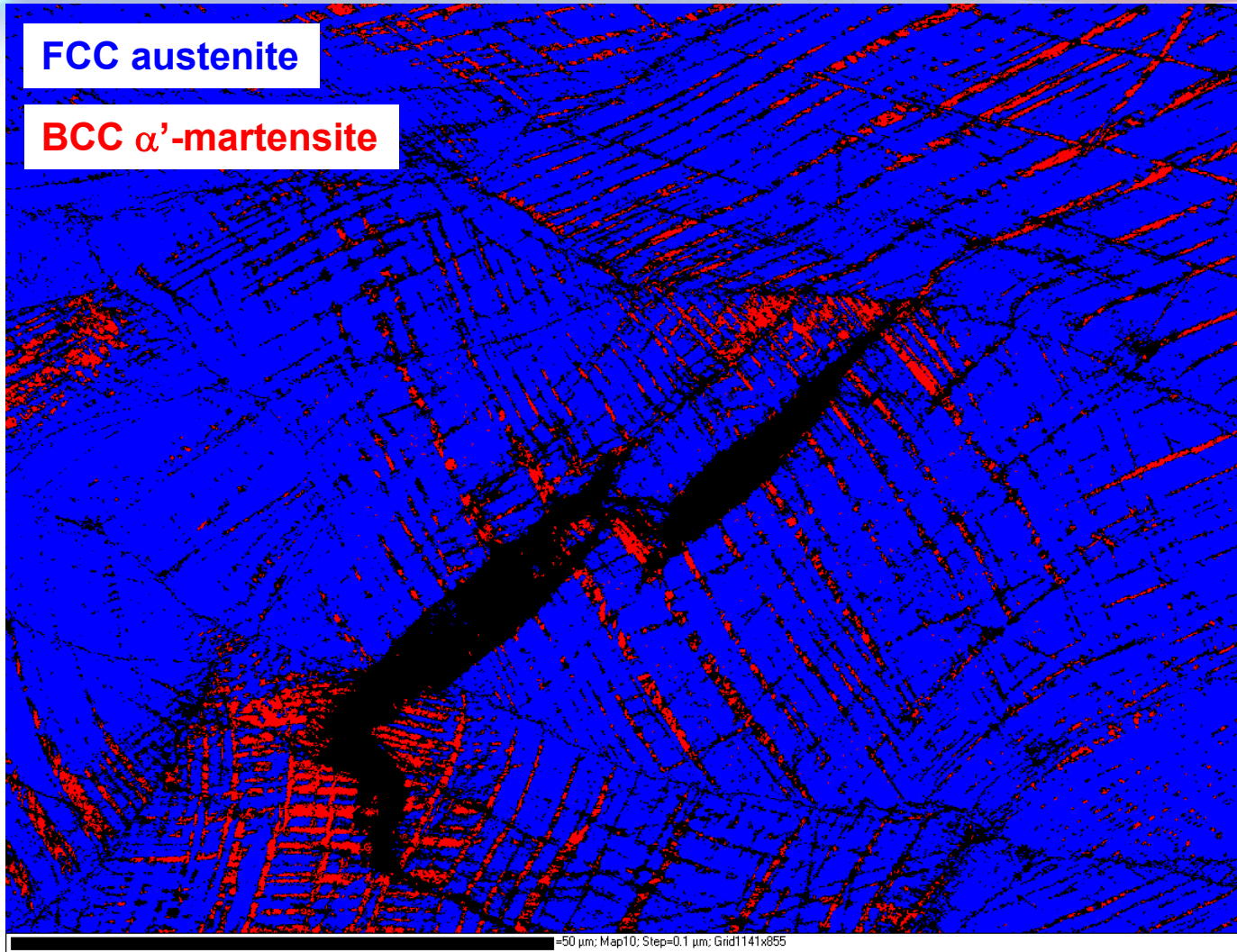
At other deformation bands



★ Forging: EBSD shows cracks initiating at and propagating along deformation bands

FCC austenite

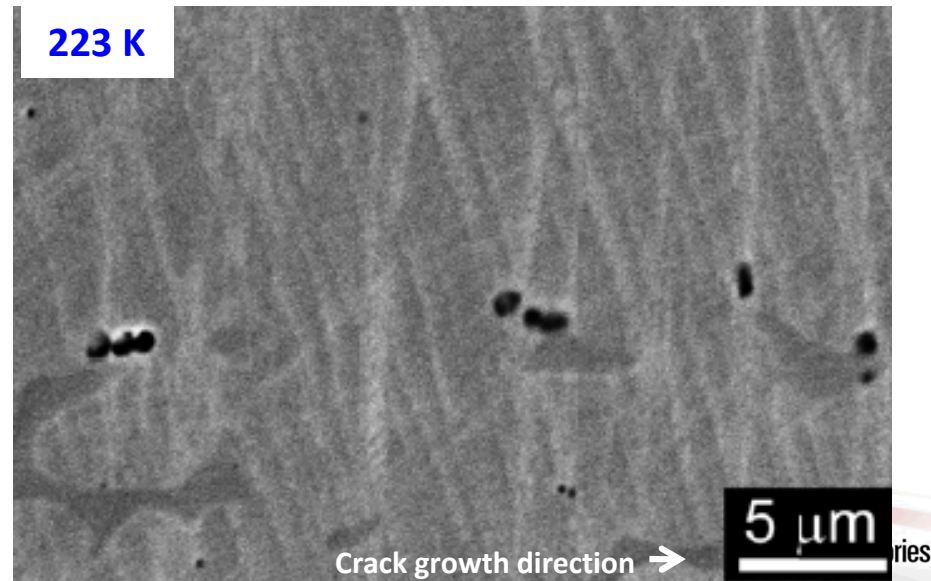
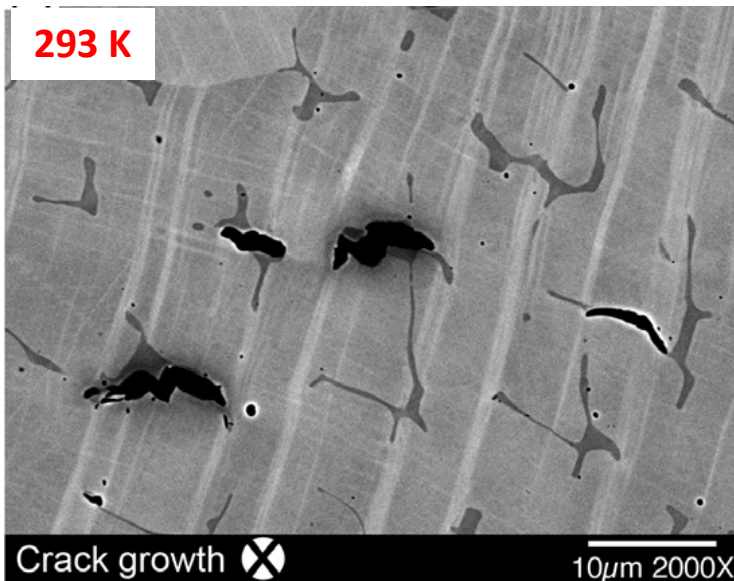
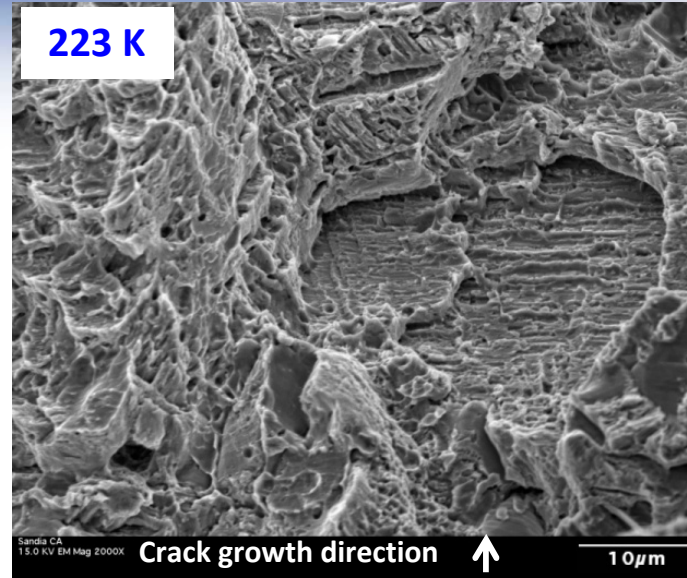
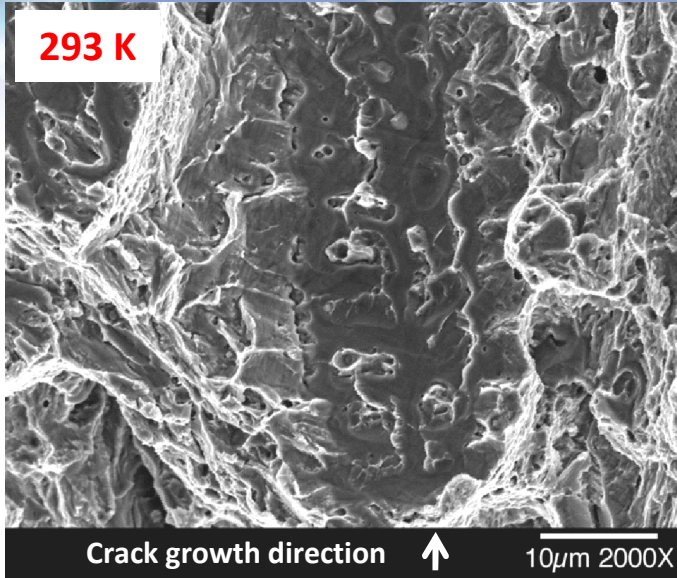
BCC α' -martensite



*J. Michael,
Org 1819*

Specimen precharged with H₂ and tested at 223 K

Welds: crack initiation shifts from δ -ferrite at 293 K to phase boundaries at 223 K

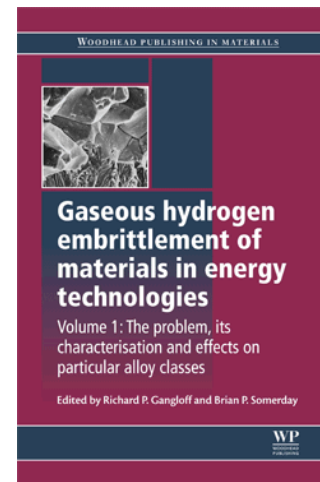
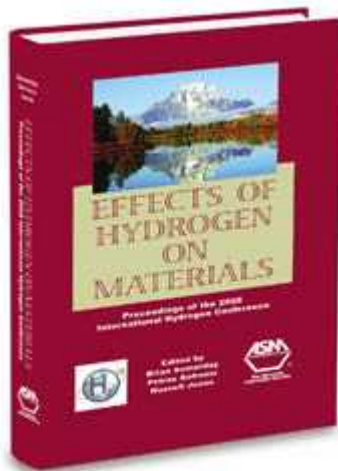


Summary

- Quantified cracking resistance in stainless steel base metal and welds as function of temperature and H₂ exposure
 - In H₂-exposed materials, sub-ambient temperature lowers fracture resistance in forged base metal but not in weld
 - At either temperature, weld more susceptible to hydrogen-assisted crack extension than base metal
- Microscopy evidence shows that hydrogen dramatically alters fracture modes
 - Link between deformation and fracture appears more pronounced in H₂-exposed stainless steels
- **Physical models of hydrogen-assisted crack propagation in stainless steels must include role of deformation mode**

Impact

- Measurements of hydrogen-assisted crack initiation resistance augment data in GTS Design Guide
- Characterizing H-assisted fracture in base metal, fusion zone, and heat-affected zone identifies vulnerabilities
 - Informs potential SFIs in Life Storage Program or stockpile
- Results guide tritium-assisted fracture testing on stainless steels at Savannah River National Lab
- Sandia/CA contributes to international leadership in hydrogen embrittlement technical community



ES project benefits from leveraging with other resources

- Objectives and results from DOE/EERE project in Safety, Codes and Standards and GTS-funded projects complement ES activities
- Hydrogen Effects on Materials Laboratory maintained by leveraging project and capital equipment funds from several NNSA and EERE sources
- Extensive collaborations with universities and research institutions, both domestic and international
 - Long-term relationship with Univ. Illinois, which specializes in developing finite-element model frameworks for H-assisted fracture
 - Relationship with new International Institute for Carbon-Neutral Energy Research at Kyushu University (Fukuoka, Japan)

Future Work

- Continue systematic characterization of hydrogen-affected deformation modes in stainless steels
 - Establish evolution of deformation mode (slip, twinning, ϵ -martensite) as a function of alloy composition, strain, and H concentration
 - Identify detailed role of deformation mode in fracture mechanism
- **Physical model of hydrogen-assisted cracking must include link between deformation and fracture**
 - **Predictive, mechanism-based finite-element models depend on establishing accurate physical models**

Acknowledgments

- Hydrogen Effects on Materials Laboratory team, Org 8252
 - Heather Jackson
 - Chris San Marchi
 - Joe Ronevich
 - Ken Lee
 - Jeff Campbell
- Dorian Balch, GTS Engineering, Org 8254
- Tony DeSousa, GTS Engineering, Org 8254 (welding)
- Joe Michael, Org 1819 (EBSD)
- Ryan Nishimoto, Org 8651 (electron microscopy)
- Andy Gardea, Org 8651 (metallography)