CANFSA

Center for Advanced Non-Ferrous Structural Alloys
An Industry/University Cooperative Research Center

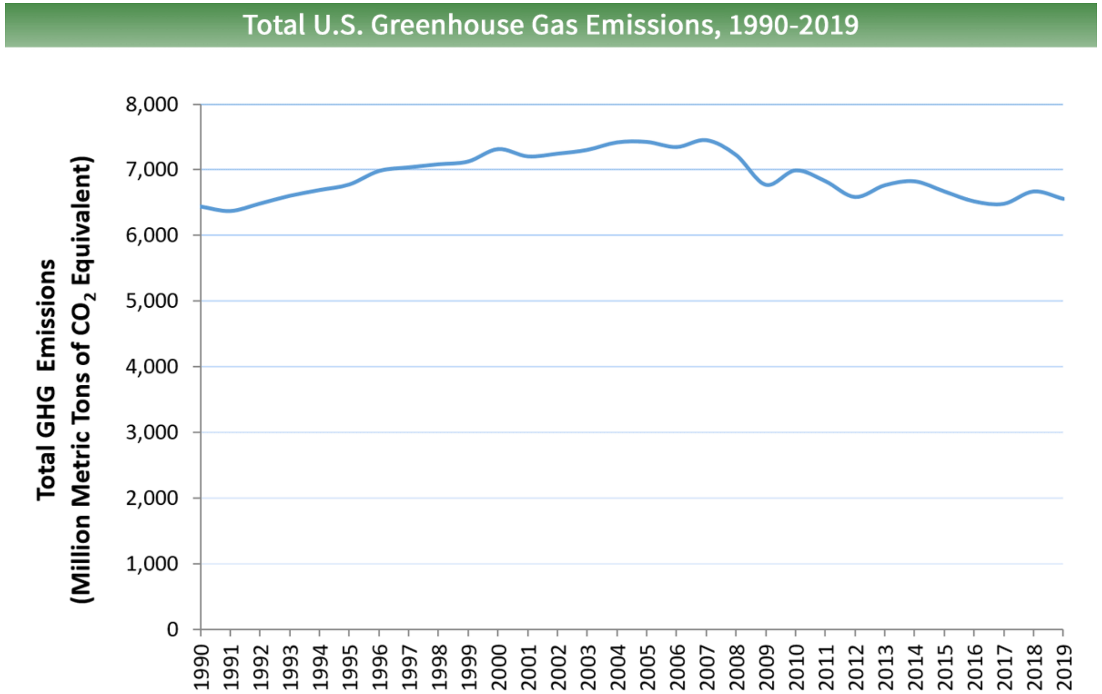
Project 57: Aluminum for H_2 Service

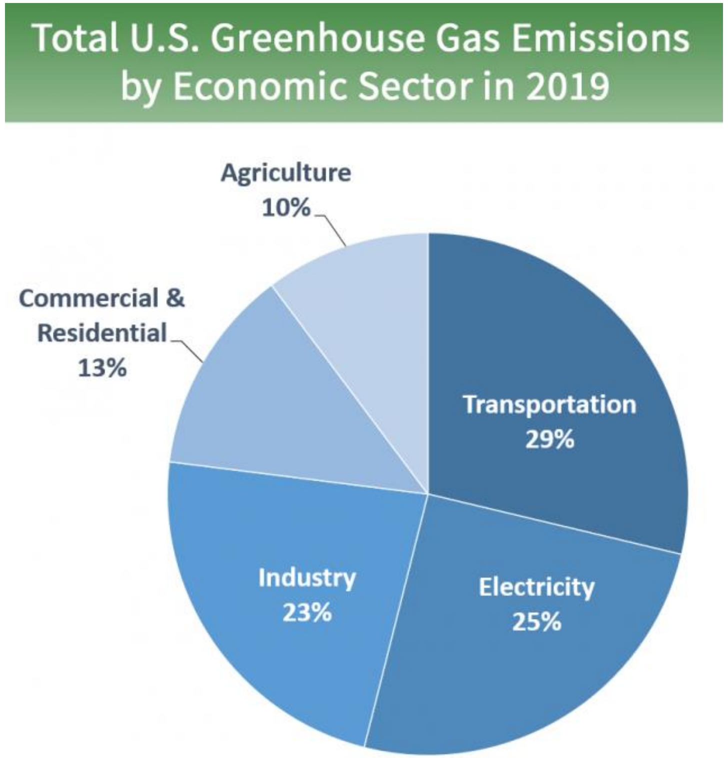
Semi-annual Spring Meeting
April 2022

- Student: Adam Freund (Mines)
- Faculty: Dr. Suveen Mathaudhu, Dr. Kester Clarke, Dr. Amy Clarke (Mines)
- Industrial Mentors: Atish Ray, John Carsley, Shawn Yu (Novelis)

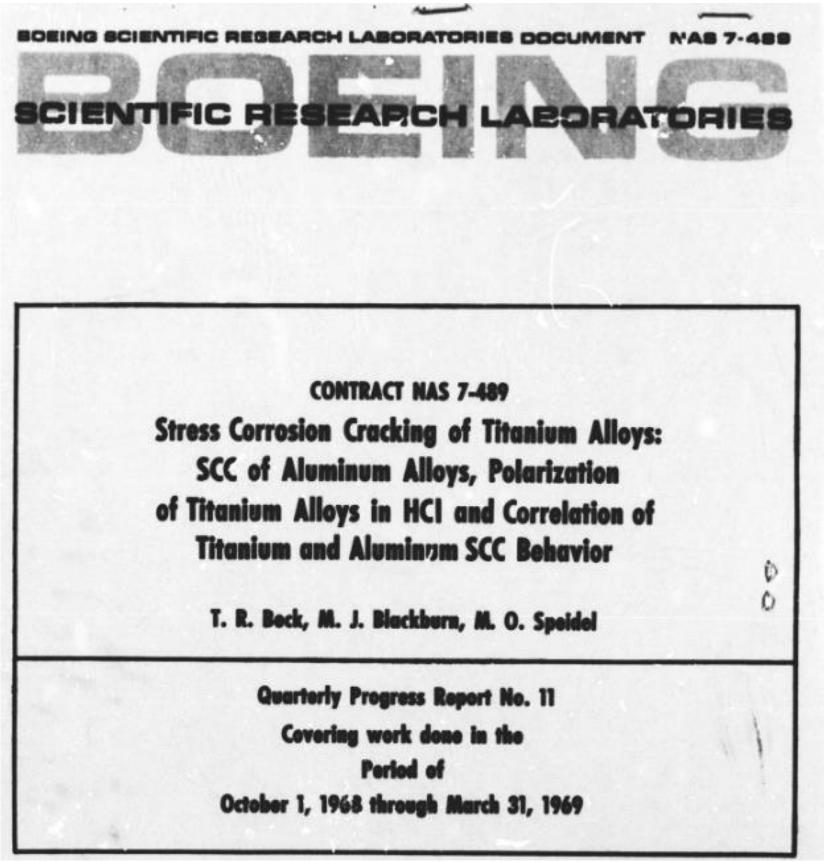
COLORADO SCHOOL OF MINES NSF IOWA STATE UNIVERSITY

The Drive for Hydrogen Research





Hydrogen Embrittlement of Aluminum



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Stress Corrosion Cracking of Titanium Alloys: SCC of Aluminum Alloys, Polarization of Titanium Alloys in HCl and Correlation of Titanium and Aluminum SCC Behavior

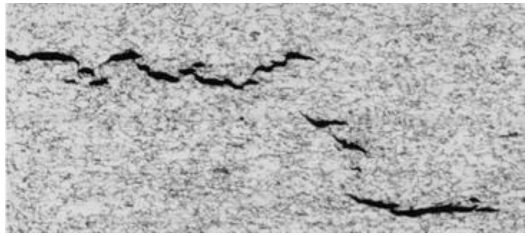
T. R. Beck, M. J. Blackburn, M. O. Speidel

Quarterly Progress Report No. 11
Covering work done in the
Period of
October 1, 1968 through March 31, 1969

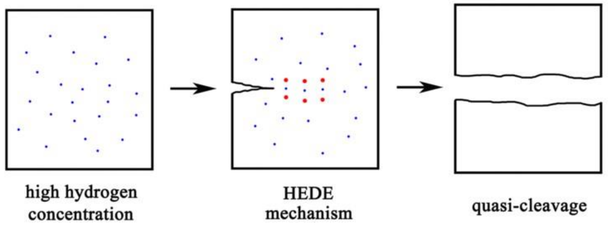
4-28-1988 After 89,090 flight cycles on a 737-200, metal fatigue lets the top go in flight.

Hydrogen Embrittlement Processes

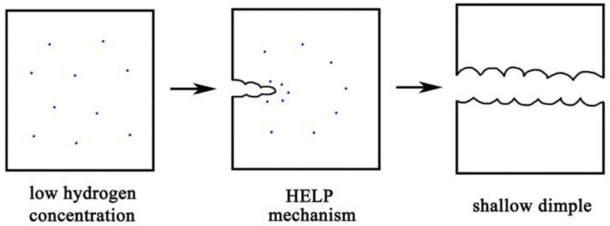
- Hydrogen-induced Cracking:
  - Cracks created by sufficiently high concentrations of hydrogen



- Hydrogen-enhanced Decohesion:
  - Presence of hydrogen reduces fracture energies at interfaces

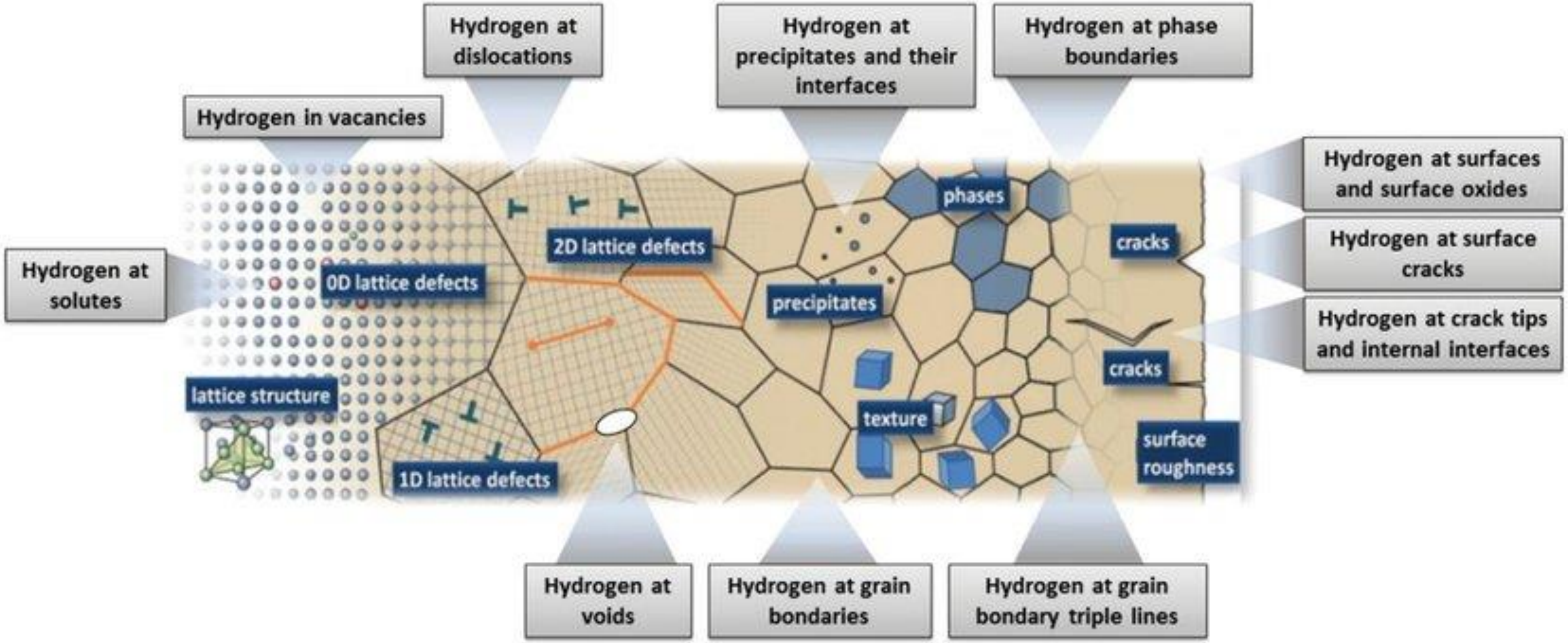


- Hydrogen-enhanced Local Plasticity:
  - Presence of hydrogen lowers activation barrier to dislocation motion



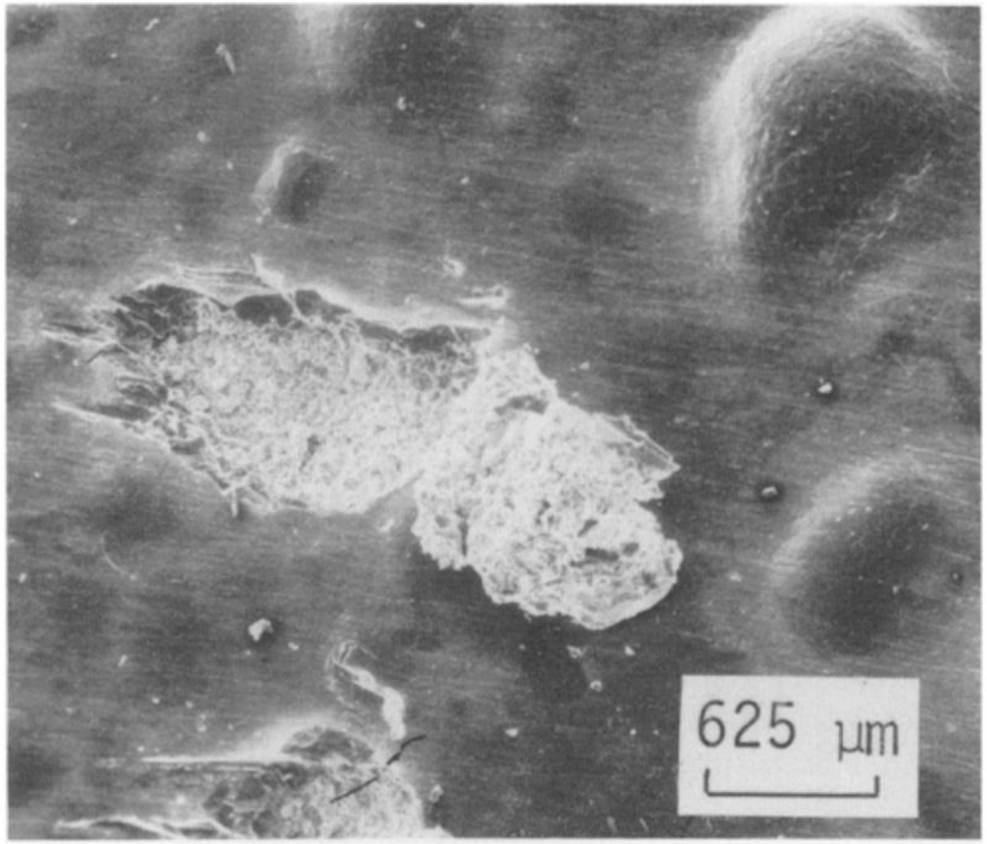
- Hydrogen-mediated microvoid distribution:
  - Coalesced molecular hydrogen creates larger cavities during high temperature deformation

Hydrogen Trapping Sites

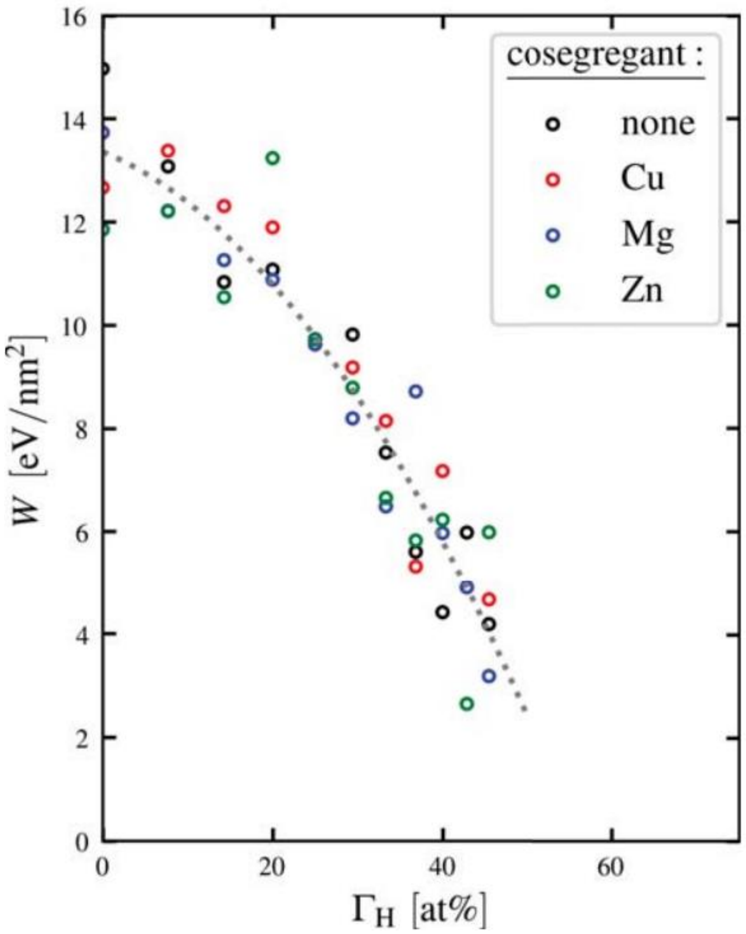


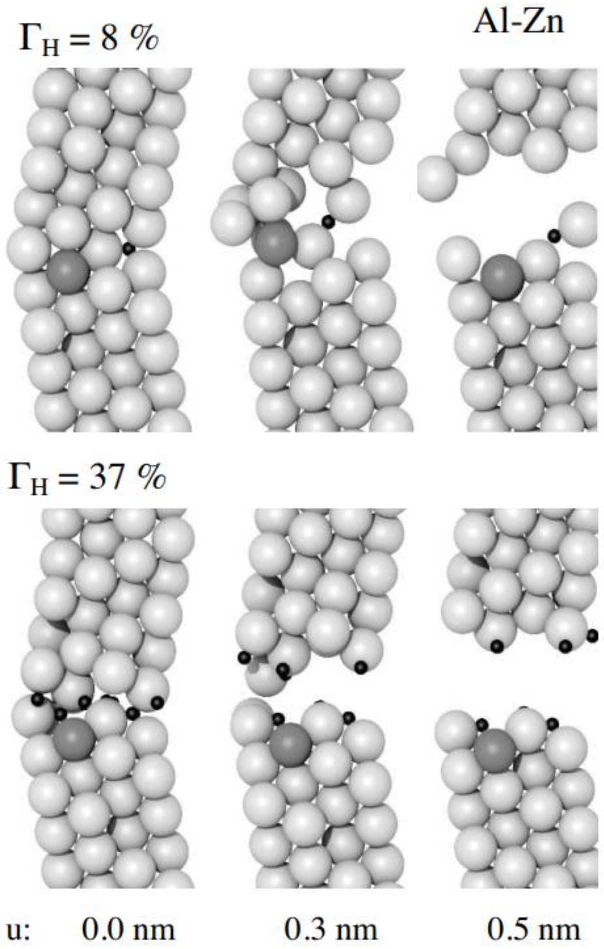
Moisture Effects on Aluminum

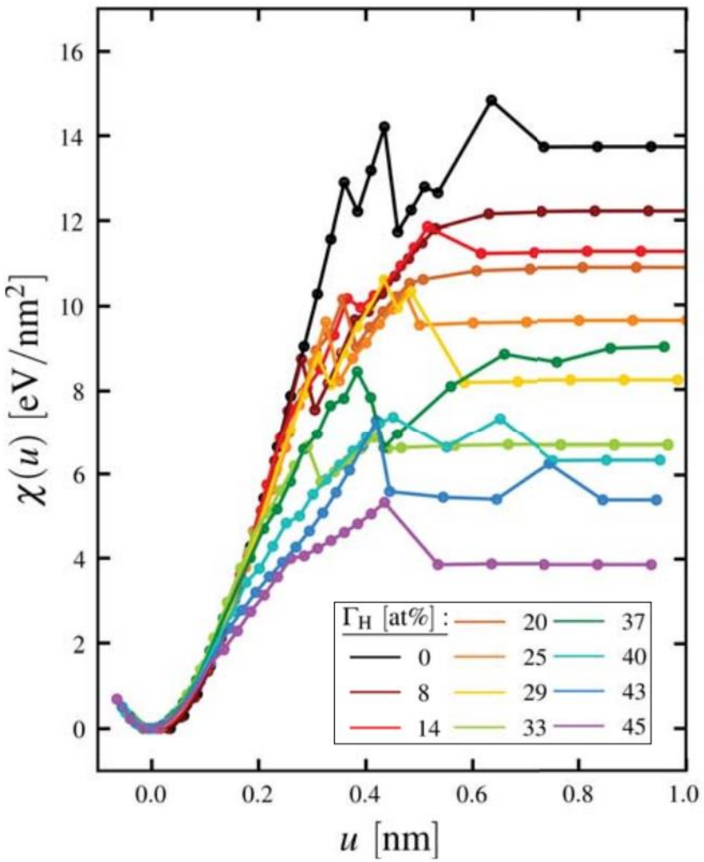
- Aluminum is highly resistant to hydrogen embrittlement*
- $2Al + 6H_2O \longrightarrow 2Al(OH)_3 + 3H_2$
- $2Al + 4H_2O \longrightarrow 2AlO(OH) + 3H_2$
- $2Al + 3H_2O \longrightarrow Al_2O_3 + 3H_2$
- Can cause surface bubbling, which will eventually break away



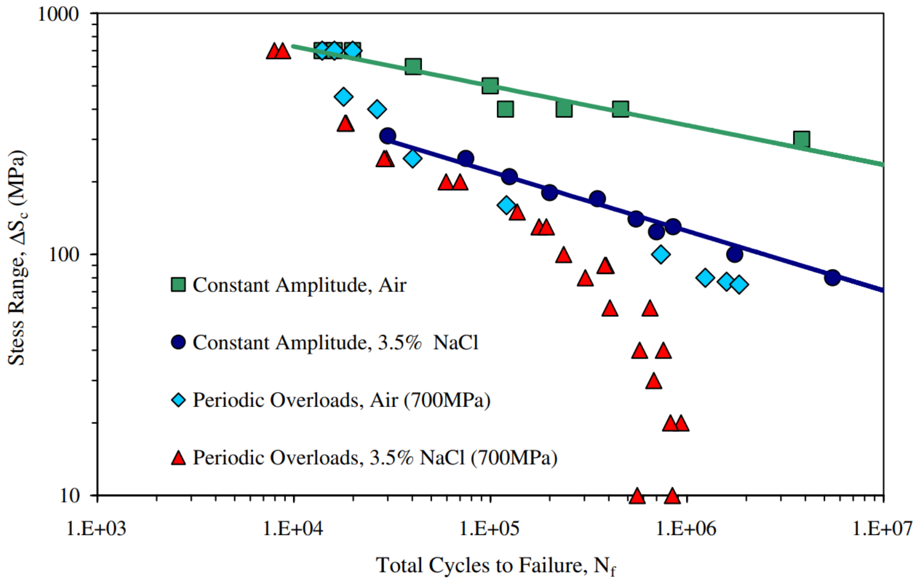
DFT Calculations and Simulations

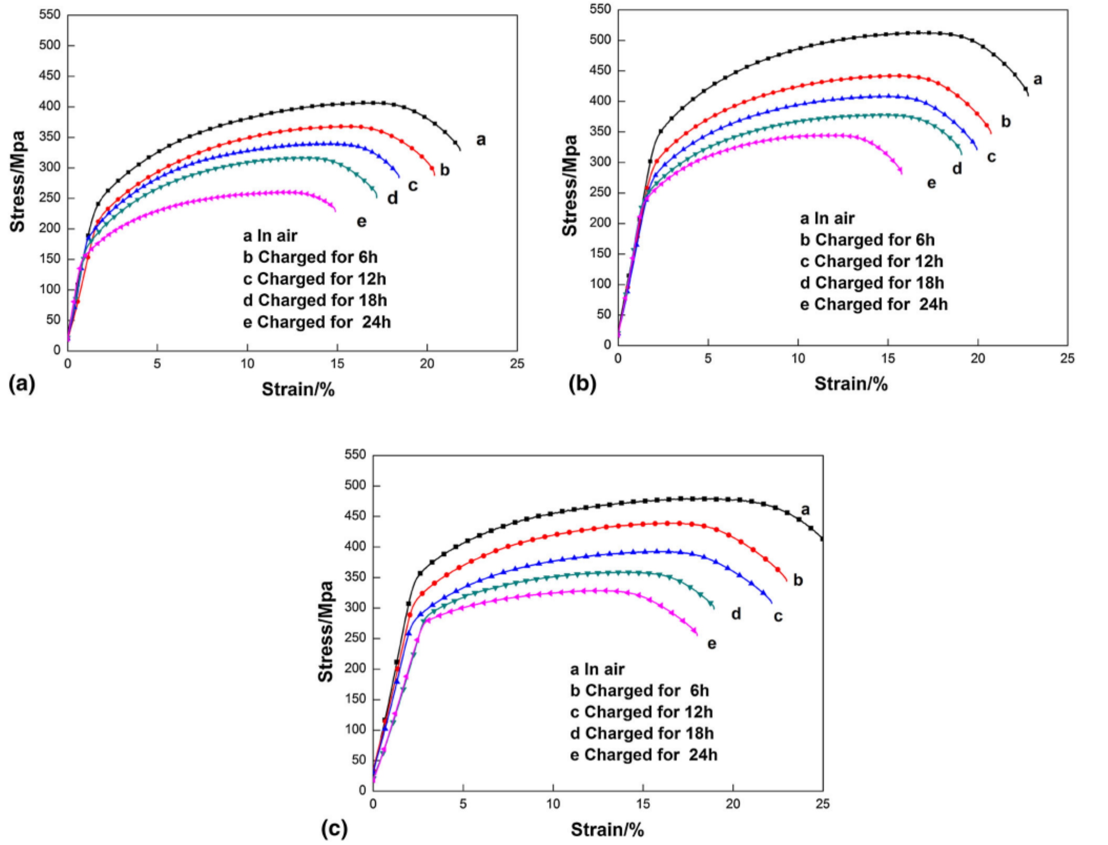






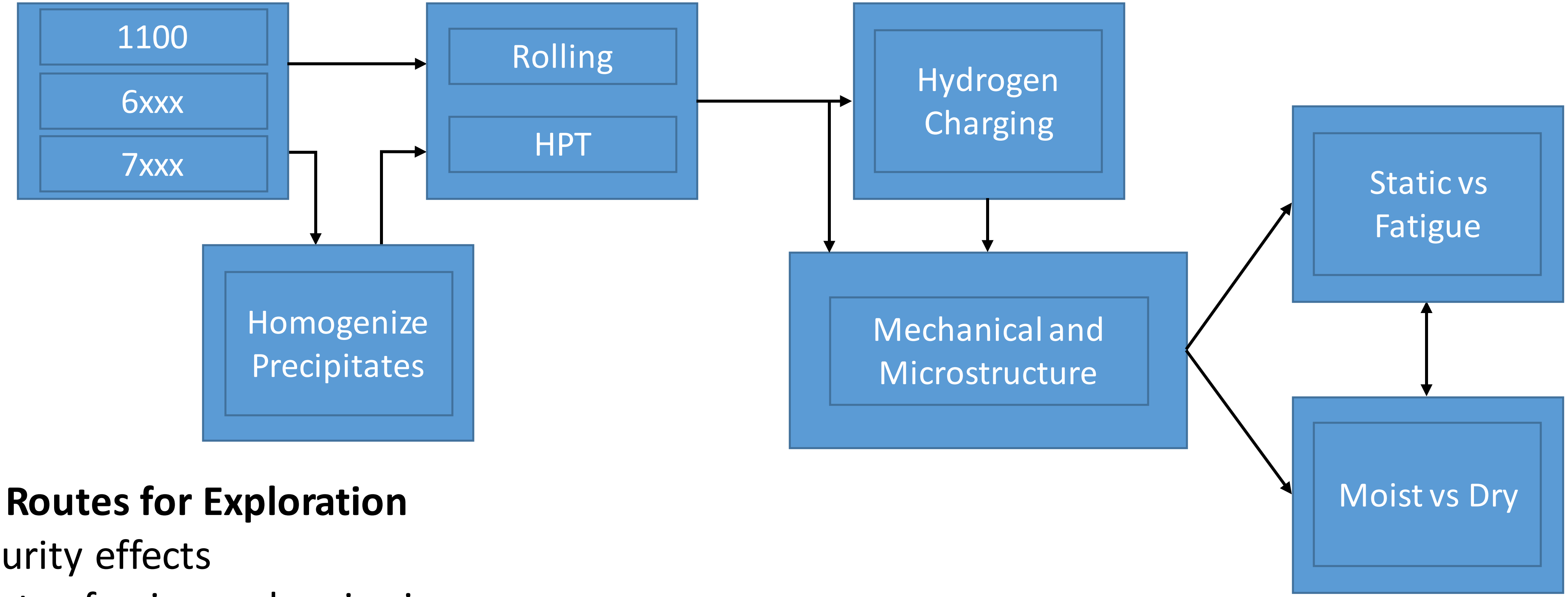
Effects on Mechanical Properties





- Exposure to hydrogen impacts quasi-static and fatigue resistance. Increased contact leads to reduced mechanical properties

Experimental Plans



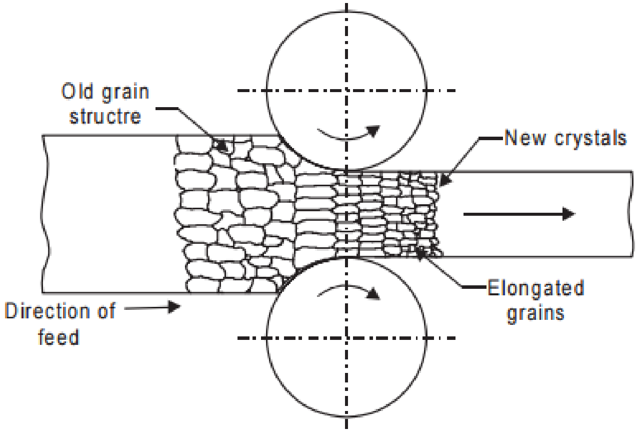
Other Routes for Exploration

- Impurity effects
- Effects of aging and grain size
- Effects on recycled materials
- Intentional inoculants as H2 sinks

Processing

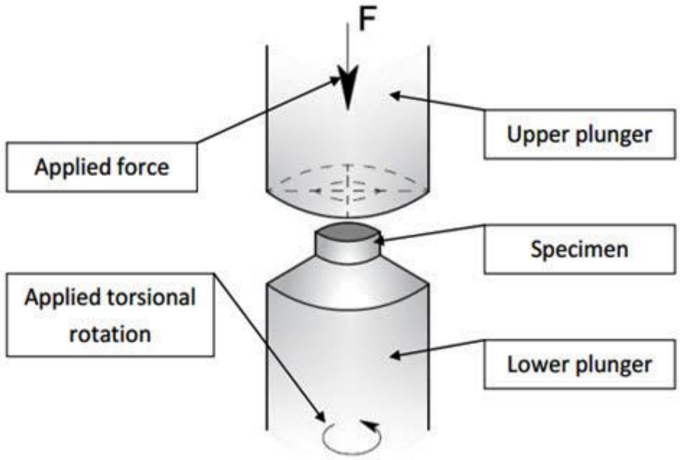
- Rolling Mill

- Hot: 200°C
- Cold: 22°C
- 0.003-0.06 m/s
- 45,000 lbF
- ε: ~1-10



- High Pressure Torsion

- Hot: 450°C
- Cold: Cryo
- 0.1-10 RPM
- 400,000 lbF
- ε: ~1000



Hydrogen Charging Methods

Electrochemical Charging

- Galvanic Process
- H_2SO_4 or HNO_3 often used
- Relatively Inexpensive
- Safer than pressure charging

Humid Air Charging

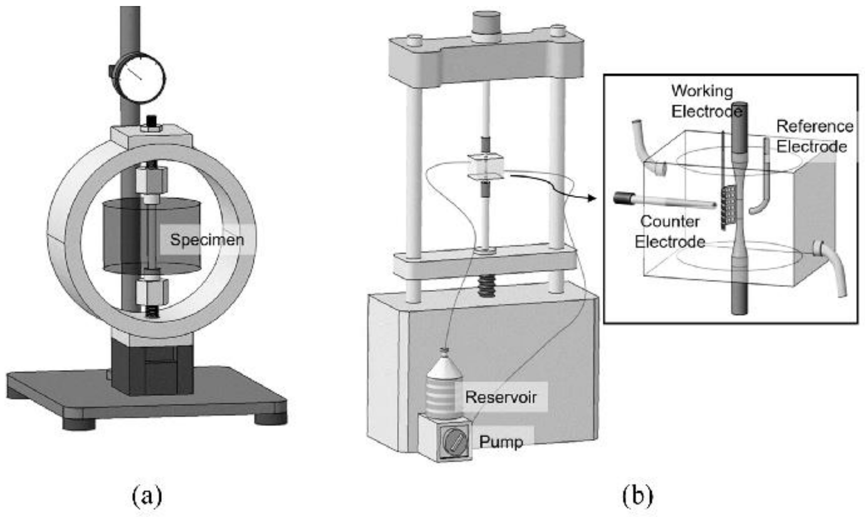
- Environmental exposure
- Temperature can be varied
- Less damage to material surface than electrochemical charging

Pressure Charging

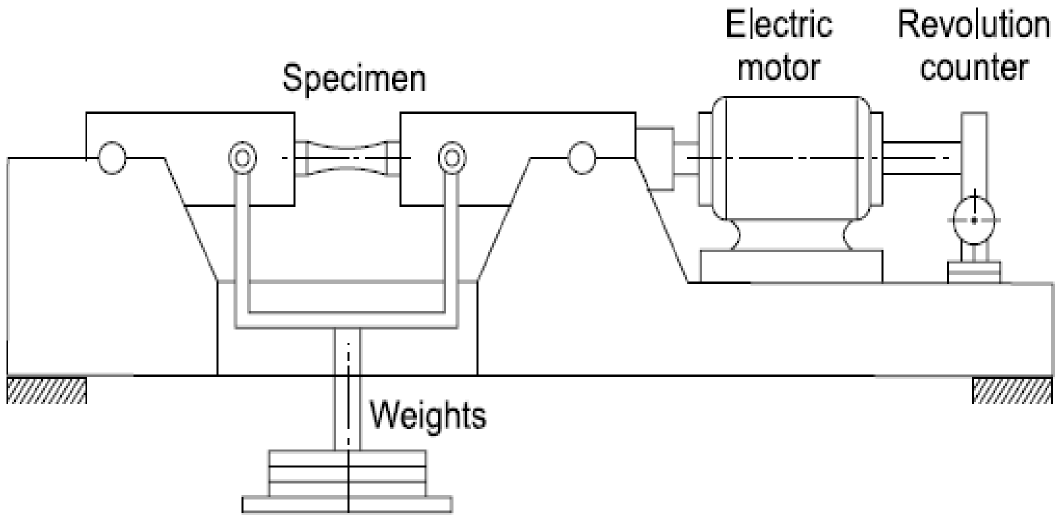
- High pressure chamber
- Fastest method
- Little to no damage to material surface

Mechanical Testing

Quasi-Static/Slow Strain Rate Testing



Cyclic Fatigue Testing



Project 57: Aluminum for H_2 Service

CANFSA CENTER FOR ADVANCED NON-FERROUS STRUCTURAL ALLOYS

- Student: Adam Freund
- Advisor(s): Suveen Mathaudhu, Kester Clarke, Amy Clarke

Project Duration

PhD: September 2021 to May 2025

- Problem: Hydrogen embrittlement severely damages aluminum's mechanical properties, even at low levels.
- Objective: Develop an in-depth understanding of hydrogen embrittlement and the critical amount of hydrogen needed for embrittlement to occur in high strength aluminum.
- Benefit: Enhanced understanding of hydrogen embrittlement can improve aluminum's resistance to hydrogen and, ultimately, part lifetime.

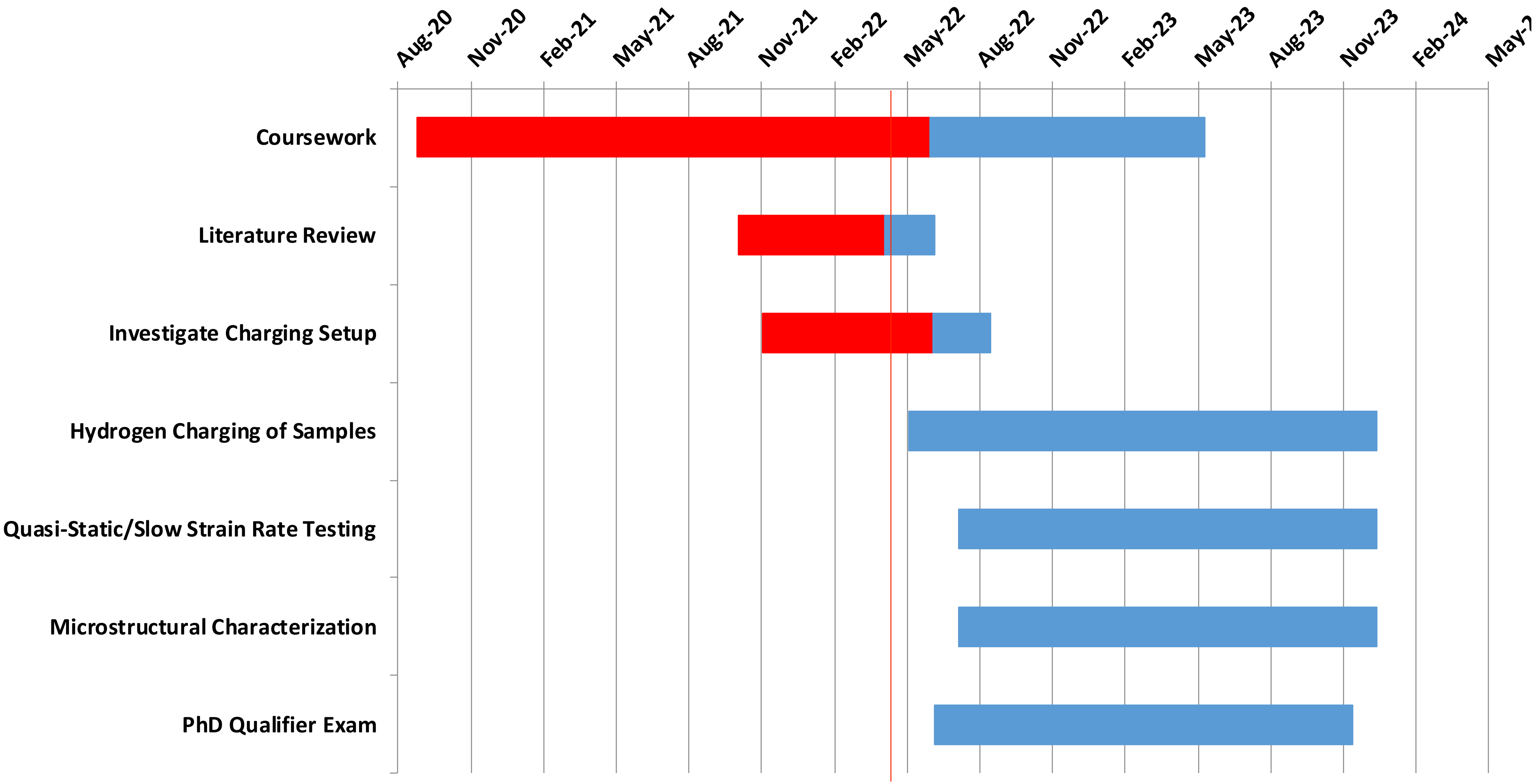
Recent Progress

- Aluminum samples have been sourced (1100, 6xxx, 7xxx)
- Optimum hydrogen charging methods have been isolated and apparatus design has begun
- Design of mechanical testing methods with in-situ hydrogen charging has begun

Metrics

Description	% Complete	Status
1. Literature review	65%	●
2. Hydrogen Charging Apparatus Optimization	12%	●
3. Quasi-Static/Slow Strain Rate Testing Apparatus Optimization	0%	●
4. Mechanical Testing	0%	●
5. Microstructural characterization	0%	●

Gantt Chart



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Aug-23
Nov-23
Feb-24
Coursework
Literature Review
Investigate Charging Setup
Hydrogen Charging of Samples
Quasi-Static/Slow Strain Rate Testing
Microstructural Characterization
PhD Qualifier Exam

Challenges & Opportunities

- Lack of deep, comprehensive prior studies and literature
  - *The majority of hydrogen research has focused on ferrous materials*
- Managing hydrogen retention for in-situ testing
  - *in-situ* methods difficult due to short time window
- Difficulty in isolating the effects of hydrogen on properties
  - *Multiple competing mechanisms at play*
- Limited alloy and processing design knowledge for hydrogen resistance
  - *What microstructural features would lend additional hydrogen embrittlement resistance?*

Thank you!

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