Development of Valid Fracture Experiments in Hydrogen Affected Materials

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Abstract:

Confidence in the design and performance of materials and structures used at Sandia National Laboratories are dependent on developing an understanding of short crack behavior in hydrogen affected materials. This requires development of increasingly difficult geometries of valid fracture experiments that can be proven to provide accurate results and eventually enable successful finite element simulations of complex structures.

The mechanical behavior of a material of interest, 21-6-9 stainless steel, has been fully characterized in two states: as- processed and hydrogen charged. This characterization data is used to fit material model parameters to develop a good description of the material mechanical behavior in each state. Next, elastic-plastic J-Integral validation experiments of increasing complexity were developed and conducted on the 21-6-9 stainless steel material in both states. In the simplest case, the fracture behavior of the material was tested using a planar CT specimen geometry. The validity of this simple geometry, particularly when the material is in its more ductile as-processed form, was not found to be acceptable. Hence, subsequent experiments used three dimensional axisymmetric geometries and three dimensional asymmetric geometries, each of varying crack length ratios. These geometries produced valid results for both material states. The experimental methods and results for these various fracture specimen designs will be presented. The results will also be compared to finite element simulations of the experiments.

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Motivation: Development of Valid Fracture Experiments in Hydrogen Affected Materials

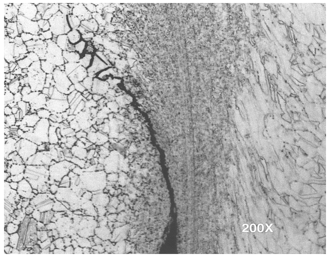
Our concerns of hydrogen effects require that we model each of the complicated manufacturing processes, capturing the material state with each successive step.

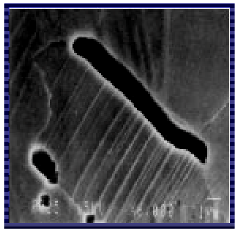
forging → welding → hydrogen   fracture

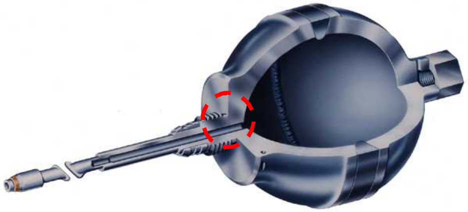
Hydrogen presence has a significant embrittlement effect on mechanical properties and reduces resistance to crack growth and fracture.

Hydrogen effect on short crack behavior (dictated by geometry) is even less understood.

Confidence in hydrogen reservoir design and 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 hydrogen reservoir.







hydrogen reservoir

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Problem and Approach: Development of Valid Fracture Experiments in Hydrogen Affected Materials

Problem Description:

- *Develop and demonstrate a validated capability to assess short crack length fracture by J-Integral methods.*
- *Use this capability to analyze reservoirs and support development of design standards.*
- *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*

Validation Issues Addressed:

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

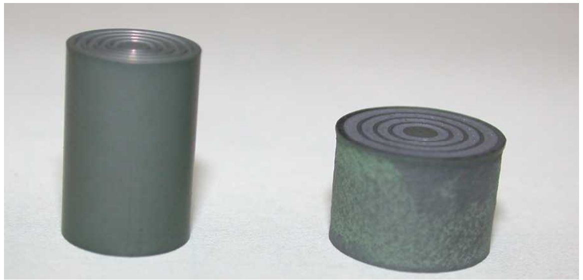
Material: Development of Valid Fracture Experiments in Hydrogen Affected Materials

Specimen removal from 2.5" DIA

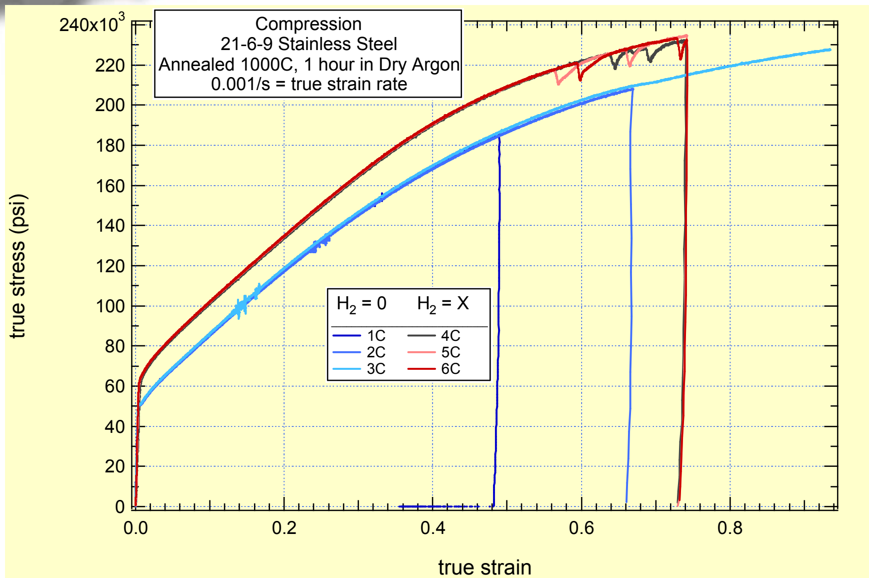
WR 21-6-9 Stainless Steel Bar Stock

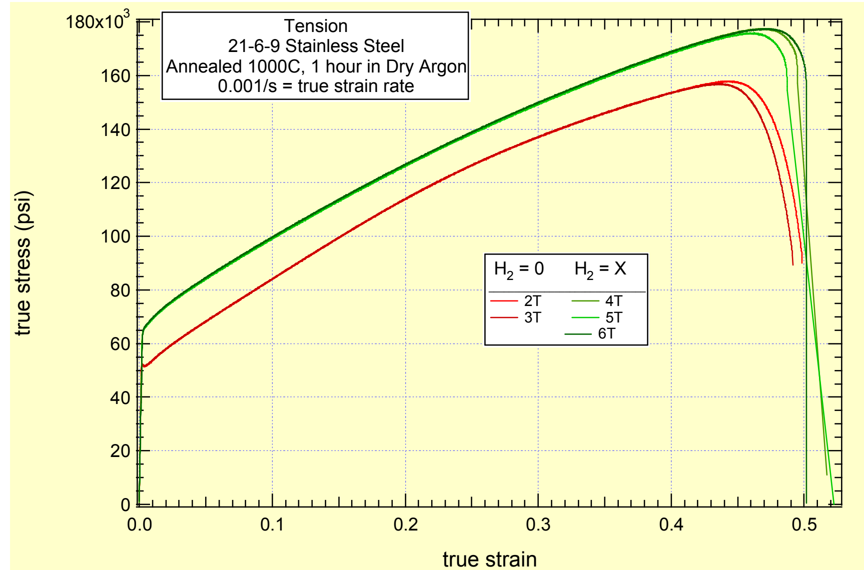
Notched Tensile Experiments

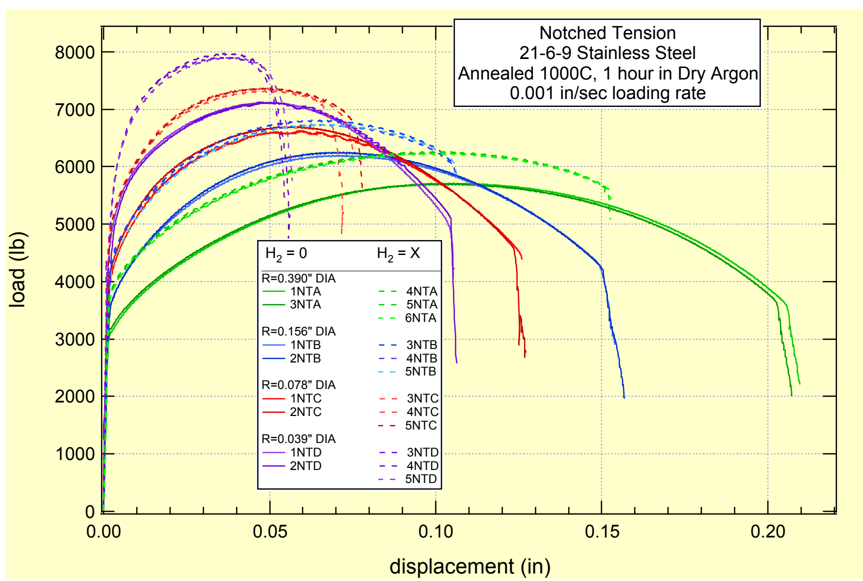
Compression specimens before and after testing



Material Characterization - Experimental Results







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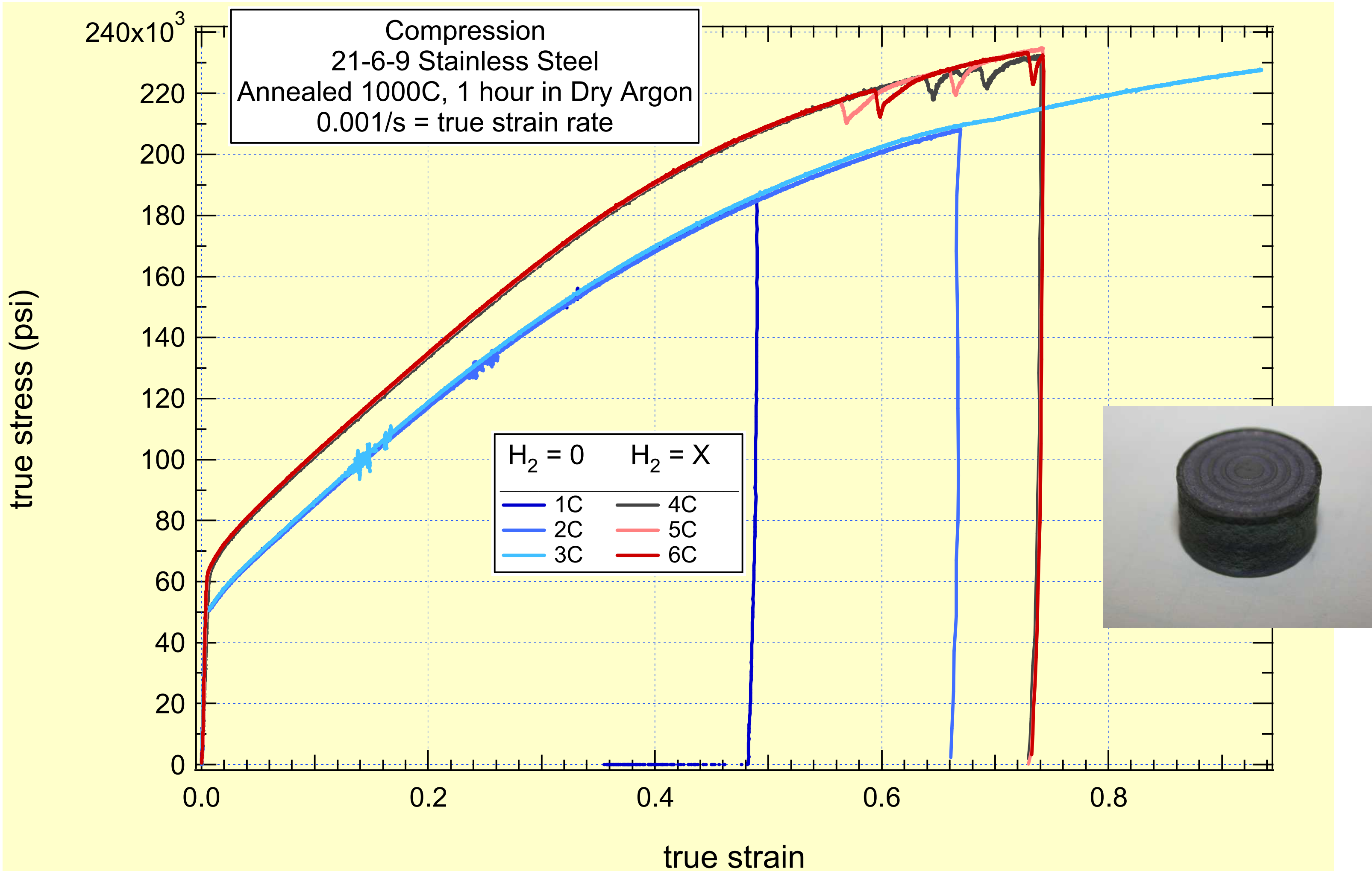
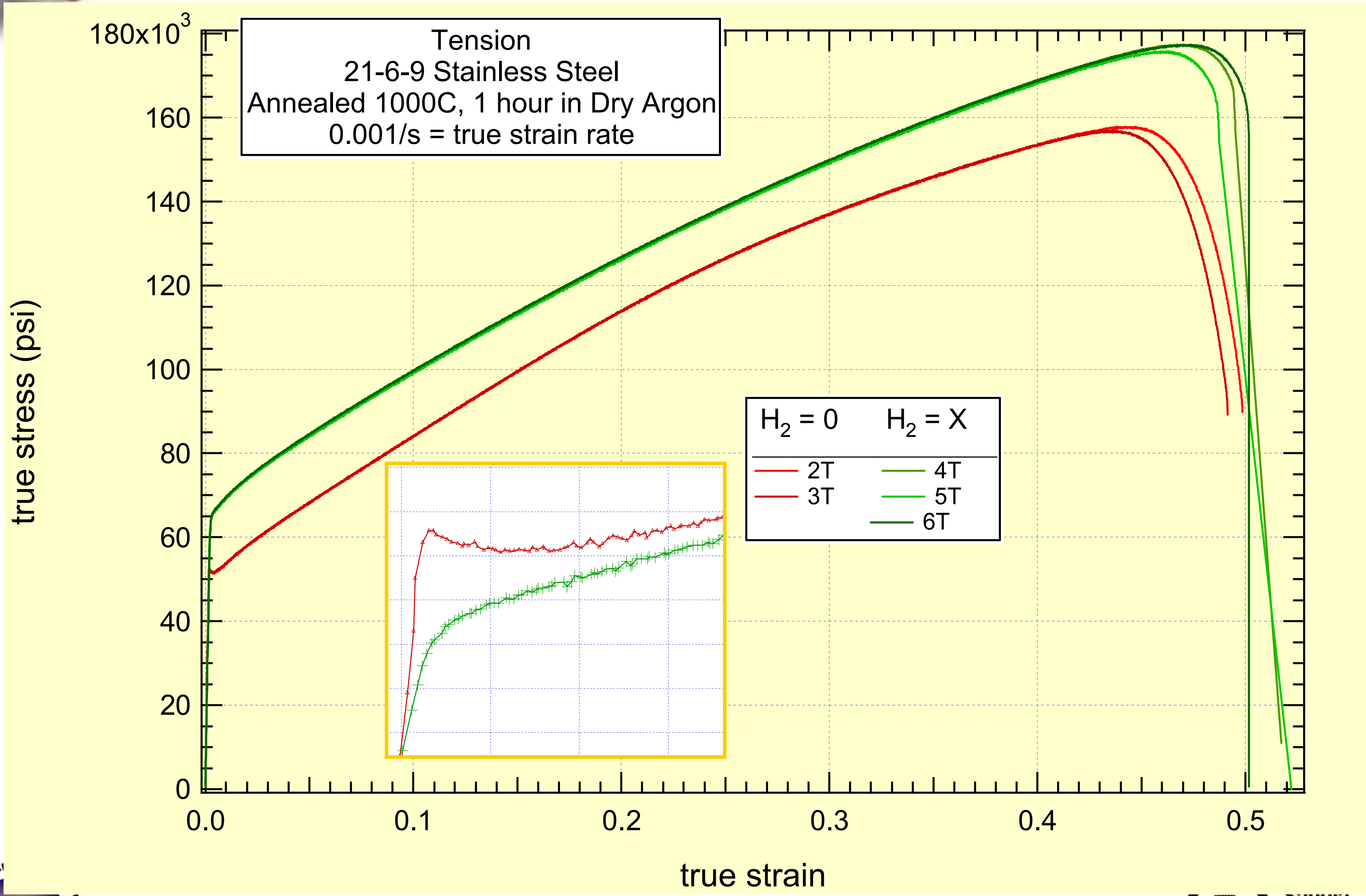
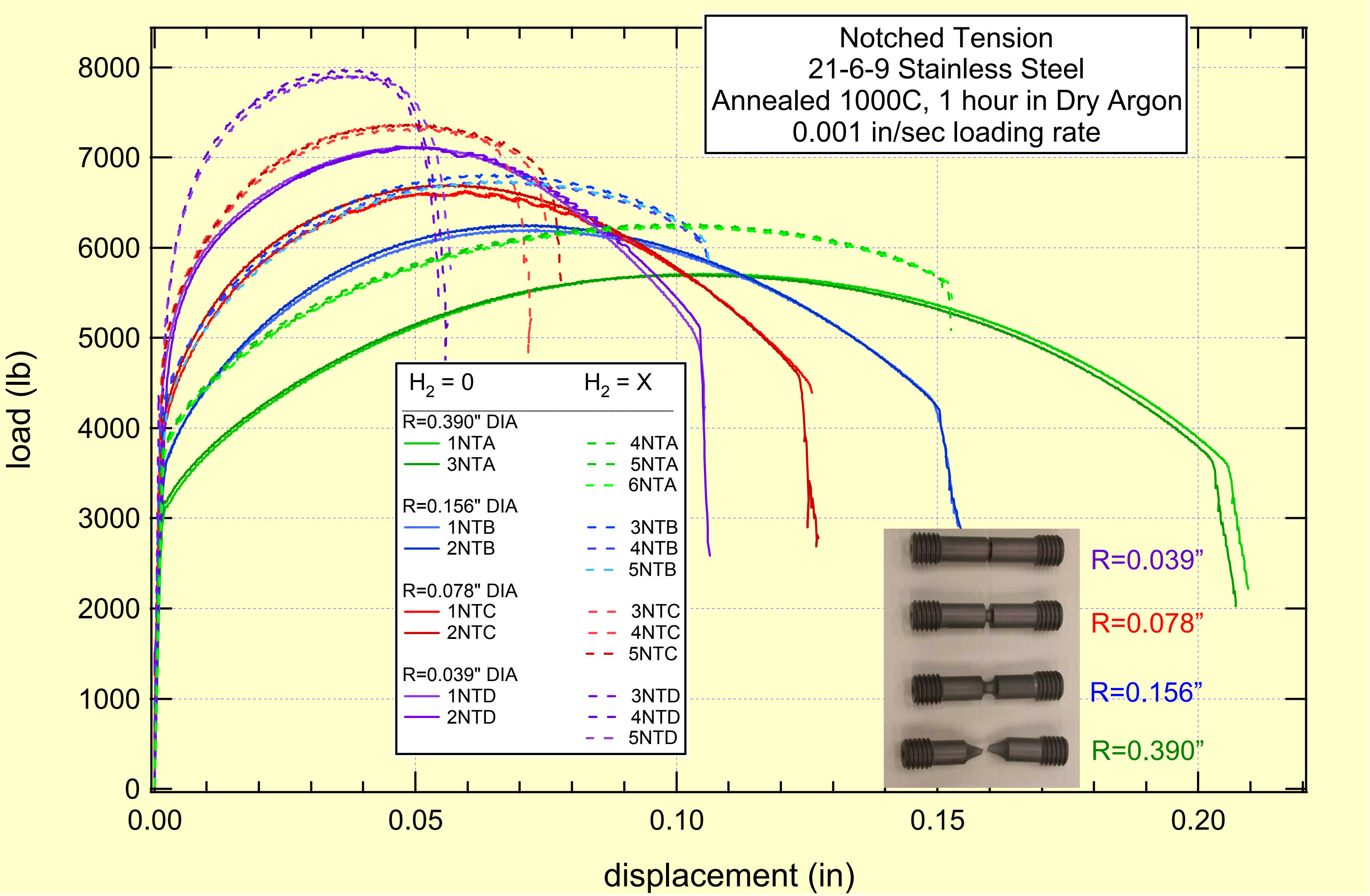
Results: Effect of Hydrogen level (0% and 1 atm %) on Compression Behavior



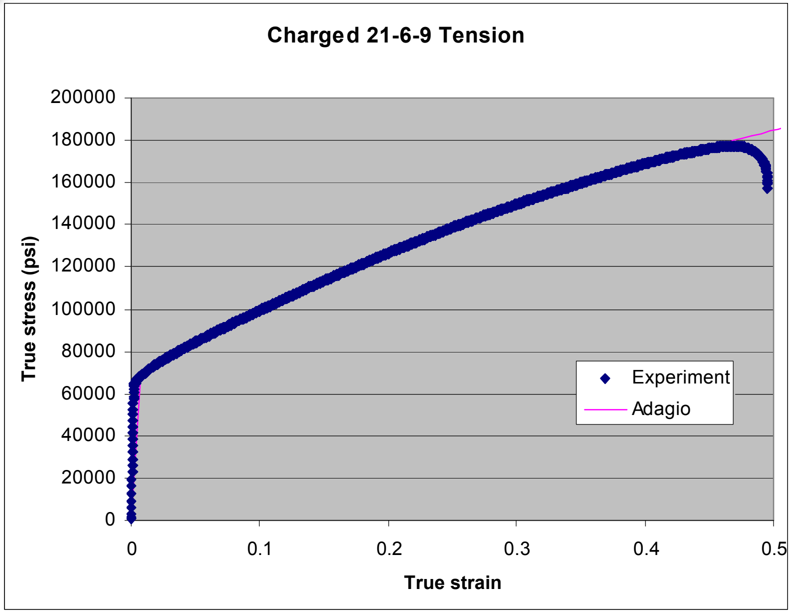
Results: Effect of Hydrogen level (0% and 1 atm %) on Tensile Behavior

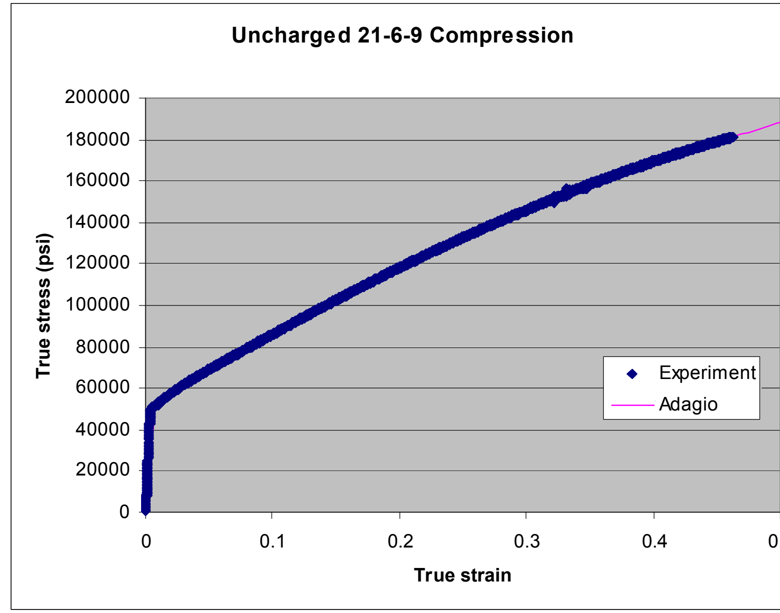


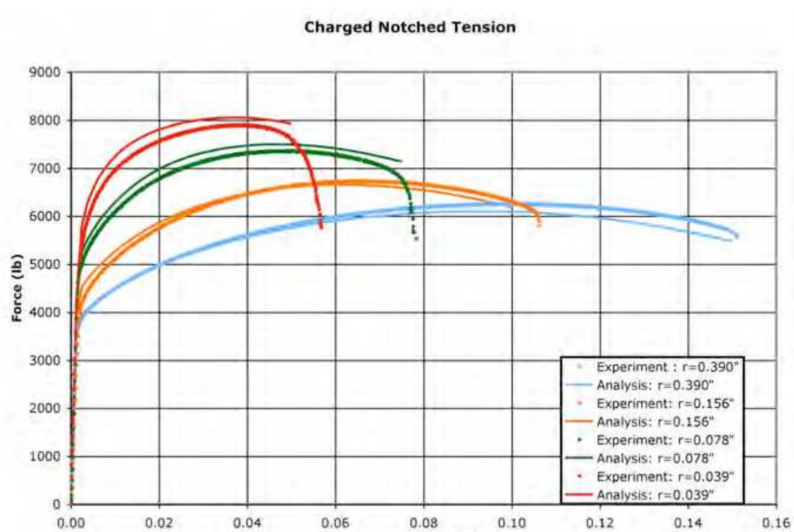
Results: Effect of Hydrogen level (0% and 1 atm %) on Notched Tensile Behavior

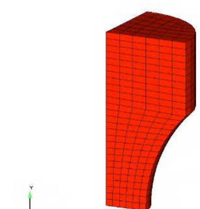


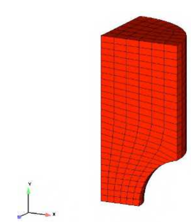
Comparison of EMMI Plasticity Model with Experimental Characterization Data











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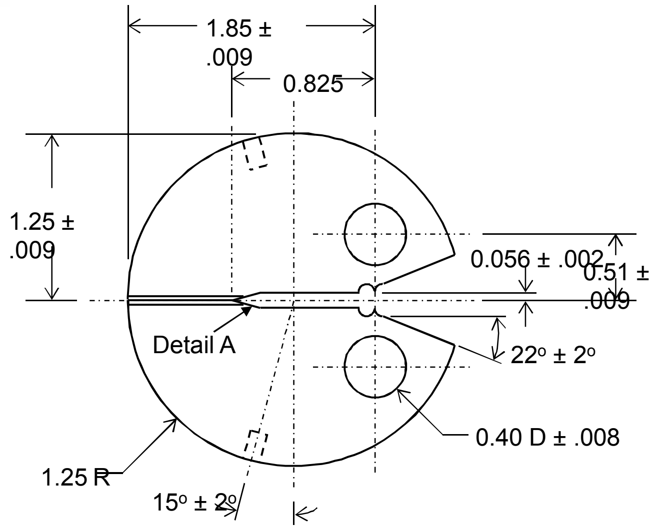
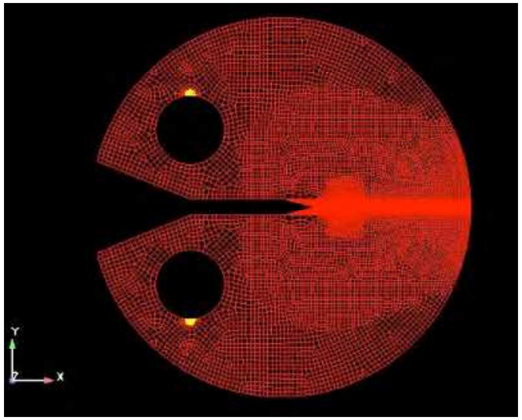
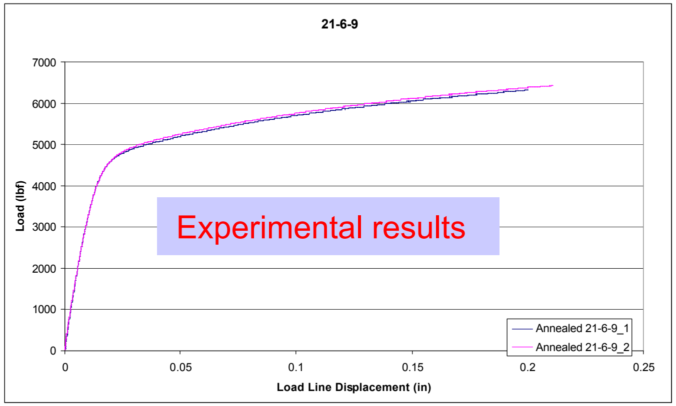
Planar Elastic-Plastic J-Integral Validation Experiments

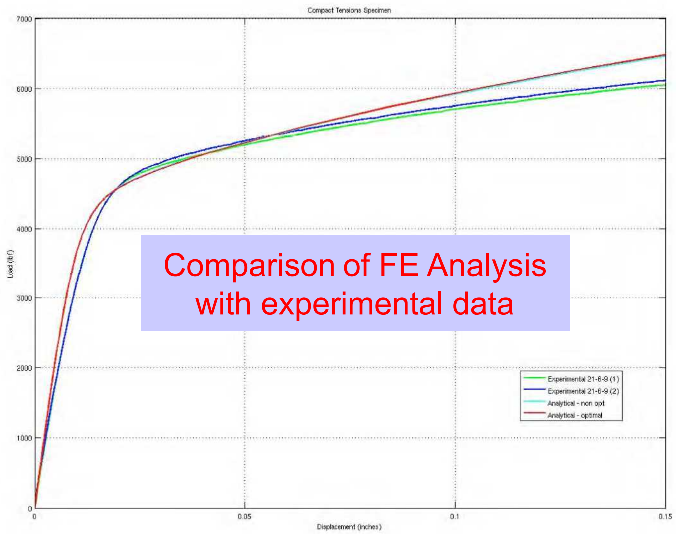
Disk-Shaped CT Specimen





21-6-9, No Hydrogen Charging





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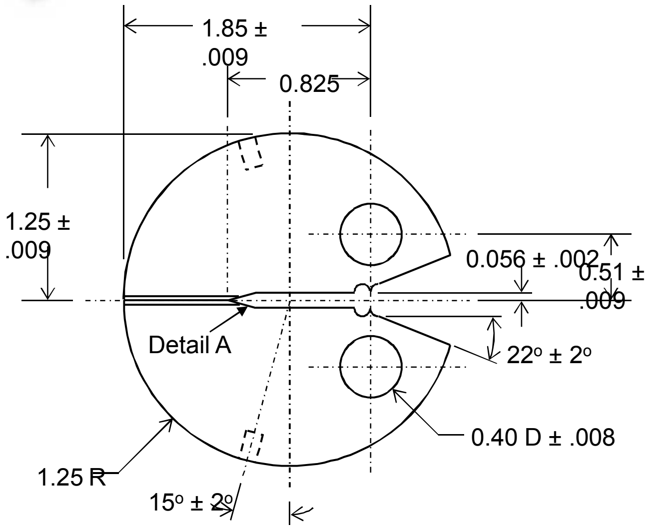
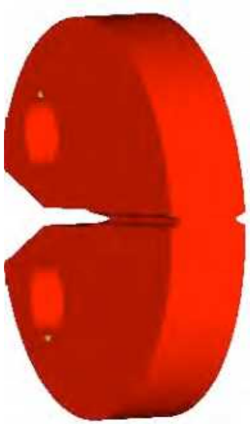
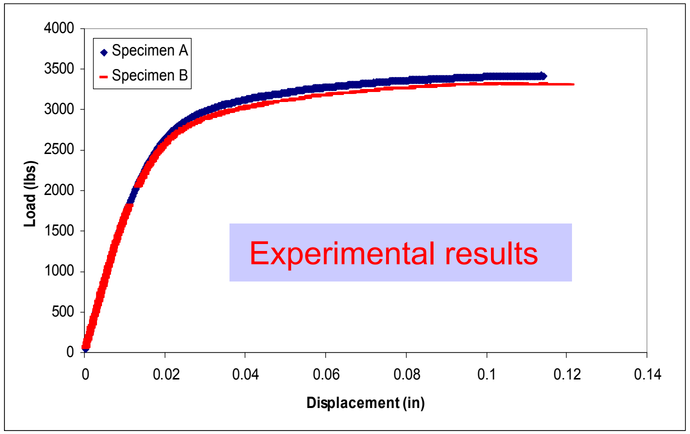
Planar Elastic-Plastic J-Integral Validation Experiments

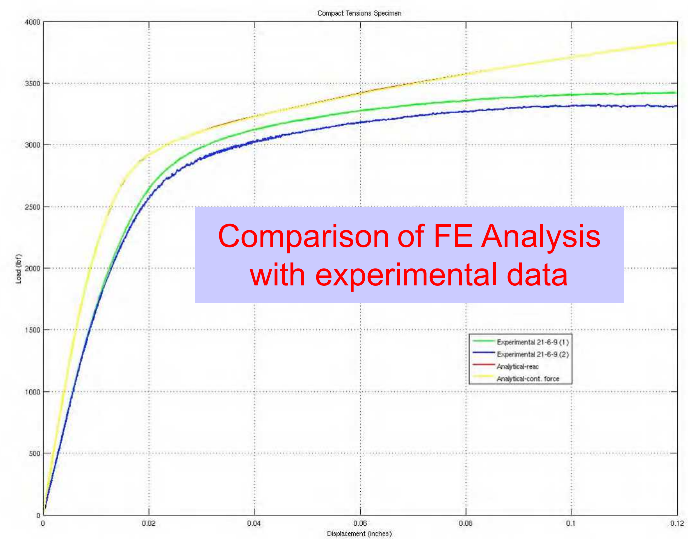
Disk-Shaped CT Specimen





Hydrogen Charged 21-6-9, 1 atm %





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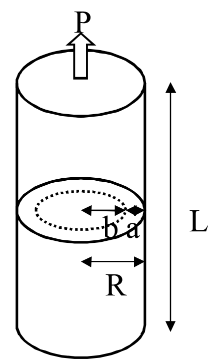
3-D Elastic-Plastic Fracture
Cracked Round Bar (CRB) Specimens

Stress-Intensity Factor Formulae

The mode-I stress intensity factor of the CRB under a uniaxial tension is given as follows

$$K_I = \frac{P}{\pi b^2}\sqrt{\frac{\pi\, ab}{R}}\,G\left(\frac{b}{R}\right)$$

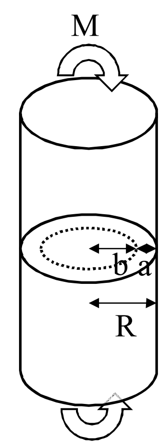


with

$$G\left(\frac{b}{R}\right) = \frac{1}{2}\left\{1 + \frac{1}{2}\frac{b}{R} + \frac{3}{8}\left(\frac{b}{R}\right)^2 - 0.363\left(\frac{b}{R}\right)^3 + 0.731\left(\frac{b}{R}\right)^4\right\}$$

The mode-I stress intensity factor of the CRB under uniform bending is also provided as

$$K_I = \frac{4M}{\pi b^3}\sqrt{\frac{\pi\, ab}{R}}\,G\left(\frac{b}{R}\right)$$



with

$$G\left(\frac{b}{R}\right) = \frac{3}{8}\left\{1 + \frac{1}{2}\frac{b}{R} + \frac{3}{8}\left(\frac{b}{R}\right)^2 + \frac{5}{16}\left(\frac{b}{R}\right)^3 + \frac{35}{128}\left(\frac{b}{R}\right)^4 + 0.537\left(\frac{b}{R}\right)^5\right\}$$

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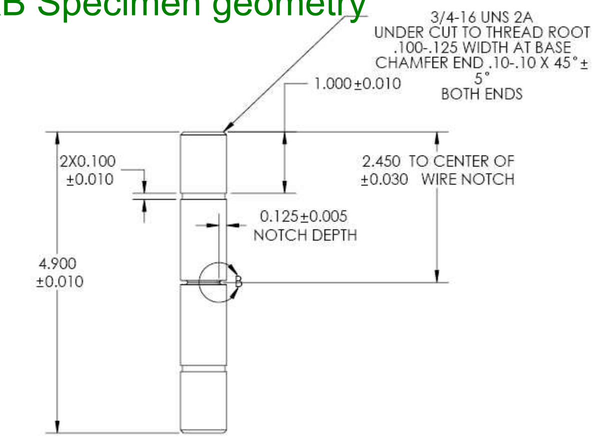
3-D Elastic-Plastic Fracture Specimens

CRB Specimen geometry



J-Integral Formula:

J value for a deep crack in a cracked round bar:

$$J = \frac{1}{2\pi\, b^2}\left\{3\int_0^{\Delta_c} P d\Delta_c - P\Delta_c\right\} \qquad (1)$$

where Δ_c is the load-point displacement due to the crack and estimated by

$$\Delta_c = \Delta - \frac{PL}{\pi R^2 E} \qquad (2)$$

for the practical evaluation of the J-integral from a load-displacement curve, introduce η-factor

$$J = \frac{1-\nu^2}{E}K^2 + \eta\frac{A_{pl}}{\pi b^2} \quad \text{with} \quad A_{pl} = \int_0^{\Delta_{pl}} P d\Delta_{pl} \qquad (3)$$

where A_{pl} is the plastic part of the energy dissipated during the test and Δ_{pl} is the plastic part of the displacement.

$$\eta = \frac{b}{2R}\frac{0.00771 + 3.05738(a/R)}{1 - 00771(a/R) - 1.52869(a/R)^2}, \qquad a/R < 0.65$$

Lei and Neal (1997)

$$\eta = -0.155 + 2.069(a/R) - 1.13(a/R)^2$$

Scibetta et. al. (2000)

J-Resistance Curve:

J-integral at the unloading point can be estimated from the incremental form of (3) in following approximation

$$J_{(i)} = \frac{1-\nu^2}{E}K_{(i)}^2 + J_{pl_{(i)}} \quad \text{with} \quad J_{pl_{(i)}} = J_{pl_{(i-1)}} + \eta_{(i)}\frac{\left(P_{(i)} + P_{(i-1)}\right)}{2\pi b^2}\left(\Delta_{pl_{(i)}} - \Delta_{pl_{(i-1)}}\right)$$

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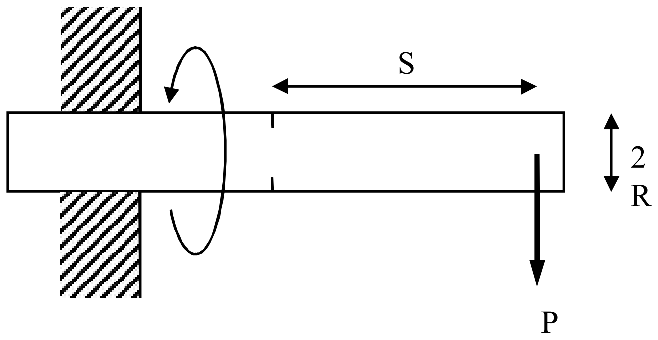
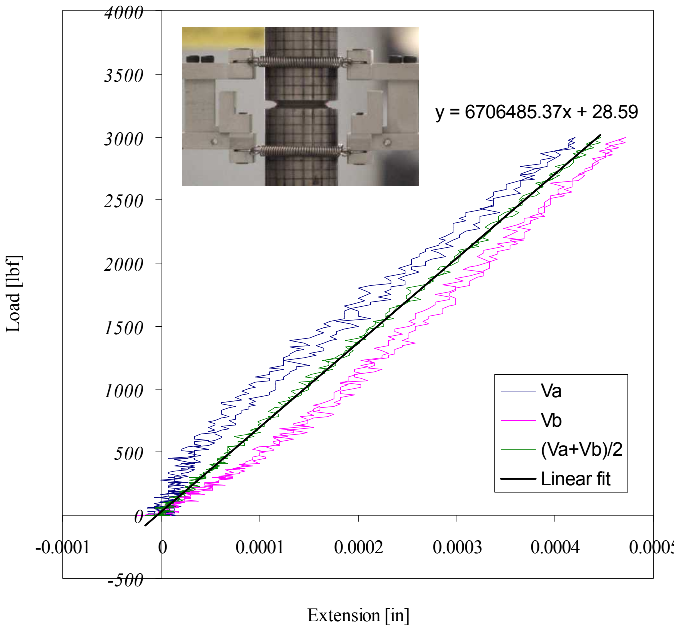
3-D Elastic-Plastic Fracture Specimen Precracking

Cantilever configuration for rotating-bending fatigue



Precracking procedure:

- Rotating bending fatigue on lathe at 5Hz
    - •In-situ monitoring of pre-crack growth using elastic compliance
    - •Every 1,000 cycles, elastic compliance measured in tension on MTS frame
- Heat tint specimen at 300ºC for 1 hour



Typical load-displacement curve during tensile loading and unloading for crack-length monitoring using the elastic compliance method

3-D Elastic-Plastic Fracture Specimen Precracking

Asymmetric precracked specimen a/r ≈ 0.7

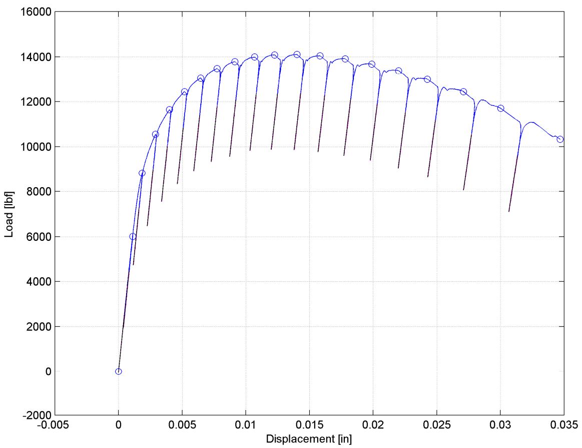
Axisymmetric precracked specimen a/r ≈ 0.6

Axisymmetric precracked specimen a/r ≈ 0.8

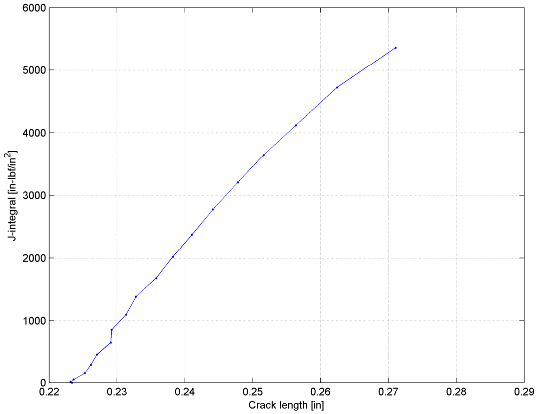
J-Integral Testing
(Determination of JIc and J-R curve of the materials)

Test matrix of annealed and H-charged 21-6-9 stainless steel

	R [in]	a/R	Annealed	H-charged
Axisymmetric	0.375	0.6	A9	A1
	0.375	0.5	A8	A7
	0.25	0.2	A6	A4
Non-axisymmetric	0.375	0.2~0.8	B1	B2

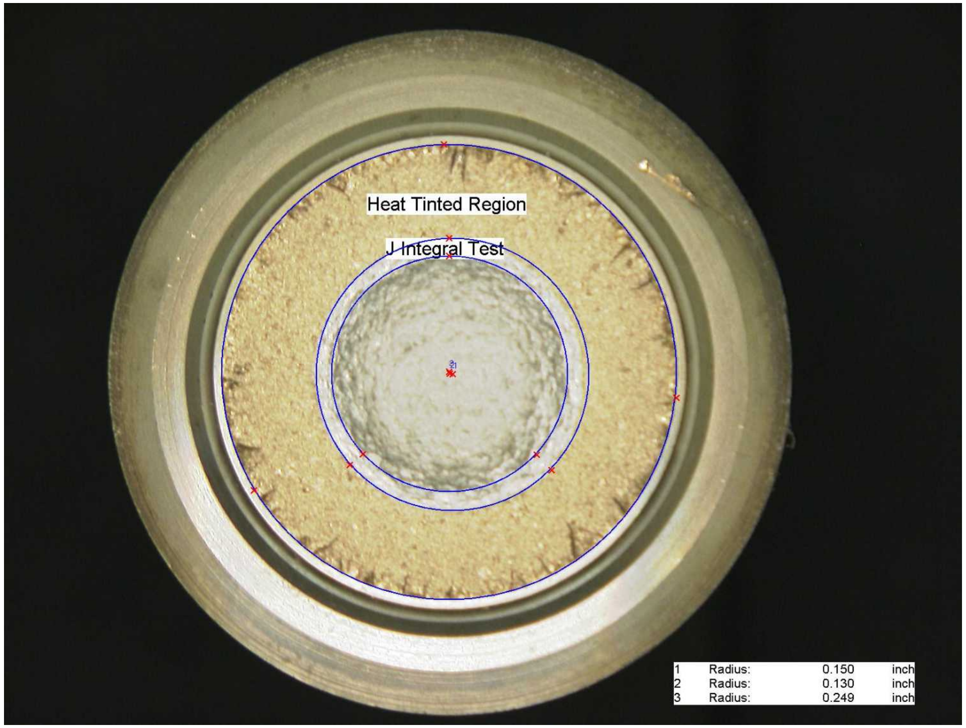


Typical load-displacement curve of J-integral test using partial unloading compliance method



Typical *J-R* curve obtained by using partial unloading compliance method

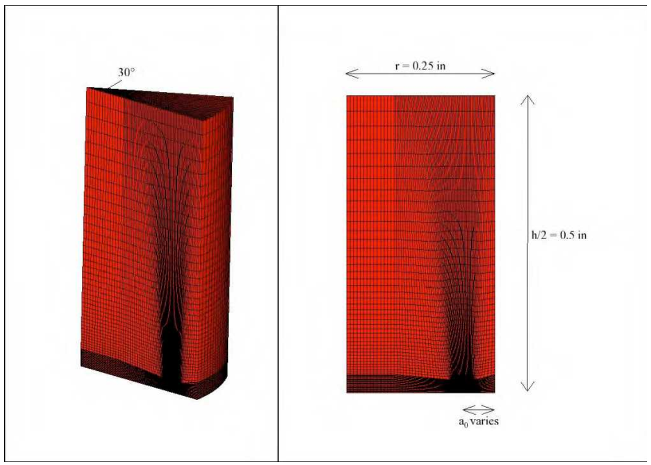
Fracture Surface Measurements



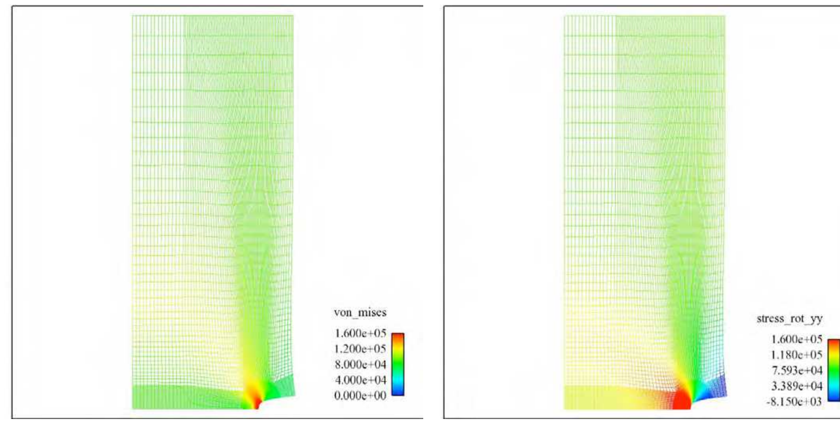
KEYENCE HD Digital Microscope

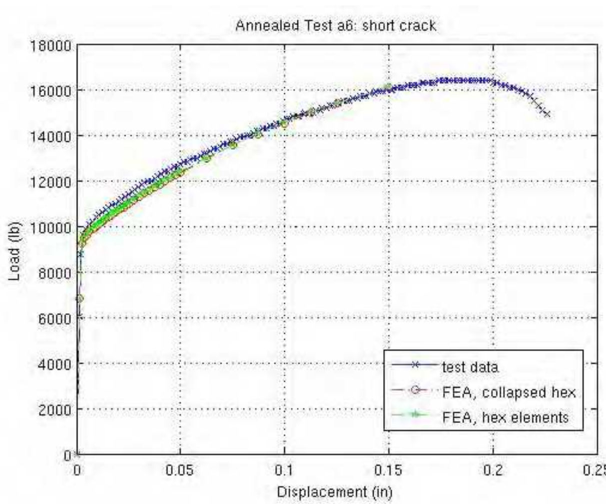
Axisymmetric CRB Fracture Results
- Short Crack Length –
H_2 = 0 atm %

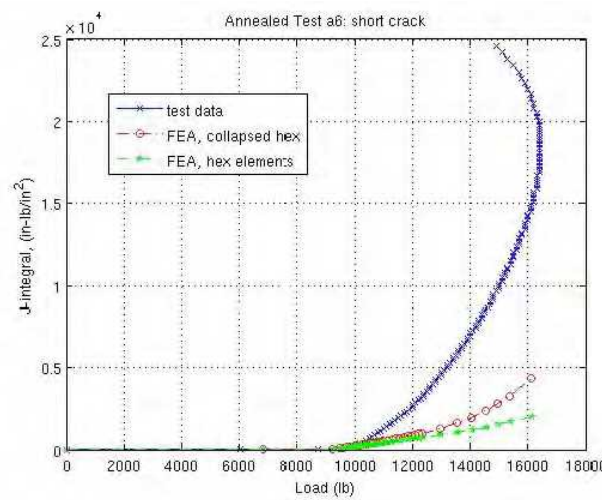
Finite element mesh of a symmetric, circumferentially CRB with a short crack (specimens A6 and A4)



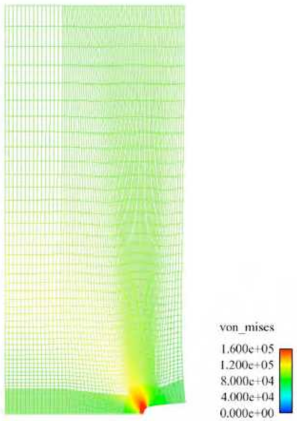
Von Mises effective stress and axial stress states of CRB specimen with a short initial crack, A6, at displacement = 0.150 inches. Regions in red meet or exceed the yield stress value of 1.6e5 psi.



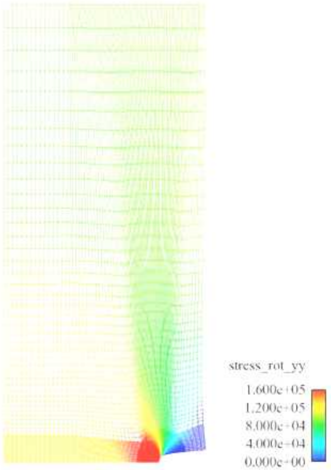


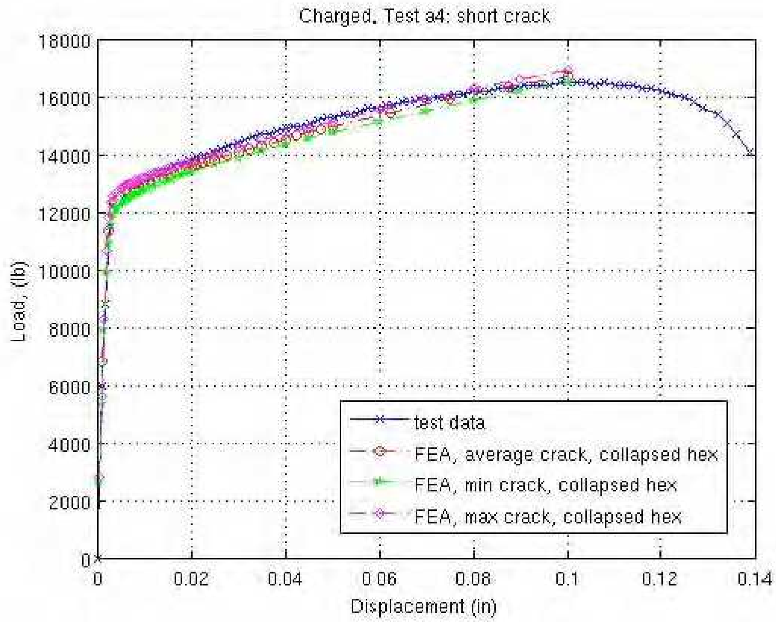


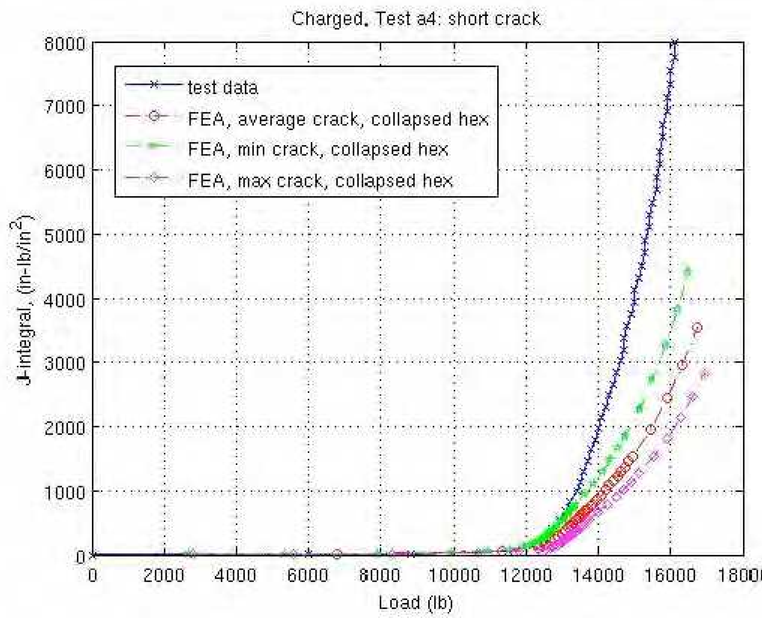
Axisymmetric CRB Fracture Results
- Short Crack Length –
H_2 = 1 atm %



Von Mises effective stress and axial stress states of a hydrogen charged CRB specimen with a short initial crack, A4, at displacement = 0.1 inches. Regions in red meet or exceed the yield stress value of 1.6e5 psi







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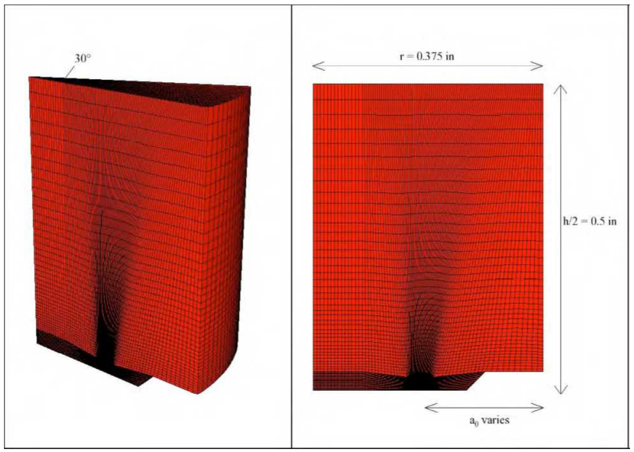
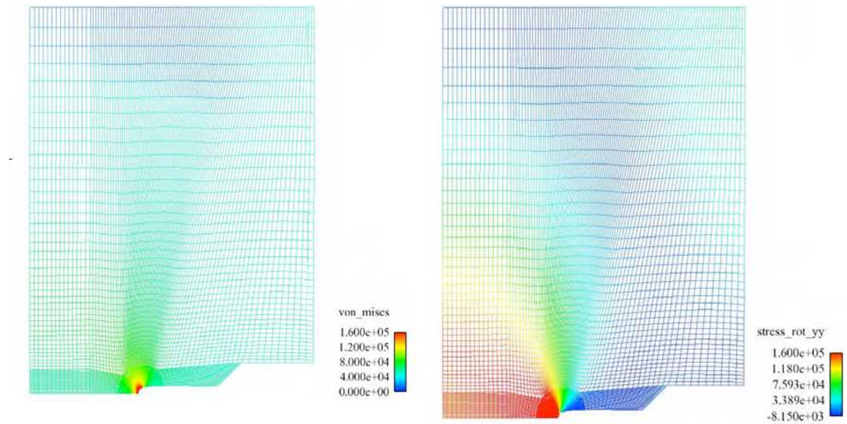
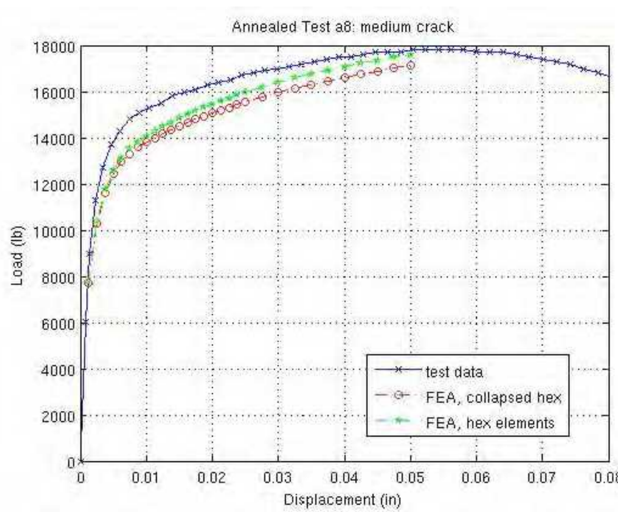
Axisymmetric CRB Fracture Results
- Medium Crack Length –
H_2 = 0 atm %

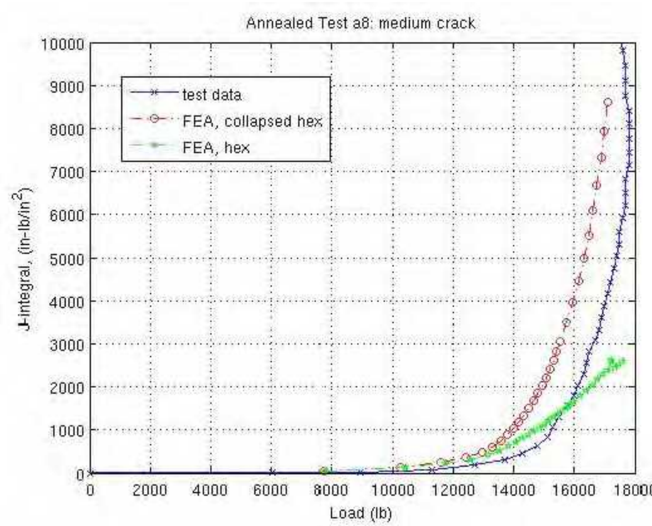
Finite element mesh of a symmetric, circumferentially CRB with medium or long crack (specimens A1, A7-A9)



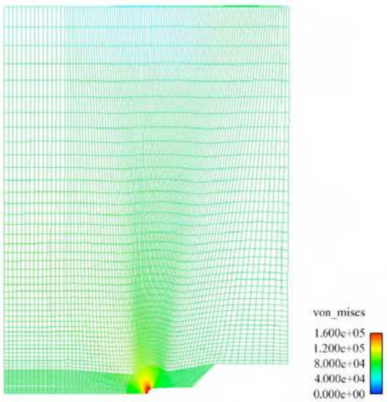
Von Mises effective stress and axial stress states of CRB specimen with a medium initial crack, A8, at displacement = 0.050 inches. Regions in red meet or exceed the yield stress value of 1.6e5 psi.



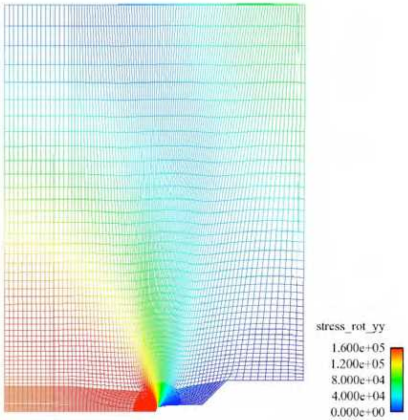


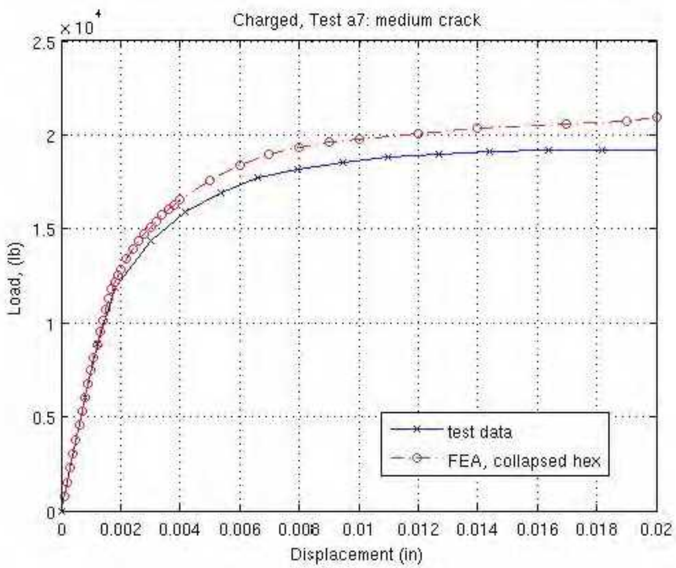


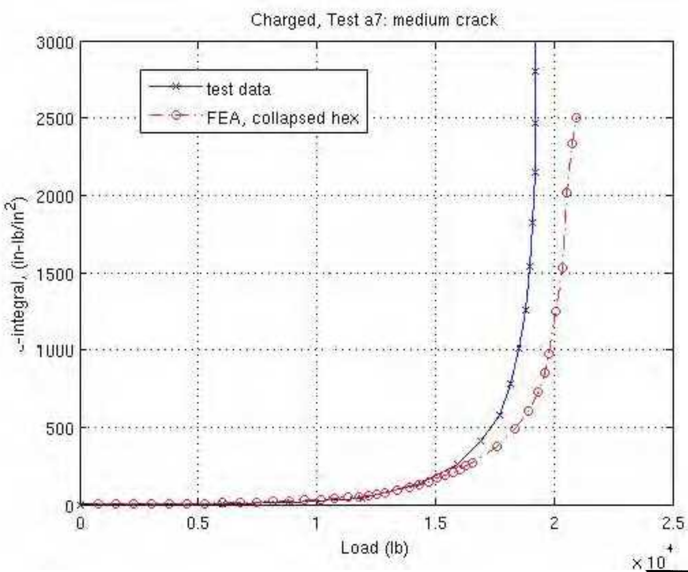
Axisymmetric CRB Fracture Results
- Medium Crack Length –
H_2 = 1 atm %



Von Mises effective stress and axial stress states of a hydrogen charged CRB specimen with a medium initial crack, A7, at displacement = 0.020 inches. Regions in red meet or exceed the yield stress value of 1.6e5 psi







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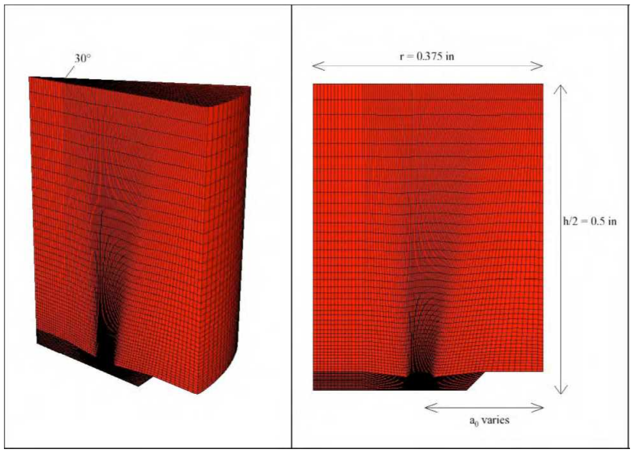
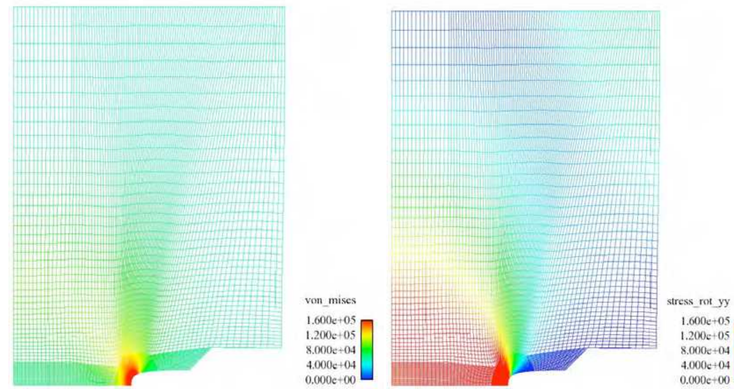
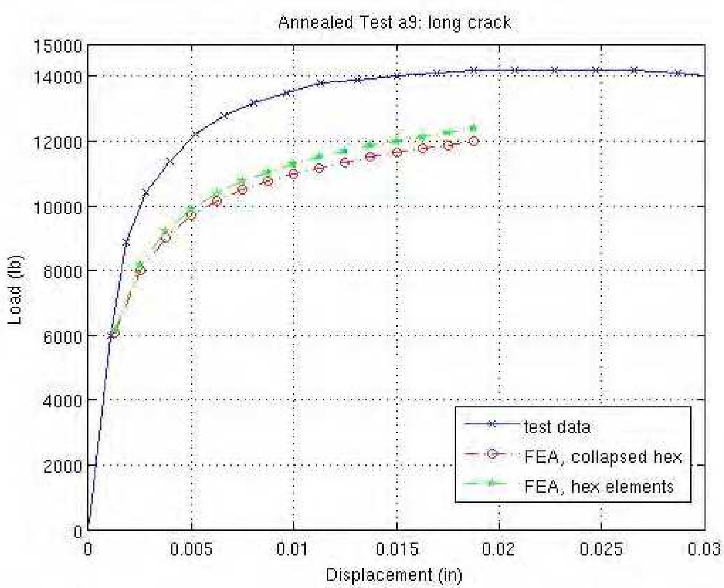
Axisymmetric CRB Fracture Results
- Long Crack Length –
H_2 = 0 atm %

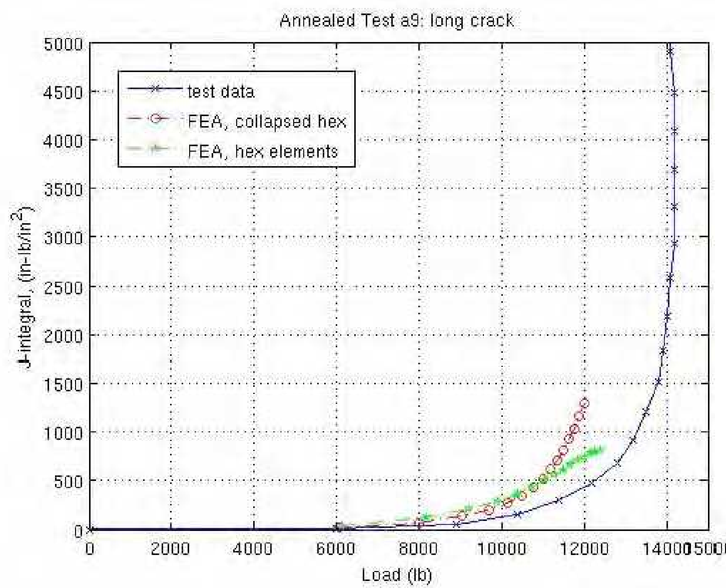
Finite element mesh of a symmetric, circumferentially CRB with medium or long crack (specimens A1, A7-A9)



Von Mises effective stress and axial stress states of CRB specimen with a long initial crack, A9, at displacement = 0.020 inches. Regions in red meet or exceed the yield stress value of 1.6e5 psi.







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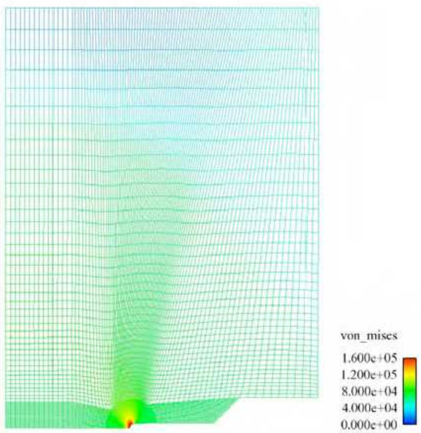
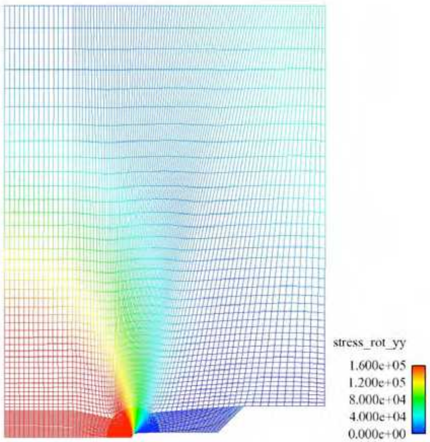
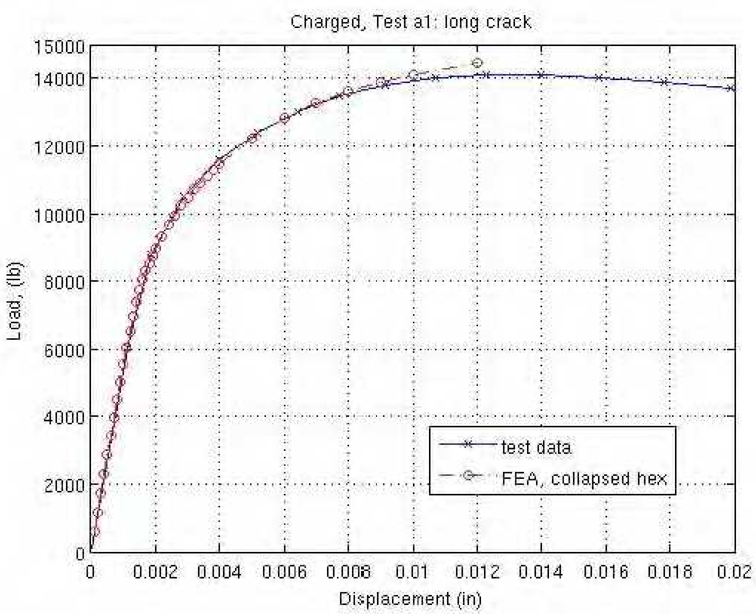
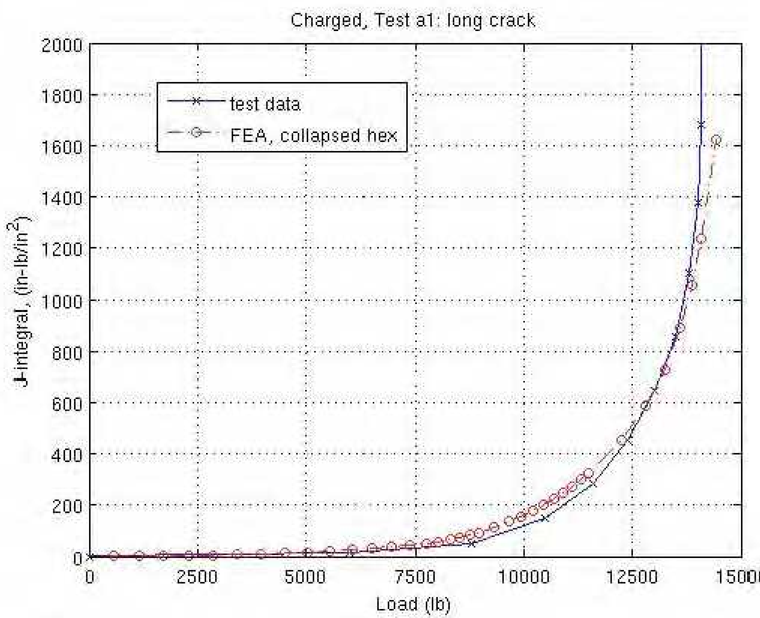
Axisymmetric CRB Fracture Results
- Long Crack Length –
H_2 = 1 atm %



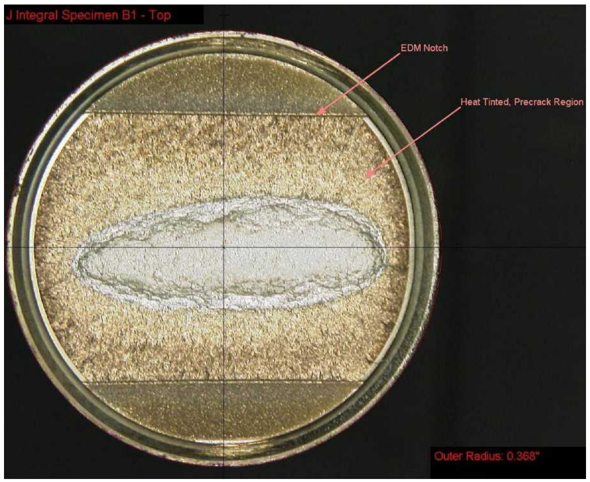
Von Mises effective stress and axial stress states of a hydrogen charged CRB specimen with a long initial crack, A1, at displacement = 0.012 inches. Regions in red meet or exceed the yield stress value of 1.6e5 psi.

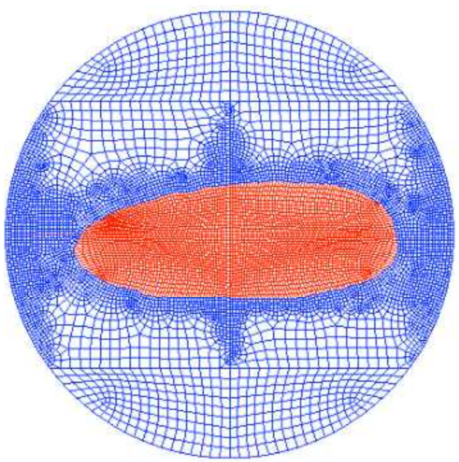


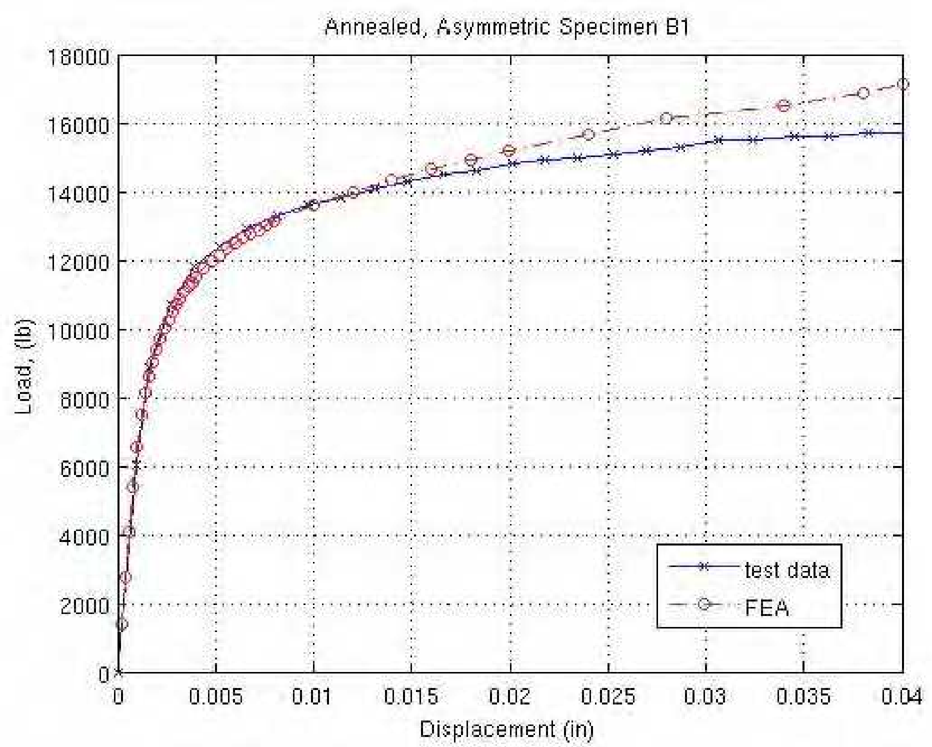




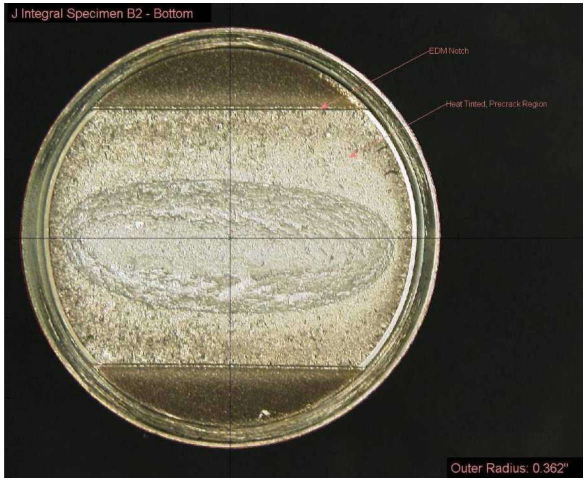
3-D Asymmetric CRB Fracture Results
H_2 = 0 atm %

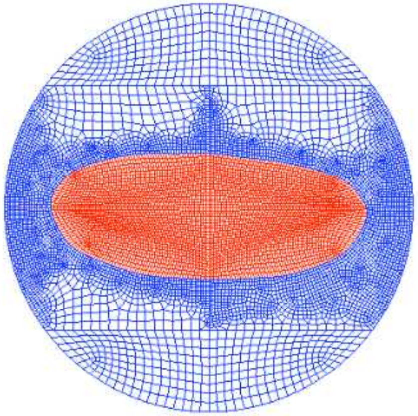


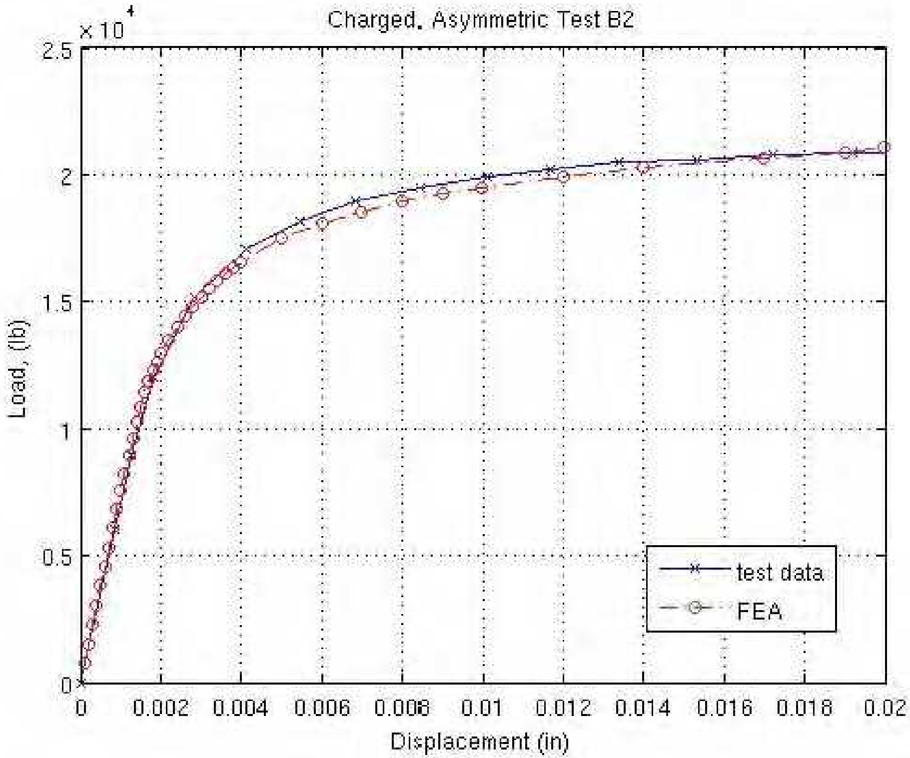




3-D Asymmetric CRB Fracture Results
H_2 = 1 atm %







Conclusions: Development of Valid Fracture Experiments in Hydrogen Affected Materials

- 21-6-9 stainless steel was fully characterized at 0 atm % and 1 atm % hydrogen levels to enable accurate modeling of experimental fracture studies
- Various elastic-plastic fracture specimen geometries (planar CT, axisymmetric CRB, asymmetric CRB) were used to measure fracture behavior as a function of hydrogen level
  - Planar specimen did not produce valid results in this ductile material, particularly 0 atm % hydrogen
  - CRB was found to produce valid results, even for 0 atm% hydrogen
  - Method of conducting valid elastic-plastic fracture experiments for highly ductile materials has been developed
- J3D code was successfully used to calculate the J-Integral from FEA results
- J3D prediction of J-Integral values
  - Reasonable for medium and long cracks
  - Inaccurate for short cracks