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Validation of Short Crack Extension and Fracture Using J-Integral Methods

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National Nuclear Security Administration

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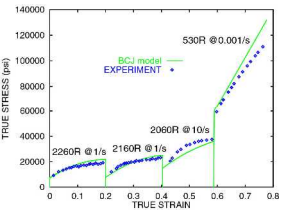
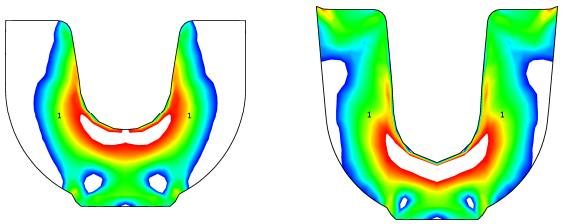
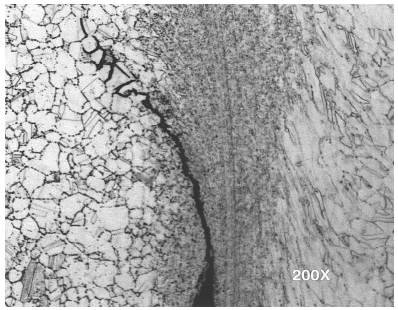
Motivation
Hydrogen Embrittlement/Deformation Mechanics

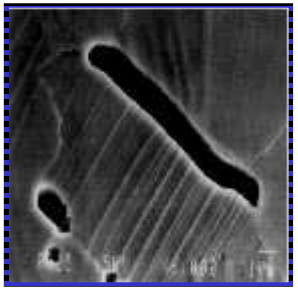
Our concerns of hydrogen effects require that we model each of the complicated manufacturing processes, capturing the material state with each successive step.



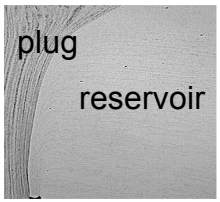


Multistage forging

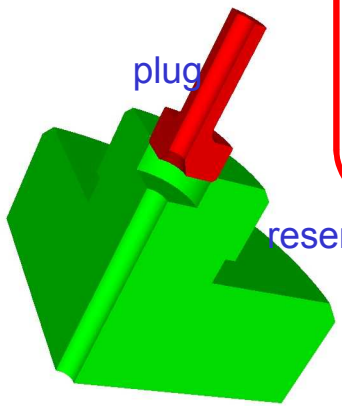




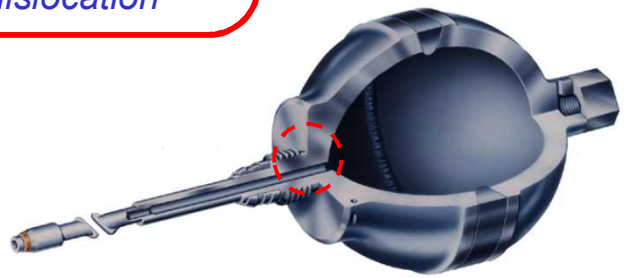
Physically-based models:
- *Hardening*
- *Recovery (static/dynamic)*
- *Recrystallization*
- *Grain growth*
- *Hydrogen-dislocation*



grain flow



resistance welding



hydrogen reservoir

forging → welding → hydrogen → fracture

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Confidence in Gas Transfer Systems reservoir design and subsequent stockpile performance are dependent on developing an understanding of short crack behavior in hydrogen affected materials. This requires a validated model and approach that has been proven successful on increasingly difficult problems leading up to and giving confidence in simulations of an actual reservoir.

The reservoir material of interest, 21-6-9 stainless steel, has been fully characterized in two states: as- processed and hydrogen charged to match service reservoir levels. This characterization data is used to fit material model parameters to develop a good description of the material mechanical behavior in each state. Additionally, elastic-plastic J-Integral validation experiments of increasing complexity are being conducted on 21-6-9 stainless steel material in both states. First, material was tested using a planar CT specimen geometry. This is being followed by a three dimensional axisymmetric geometry that is currently being designed, and finally a three dimensional asymmetric geometry will be designed and tested as the most challenging validation experiment for modeling. Experimental results and methods will be presented.

Short Crack/J-Integral Methods Problem and Approach

Problem Description:

- *Develop and demonstrate a validated capability to assess short crack length fracture by J-Integral methods.*
- *Use this capability to analyze GTS reservoirs and support development of the GTS Design Standard.*
- *Develop experimental methods for characterizing and validating short crack behavior.*

Technical Approach:

- *Material Characterization: 21-6-9 stainless steel in the as-processed and hydrogen-charged conditions.*
  - *Tension, notched-tension, compression experiments*
- *Elastic-Plastic J-Integral Validation Experiments: Incrementally increasing complexity*
  - *Planar CT specimen geometry*
  - *3-dimensional axisymmetric geometry*
  - *3-dimensional asymmetric geometry*

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Short Crack/J-Integral Methods
Problem and Approach

Validation Issues Addressed:

- *Elastic/Plastic reservoir properties*
- *Fracture, short cracks, crack growth*
- *J-Integral methods*
- *Hydrogen embrittlement*

Applications:

- *GTS reservoir safety and design*
- *Nuclear power industry/Hydrogen economy infrastructure*
- *Sandia-wide interest in short crack behavior*

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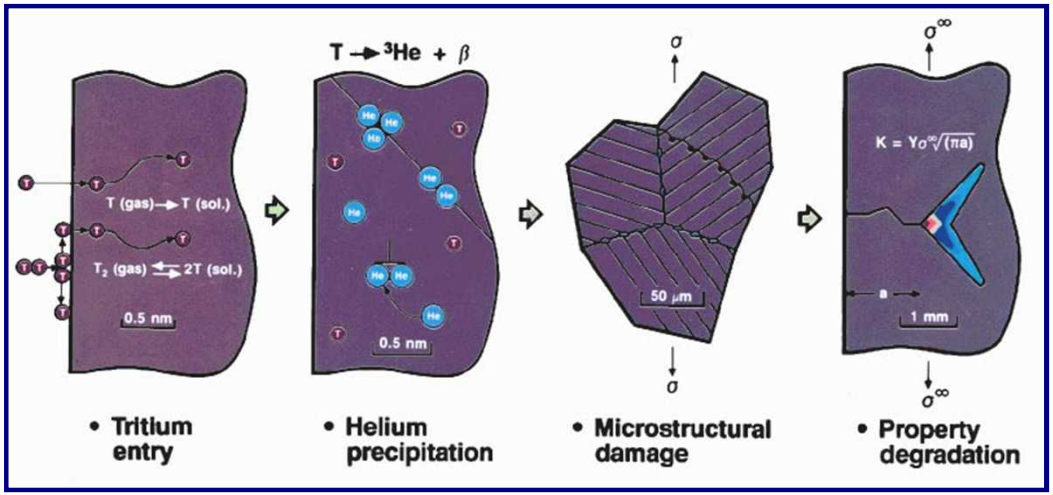
Background

Consideration of Hydrogen Embrittlement:

- Gas transfer system reservoirs are a key component of all modern nuclear weapons.
- GTS reservoirs are manufactured by forging process to obtain strength, grain size and grain flow required for tritium compatibility.
- Hydrogen presence has a significant embrittlement effect on mechanical properties and reduces resistance to crack growth and fracture.
- Predictive capability to quantitatively assess hydrogen embrittlement effects on reservoir performance is critical for weapon certification but does not exist.



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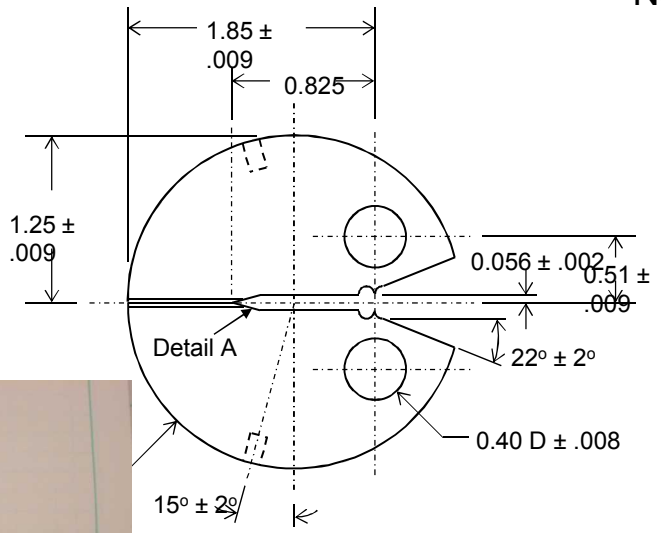
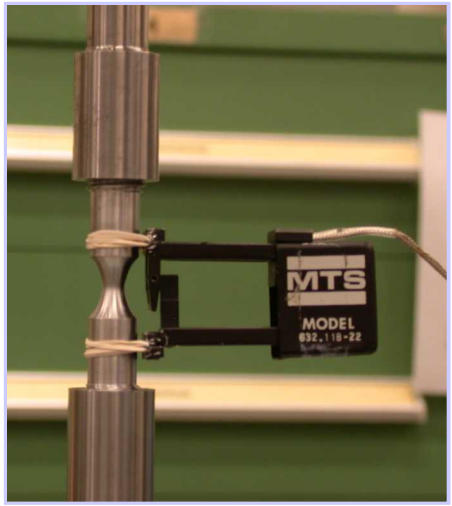
Short Crack/J-Integral Methods

Specimen removal from 2.5” DIA
WR 21-6-9 Stainless Steel Bar Stock

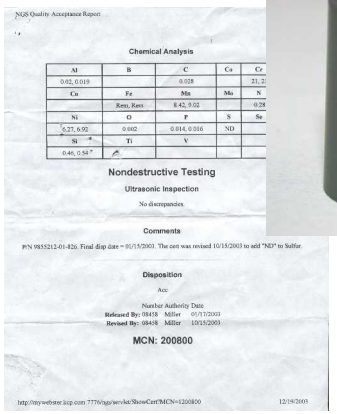
Disk-Shaped CT Specimen

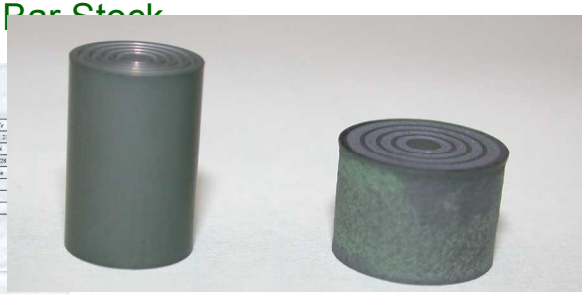


Notched Tensile Experiments



21-6-9 Stainless Steel Bar Stock





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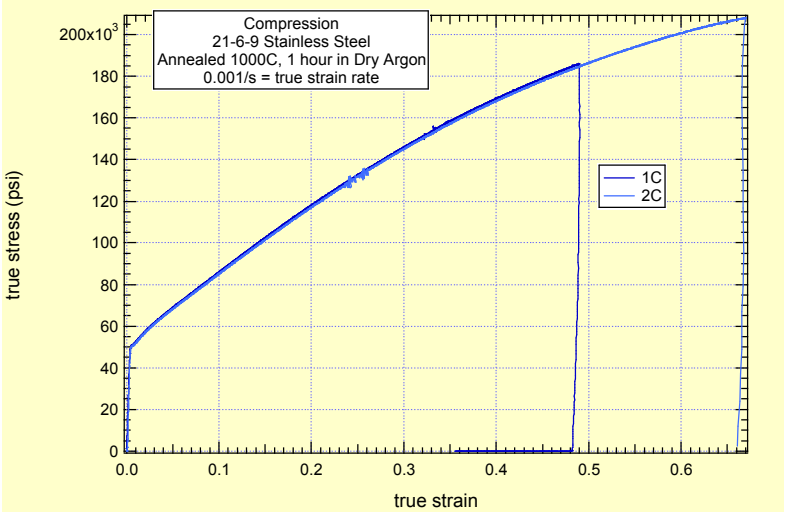
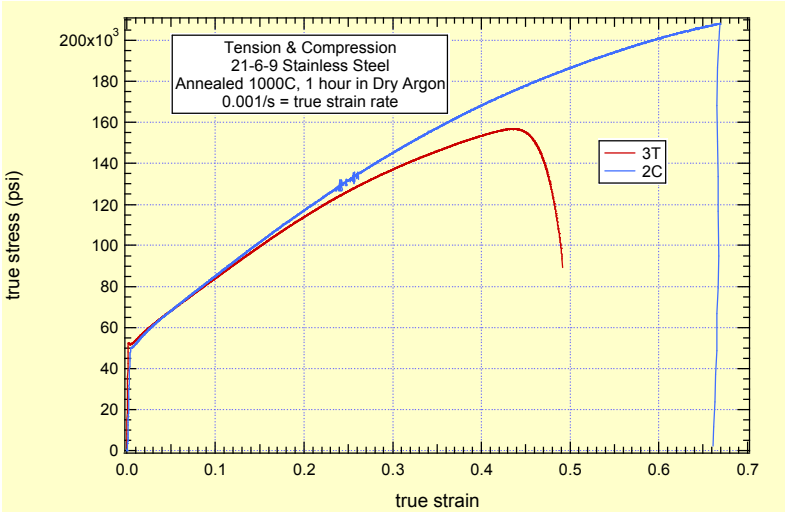
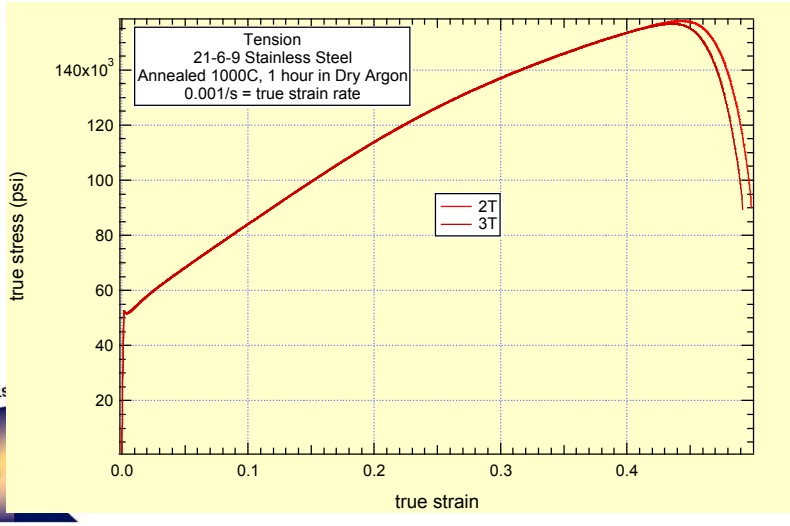
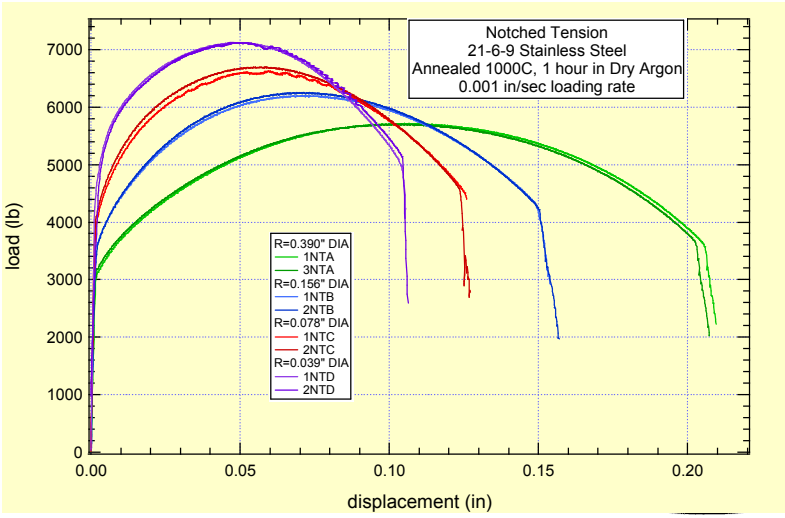
Material Characterization - Experimental Results (No Hydrogen Charging)

- Annealed @ 1000C for 1 hour in dry Argon









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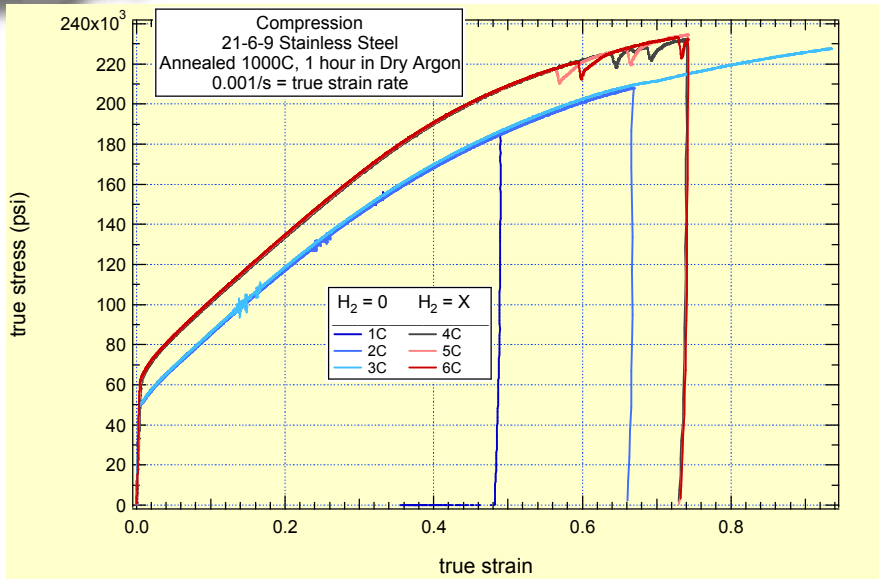
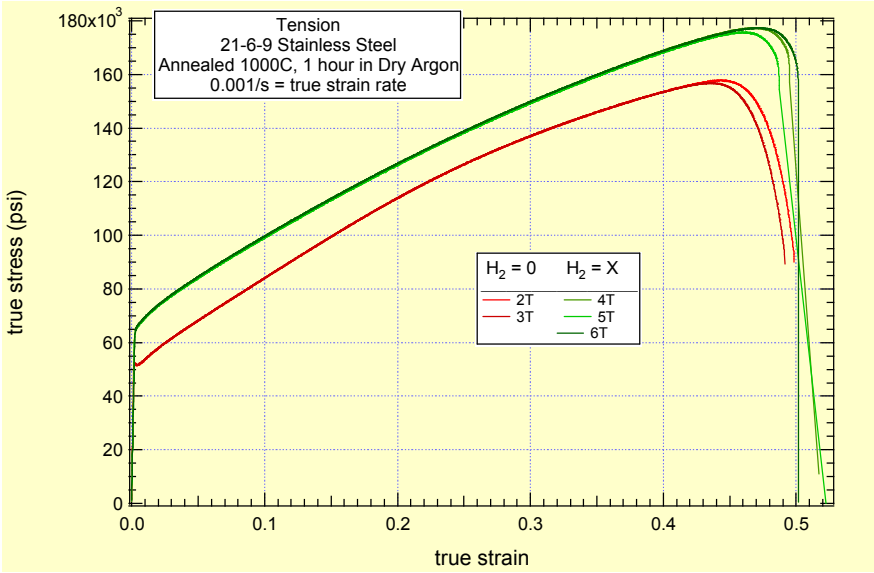
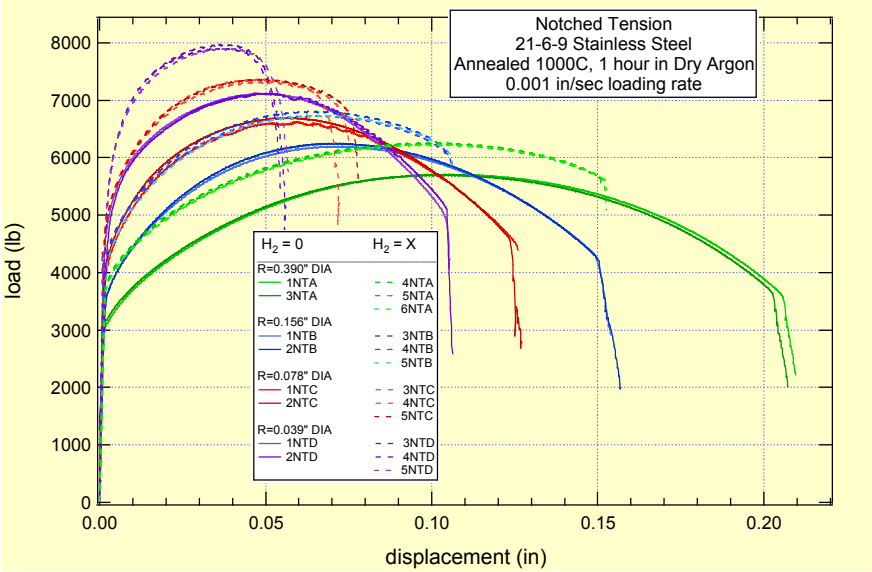
Material Characterization - Experimental Results (Hydrogen Charged Specimens)







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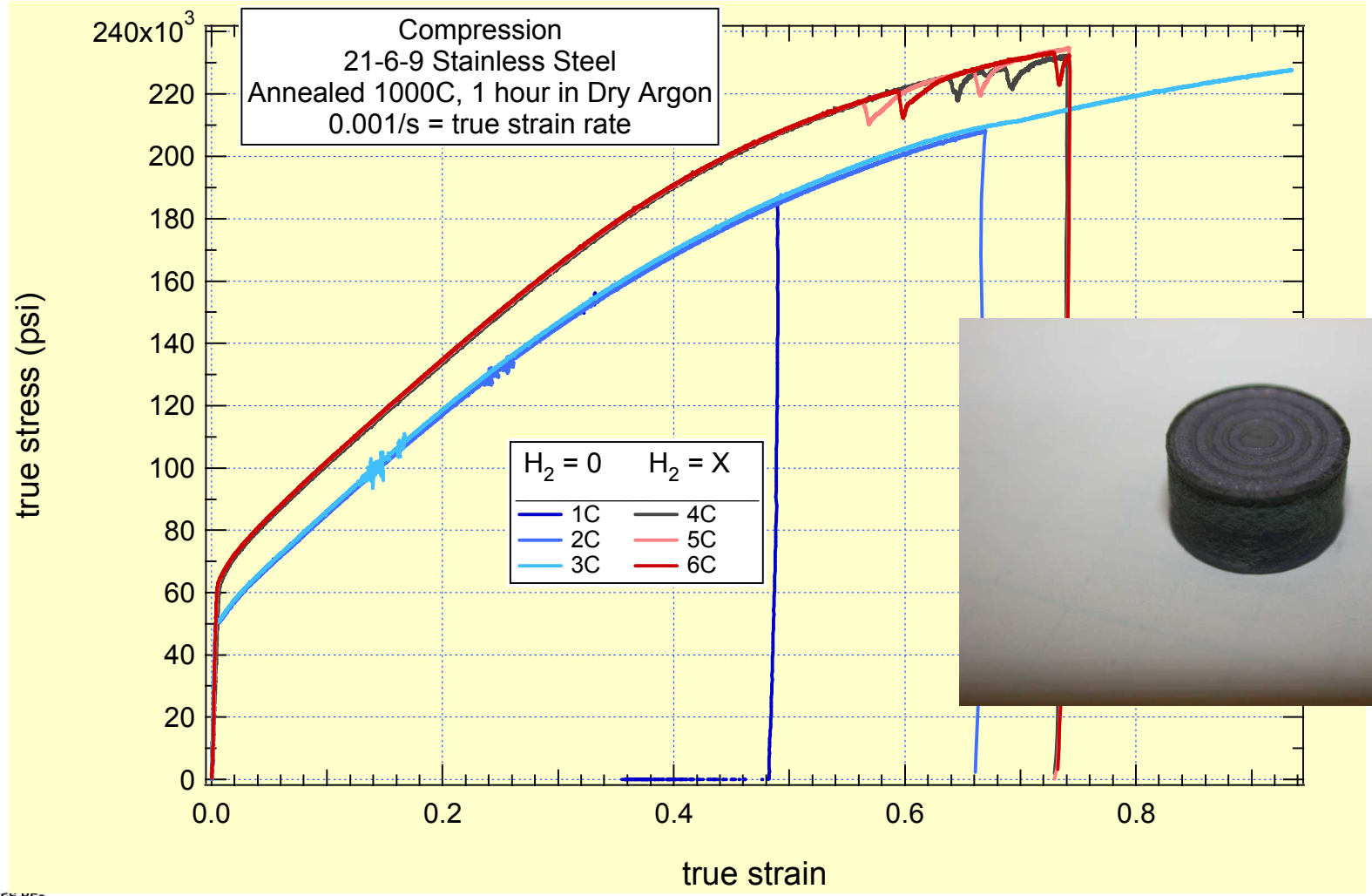
Results: Effect of Hydrogen level (0% and 1 atm %) on Material Plasticity



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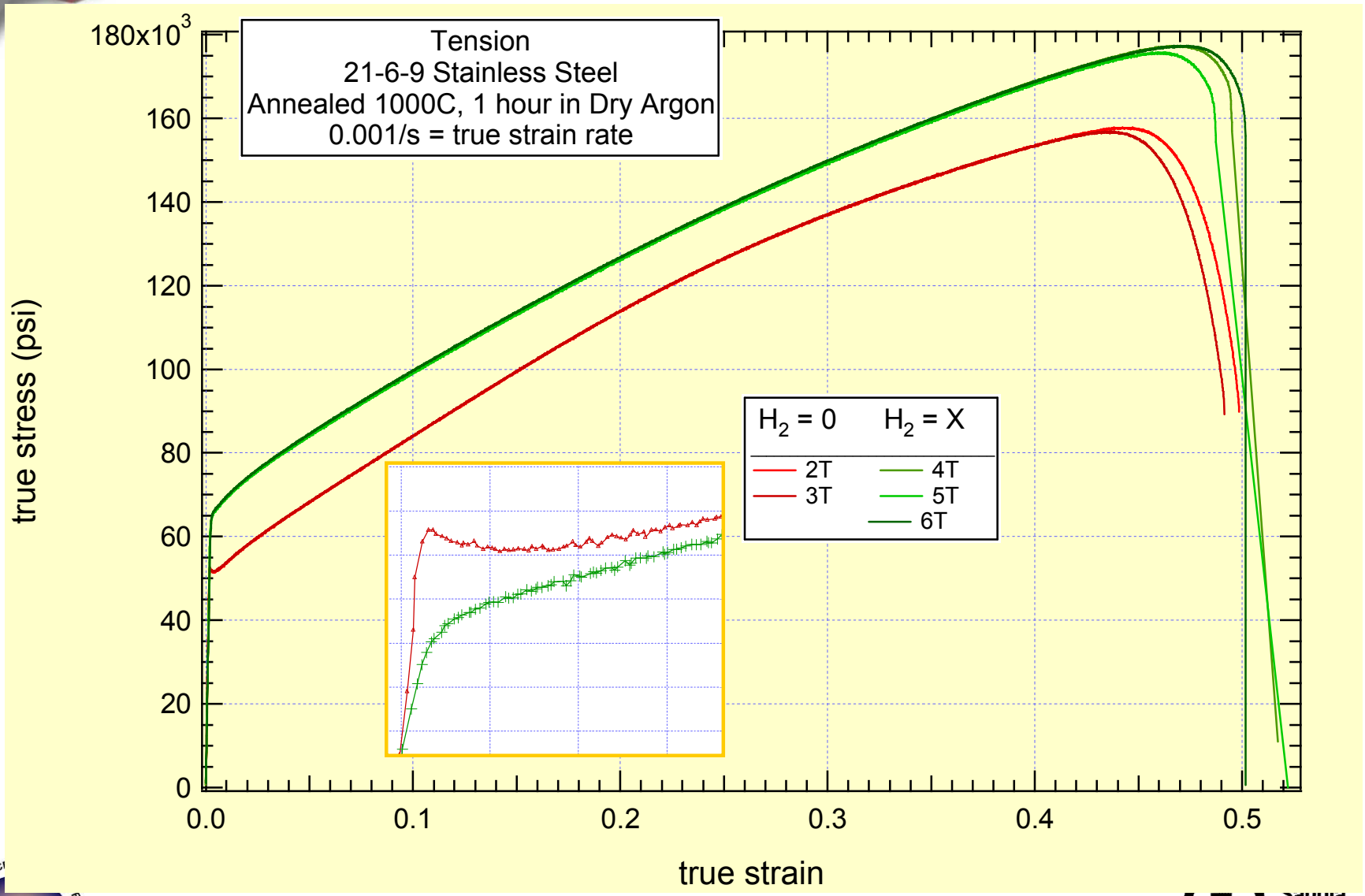

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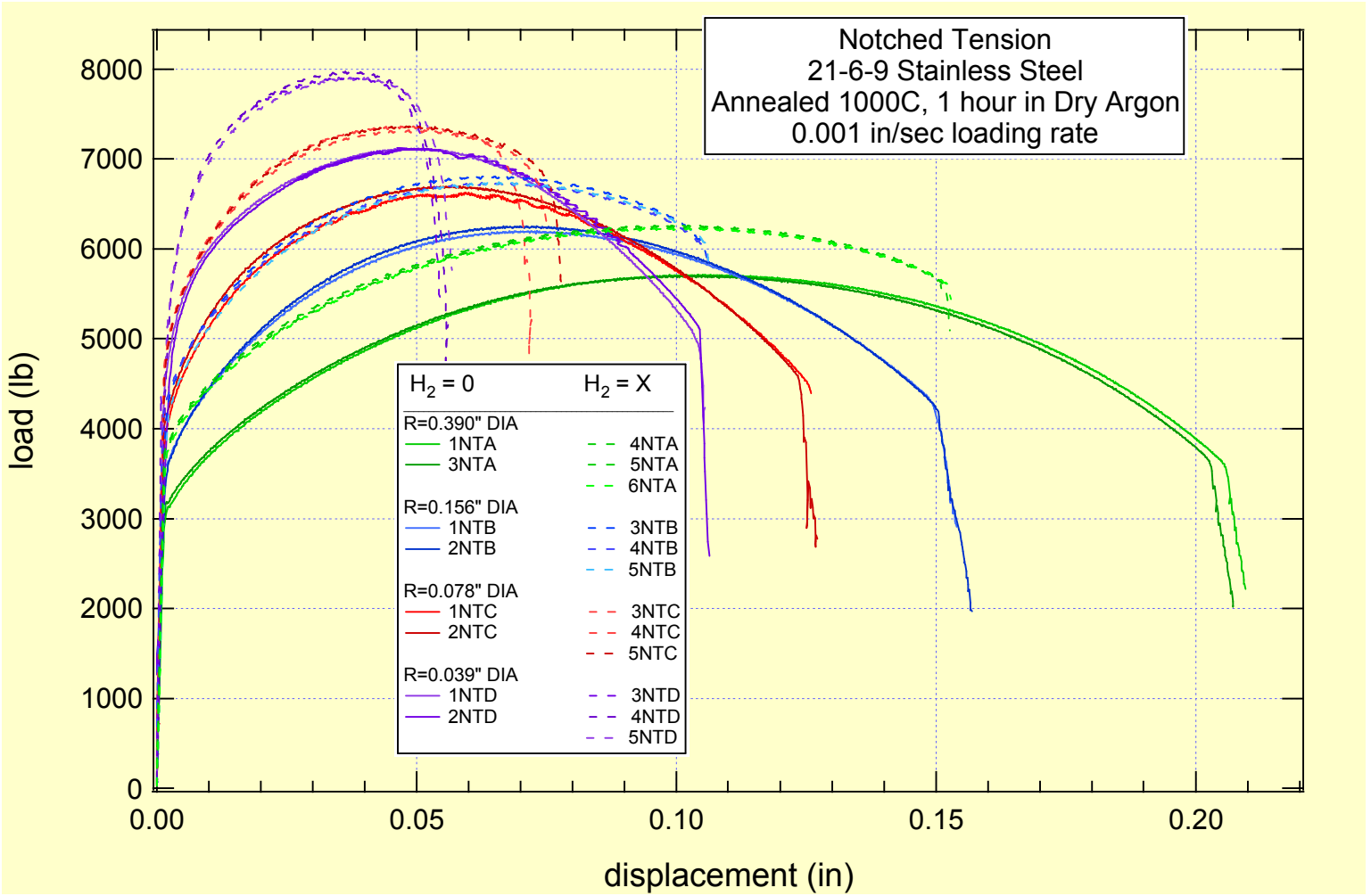

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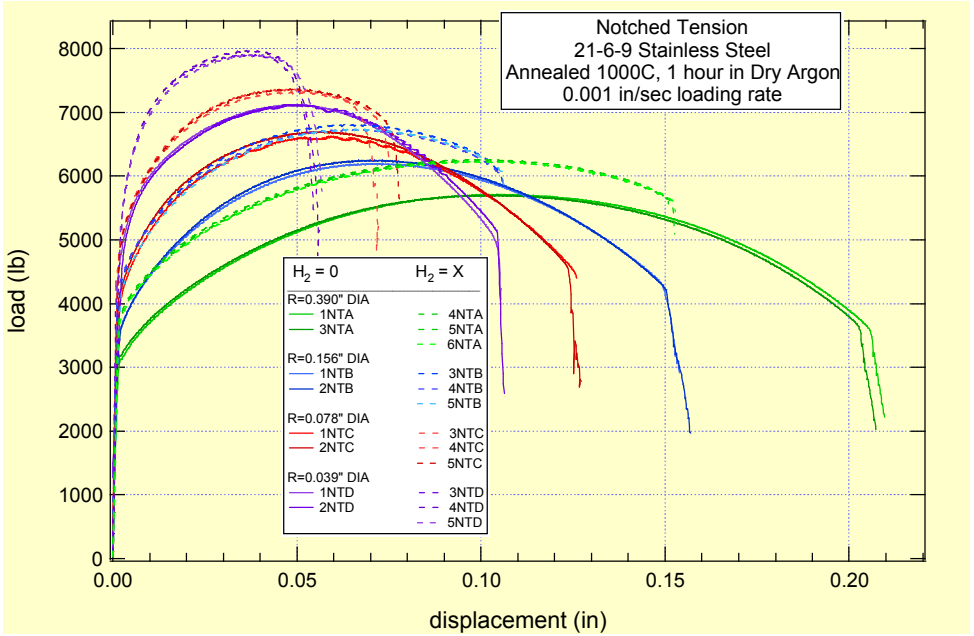
Comparison of EMMI Model with Experimental Data



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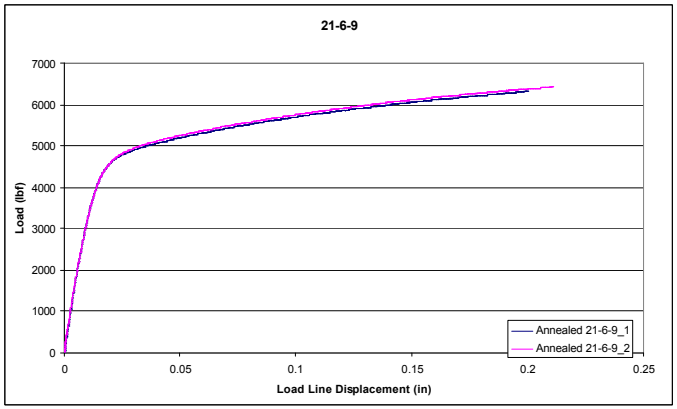
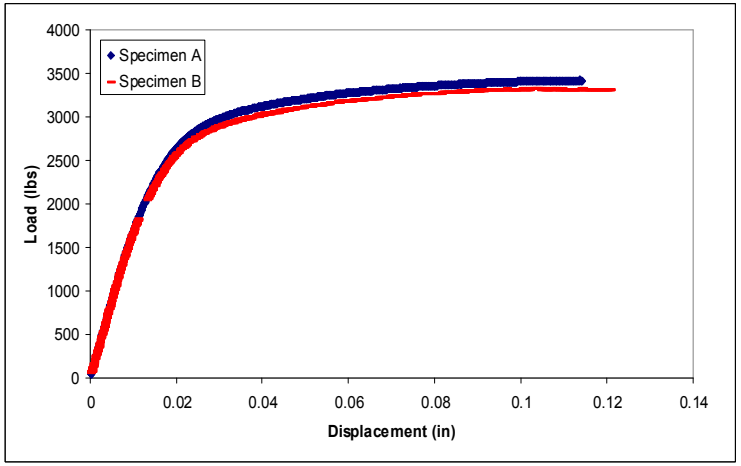
Elastic-Plastic J-Integral Validation Experiments (Hydrogen Charged Specimens)

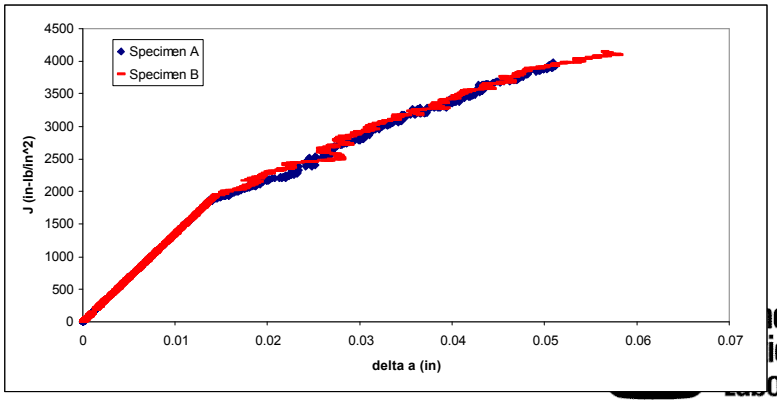
- Deliverable:
  - ➢Complete hydrogen-charged planar elastic-plastic J-Integral validation experiments.

No Hydrogen Charging



After Hydrogen Charging





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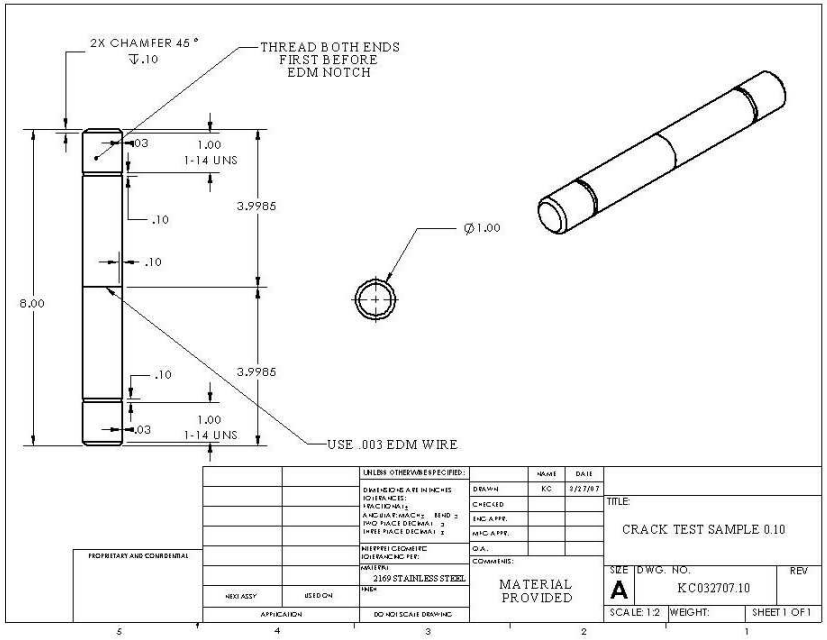
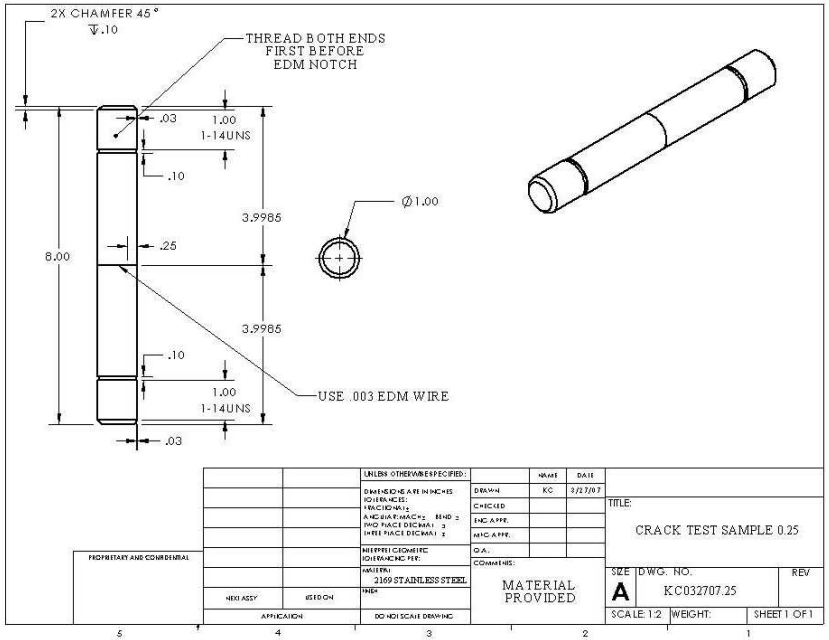
Axisymmetric Validation Specimen Design

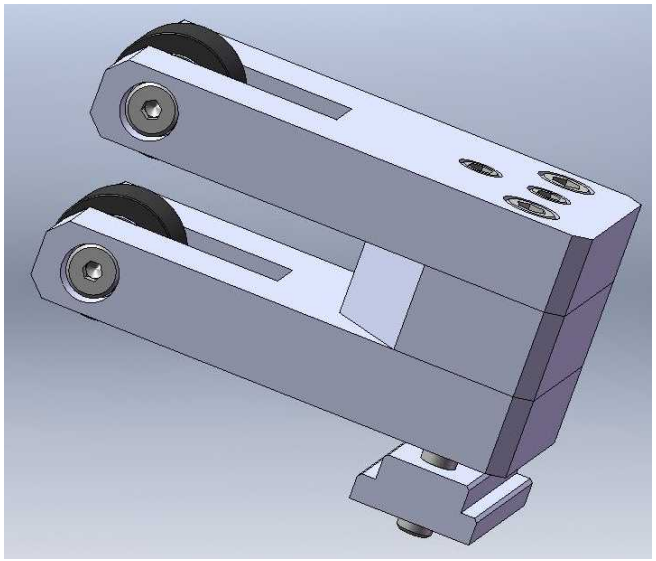
- Q3 Deliverable:
  - Develop 3-dimensional *axisymmetric* elastic-plastic J-Integral validation experiment, design experimental procedure, apparatus.

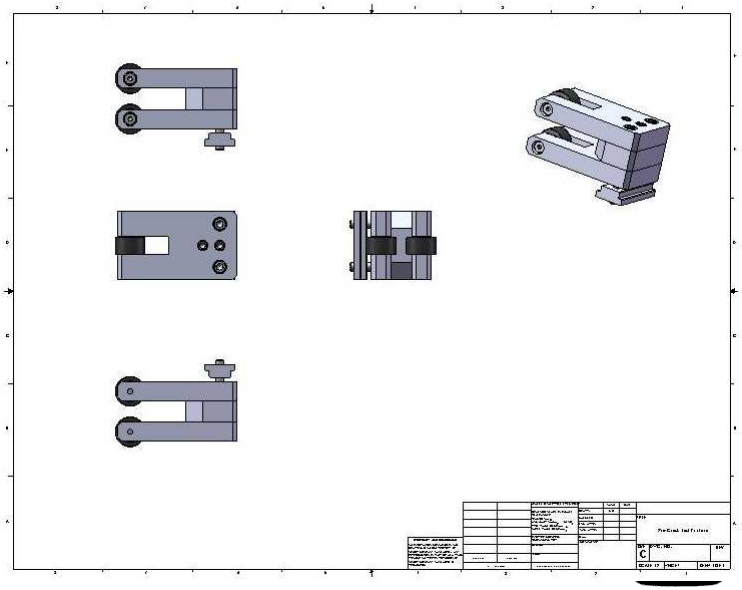




Axisymmetric Validation Precracking Fixture Design

- Two methods of precracking the axisymmetric specimens are planned:
  - ➢ Axial fatigue loading on 50 Kip MTS test frame with precracking software (fixtures available)
  - ➢ Bending fatigue loading on B972 lathe with newly designed adjustable displacement-controlled loading fixtures shown below
- Status: Design complete, fixtures and specimens on order.





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Asymmetric Validation Specimen Design

- Deliverable:
  - Develop 3-dimensional *asymmetric* elastic-plastic J-Integral validation experiment, design experimental procedure, apparatus.