

# 2010 DOE Hydrogen Program Review

Project ID#: PD049

## **H<sub>2</sub> Permeability and Integrity of Steel Welds**

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June 07, 2010

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# Overview

## Timeline

- Start – March 2004
- Finish – September 2011
- 60% Complete

## Budget

- Total Project Funding
  - DOE share: \$1,177,014
  - Contractor share: N/A
- Funding received in FY09: \$100,000
- Funding for FY10: \$150,000

## Barriers Addressed

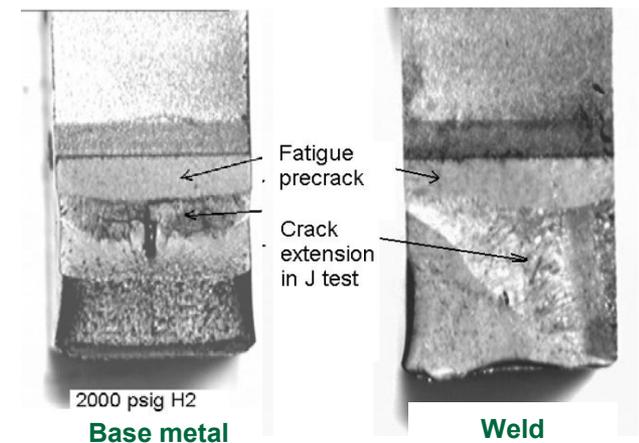
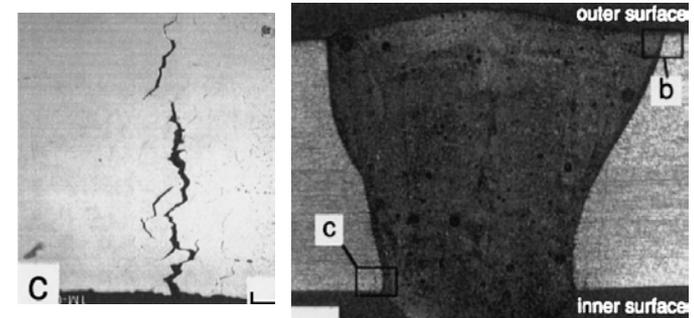
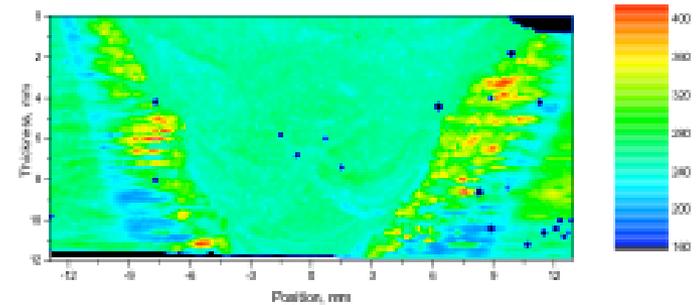
- High capital cost and hydrogen embrittlement (HE) of steel pipelines
  - Preventive measures for HE and permeation
  - Improved joining methods to reduce cost and mitigate HE
- Safety, codes and standards

## Partners

- Oak Ridge National Laboratory
- Savannah River National Laboratory
- University of Illinois
- Praxair
- MegaStir Technologies
- ESAB
- Edison Welding Institute

# Relevance to DOE H<sub>2</sub> Production and Delivery Program

- Overarching Goal:
  - Improve resistance to hydrogen embrittlement (HE) in steel welds and reduce welding related construction cost
- Technical Challenges:
  - Weld region: weakest link in a transmission pipeline as it's especially vulnerable to hydrogen-induced property degradation
  - Conventional testing methods difficult to quantify weld property degradation to HE
  - Lack of technical basis and guidelines for managing hydrogen, stresses, and microstructure in welds to ensure safety and reliability



# Objectives – Relevance

## Project objectives over past year (Jun 2009 – May 2010)

- Quantify effects of high-pressure hydrogen on fracture toughness of steel welds
- Develop welding technology that can improve weld resistance to hydrogen embrittlement

## Project impact on addressing barriers

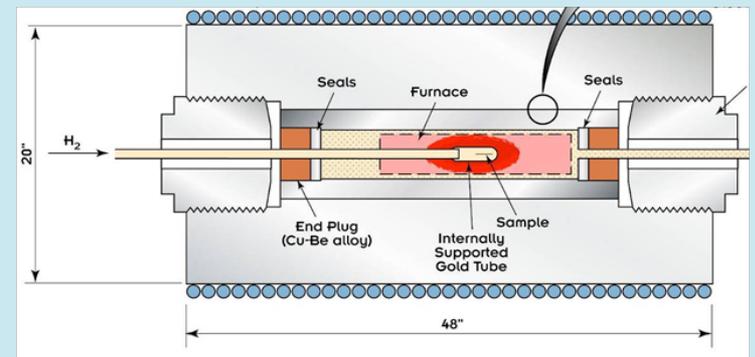
Barrier	Project impact
Preventive measures for HE & permeation	<ul style="list-style-type: none"><li>• Measurement and modeling of high-pressure hydrogen permeation and diffusion</li><li>• Development and validation of tests for measuring weld property degradation in high-pressure H<sub>2</sub></li></ul>
Improved joining methods to reduce cost and mitigate HE	<ul style="list-style-type: none"><li>• Development of solid-state friction stir welding process for welding of steel pipes</li></ul>

# Overall technical approach

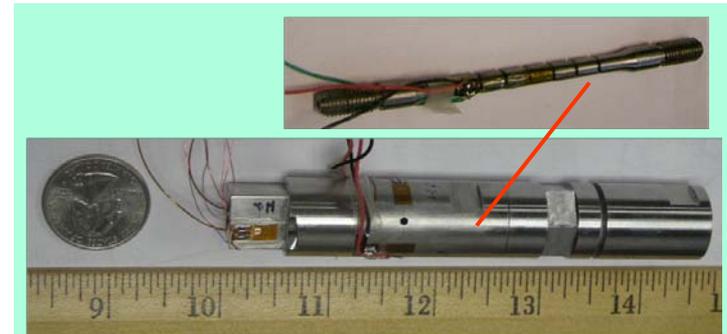
- Understand hydrogen transport behavior in base steels and welds
  - High pressure (up to 5,000 psi) hydrogen permeation and diffusion measurement and modeling
  - Effect of steel composition and microstructure
  - Effect of surface conditions
- Determine mechanical property degradation in weld region
  - Effective testing methods for welds
    - Quick screening/comparative test
    - Generating weld property data for fracture-mechanics based pipeline design
  - Evaluation of weld microstructure effect in old and new pipeline steels
- Develop welding technology for new construction, repair and retrofitting existing pipeline infrastructure for hydrogen delivery
  - Weld residual stress and microstructure management
  - Hydrogen management
- Develop technical basis and guidelines for welding construction and maintenance of hydrogen transmission pipelines

# Technical Accomplishments: *Previous Years*

- High-pressure hydrogen permeation measurement system development & verification
- Multi-notch tensile specimen as a simple way for screening and comparative test of different regions of weld and heat-affected zone (HAZ) relative to base metal
- Spiral notch torsion test (SNTT) for measuring fracture toughness of AISI 4340 base steel in air and high-pressure  $H_2$



ORNL's system for high-pressure hydrogen permeation measurement



Multi-notch tensile test specimen and loading fixture



SNTT test specimen and fracture surface

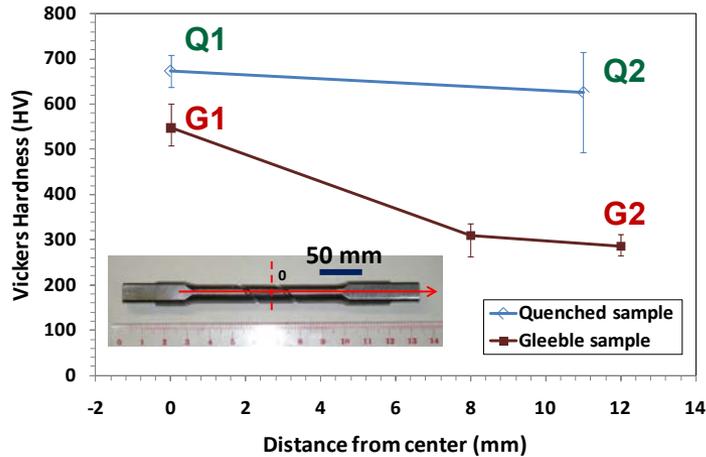
## Technical Accomplishments:

# Effect of microstructure distribution on fracture toughness

- Preparation of two groups of fracture toughness samples via different heat treatment
  - For procedure development purpose, AISI 4340 high strength steel was chosen since it is sensitive to HE.
- First group designed to introduce non-uniform microstructure similar to that encountered in a weld heat-affected zone (HAZ)
  - Using Gleeble system, samples were heated to 850 °C at a rate of 10 °C/s, held at this temperature for 5 s, and quenched to room temperature using helium gas.
- Second group having uniform microstructure distribution as that in base steel
  - Samples were furnace-heated to 850 °C, held at this temperature for one hour, and oil-quenched to room temperature.

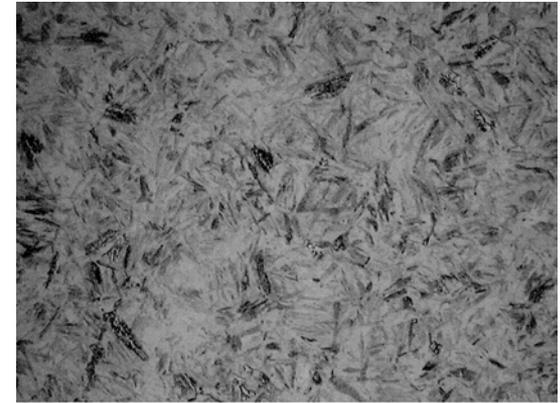
# Technical Accomplishments:

## Distribution of hardness & microstructure in sample axial direction



Q1

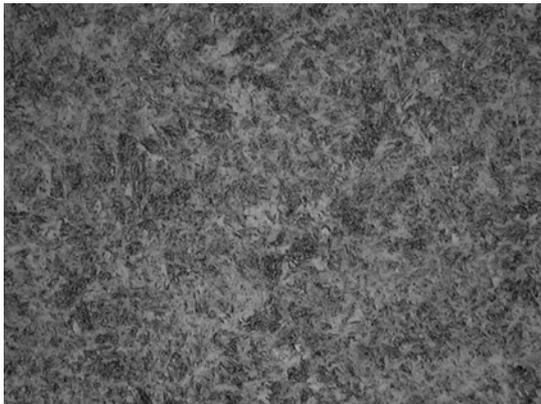
1000X 5µm  
2% Nital



Q2

1000X 5µm  
2% Nital

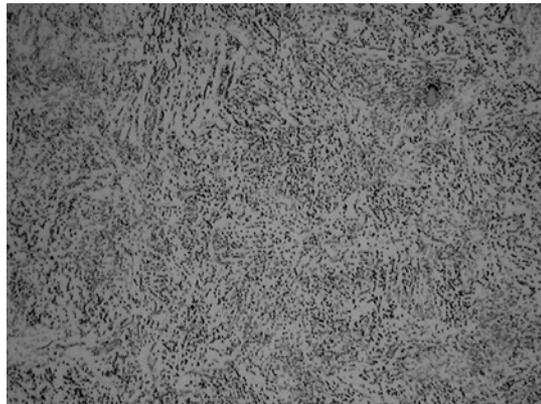
Predominantly martensite



G1

1000X 5µm  
2% Nital

Mixture of bainite and martensite



G2

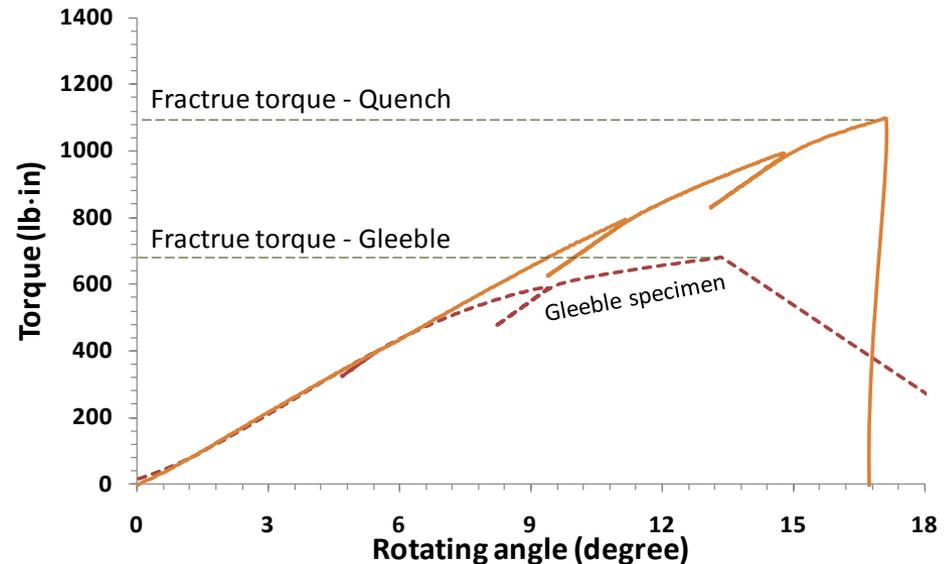
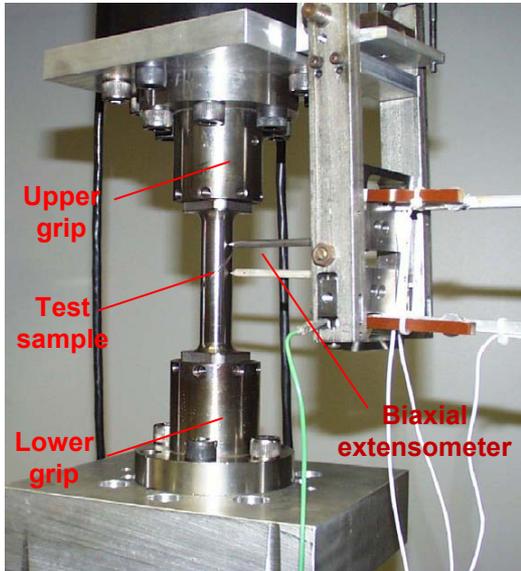
1000X 5µm  
2% Nital

Bainite

Note: The microstructure in quenched sample is more chemically homogenous than that in Gleeble sample due to the high-temperature holding.

# Technical Accomplishments:

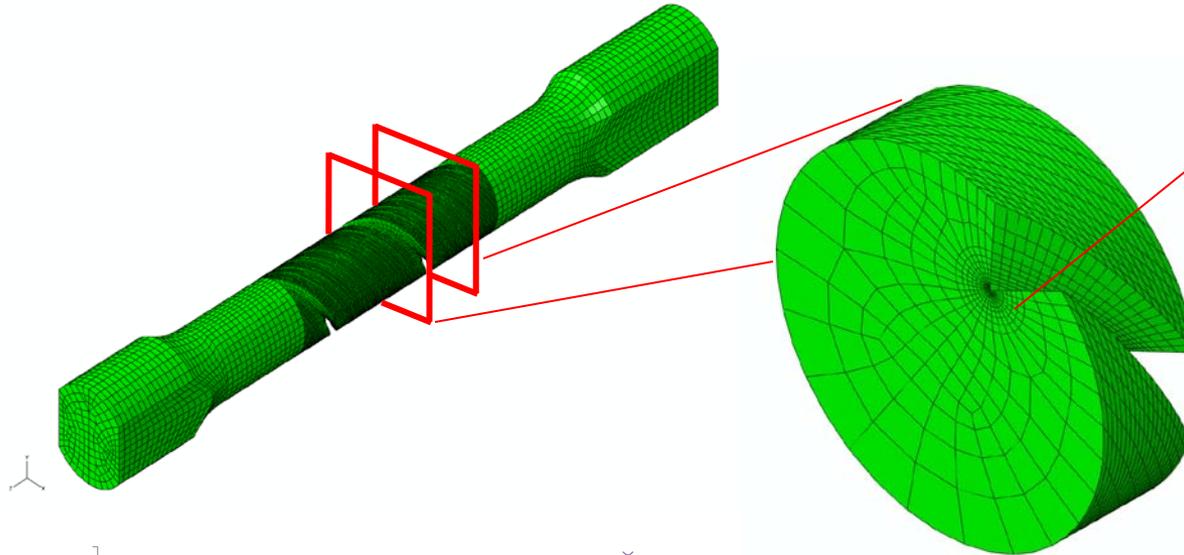
## Drastically different mechanical behavior during spiral notch torsion test



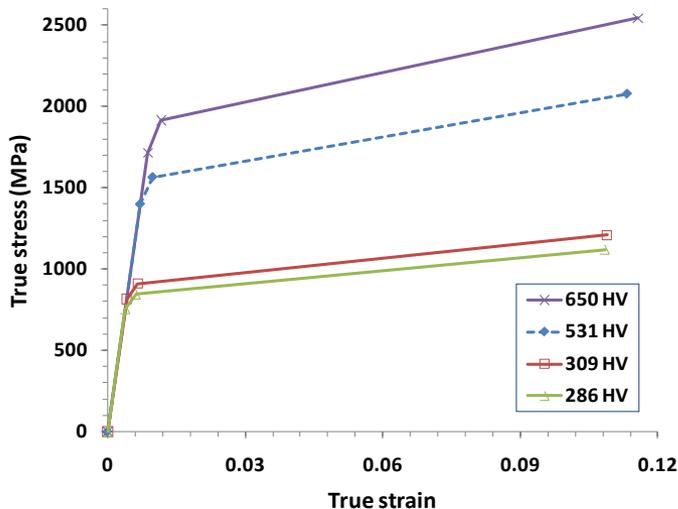
- Quenched sample with uniform microstructure distribution
  - Torque increased almost linearly with rotation angle
  - Sample fractured abruptly at torque = 124 kN·m (1,100 lb·in)
- Gleeble sample with non-uniform microstructure distribution
  - Significant non-linearity especially at high torque
  - Sample failed a lower fracture torque of 77 kN·m (680 lb·in)
- Fracture initiated from the middle section which had highest hardness
- Use of biaxial extensometer is work-in-progress

# Technical Accomplishments:

## Fracture mechanics finite element analysis to elucidate microstructure effect



- Concentric rings of elements centered on the notch/crack tip line to facilitate the contour integral calculation to determine fracture toughness.
- Element type: 20-node quadratic brick

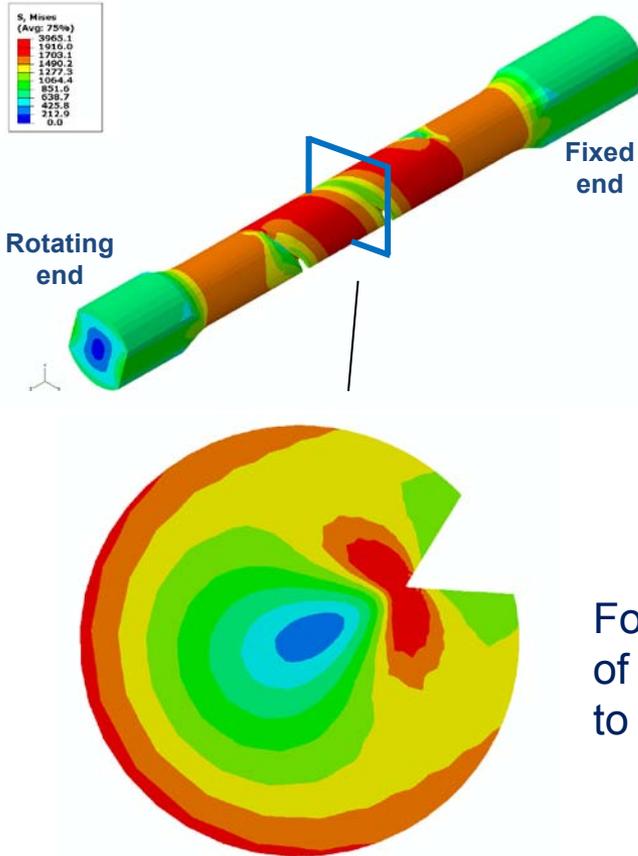


### Mechanical property

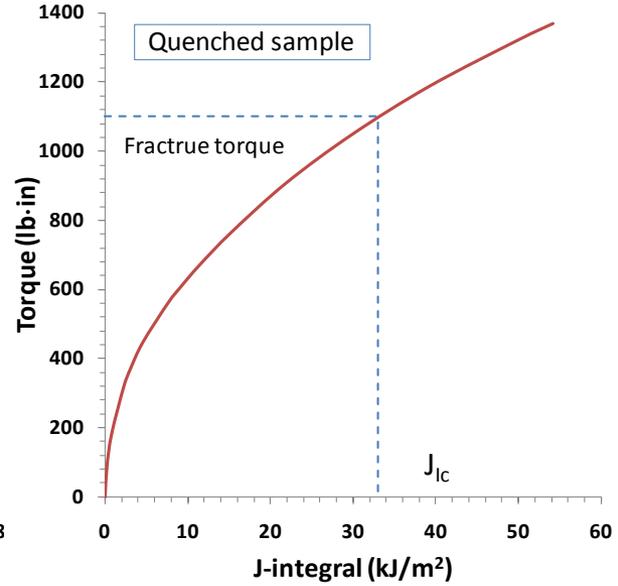
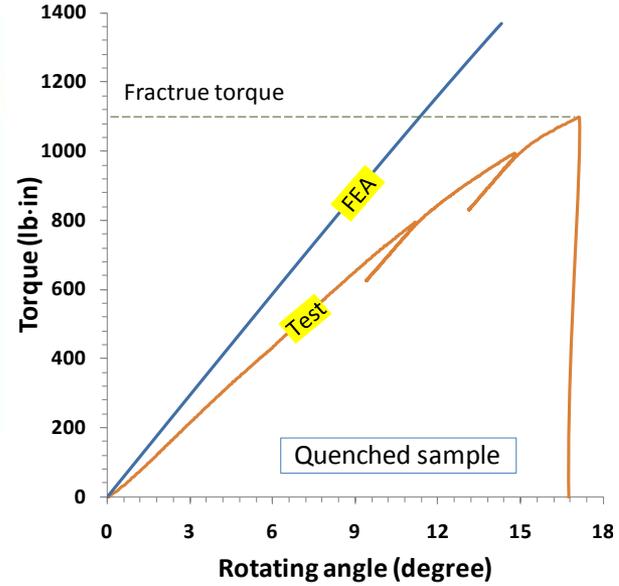
- Young's modulus and Poisson's ratio – microstructure independent
- Stress-strain curves – microstructure dependent
  - Literature data for the reference curve for 531 HV
  - Curves for other hardness calculated by linearly scaling the reference data by the hardness ratio

# Technical Accomplishments:

## Uniform microstructure – Mechanical behavior and fracture toughness



Battery-fly shaped high stress region directly in front of crack tip



For simplicity, the plastic component of  $J_{Ic}$  assumed to be small compared to the elastic component. Hence:

$$J_{Ic} = \frac{K_{Ic}^2}{E} (1 - \nu^2)$$

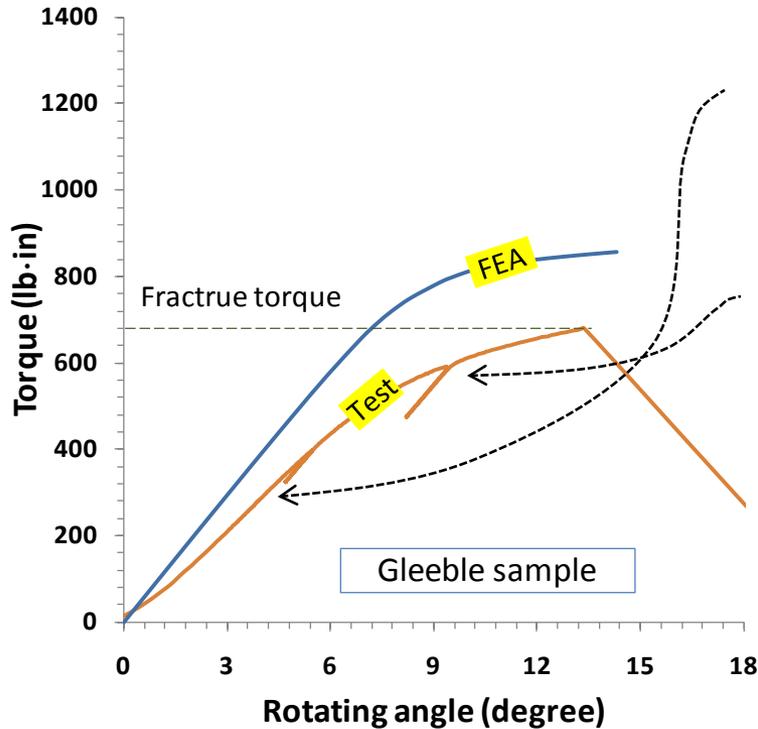
\*  $K_{Ic}$  of 4340 base steel by SNTT:  
 84.1 MPa·√m (76.5 ksi·√in)

$K_{Ic}$  from compact tension: 67 to 86 ksi·√in

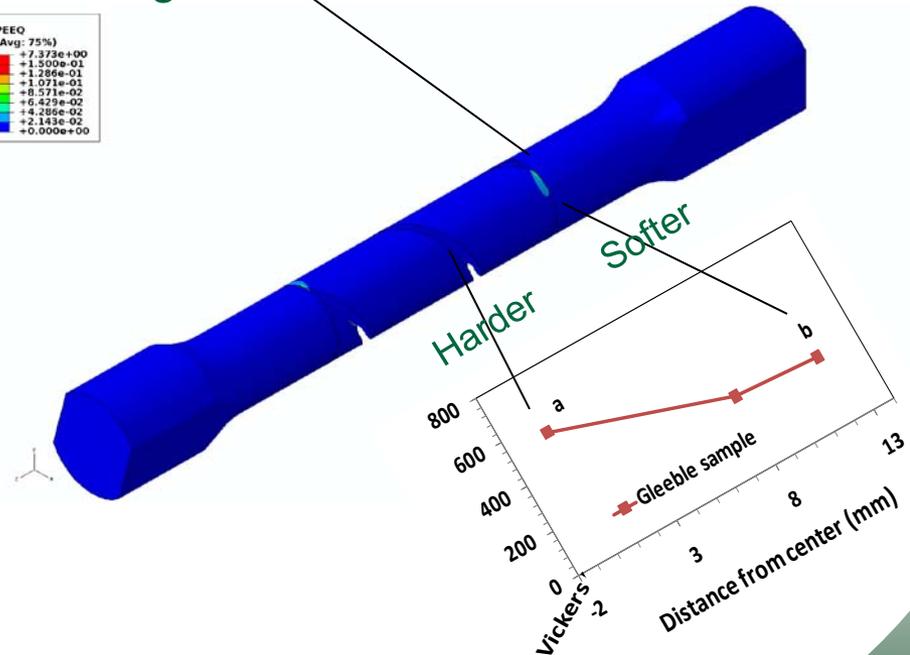
N. Bandyopadhyay, et al.: Metallurgical Transactions A, 1983.

# Technical Accomplishments:

## Non-uniform microstructure – Mechanical behavior

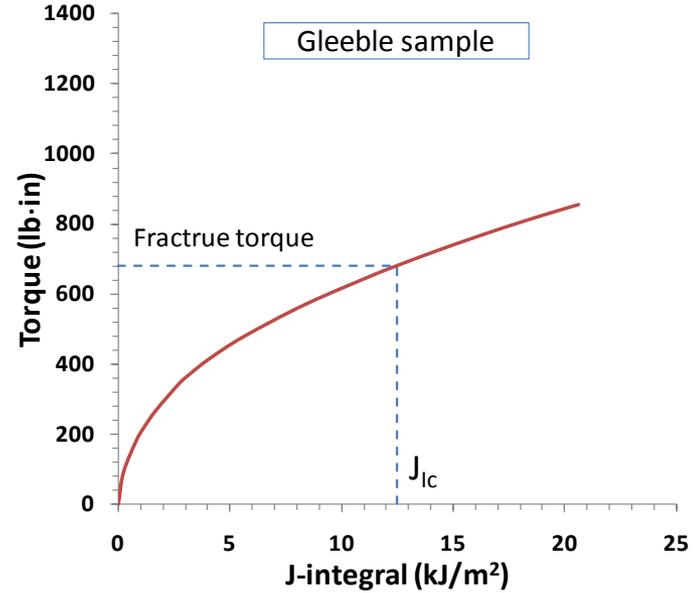
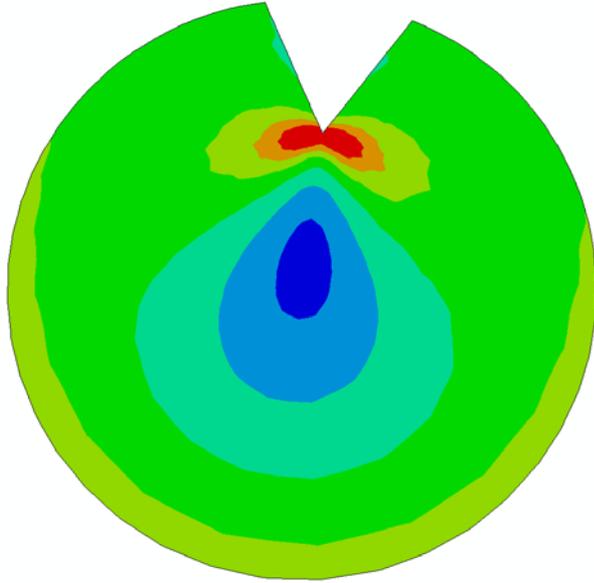
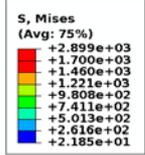


- As the applied torsion load increases from zero, the stress in the sample rises till the soft (low hardness) region starts to yield.
- Once yielding occurs, the stress rise begins to level off & more plastic strain accumulates in the soft region.

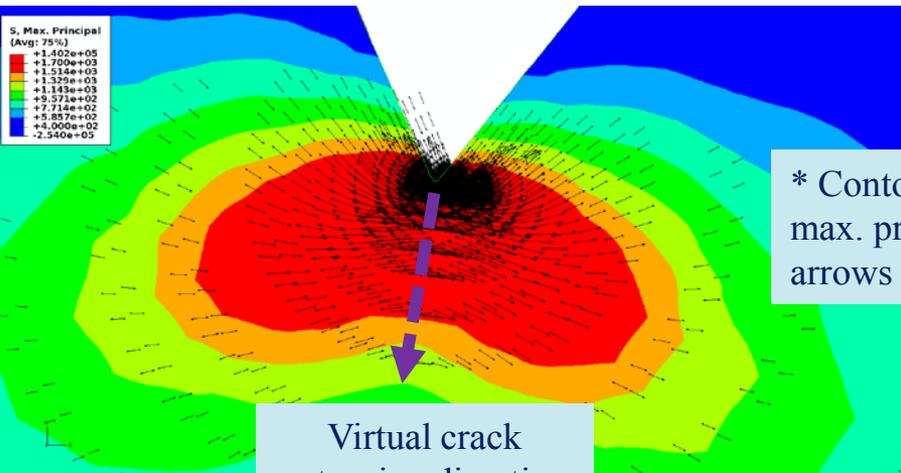


# Technical Accomplishments:

## Non-uniform microstructure – fracture toughness



\* K<sub>IC</sub> of 4340 steel weld HAZ:  
51.8 MPa·√m (47.1 ksi·√in)  
i.e., 62% of that of base metal



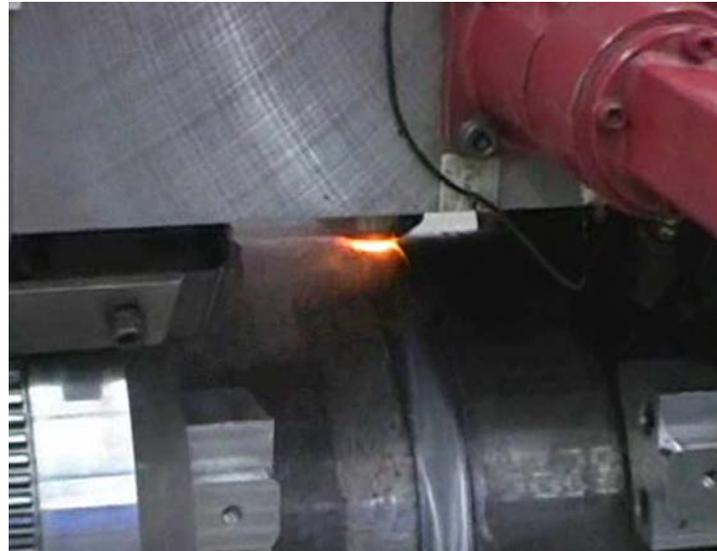
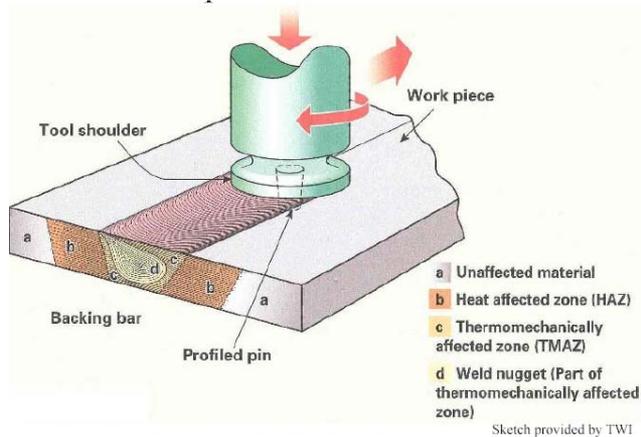
\* Contours show the values of max. principle stress, while arrows indicate the directions.

○ Max. principal stresses ahead of crack tip are mostly perpendicular to the virtual crack extension direction

# Collaborations

## Development of friction stir welding procedure and performing welding trials

- MegaStir and ESAB (industry partners):
  - FSW procedure was developed and welding trials were performed.
- EWI (industry partner):
  - Gas metal arc (fusion) welding of pipeline steels are planned.



# Proposed Future Work

- FY 2010
  - Mechanical property test of weld
    - Fracture toughness test of weld HAZ in high-pressure hydrogen with SNTT
    - Comparative test of X52 welds and X100 welds with multi-notch tensile delay cracking test
  - Microstructure characterization
    - Optical microscopy and electron microscopy imaging of weld and fracture microstructure
- FYI 2011
  - Welding technology development
    - Mechanical properties of friction stir welds vs. fusion welds
    - Weld residual stress and microstructure management
    - Cost-effective hydrogen management

*Note: future work may be adjusted depending on DOE funding priority & level.*

# Summary - Project ID # PD049

- **Relevance:** Improve fundamental understanding of weld performance necessary for ensuring safety, reliability, and durability of hydrogen transmission pipelines
- **Approach:** Develop and apply unique weld property testing techniques and solid-state joining process for pipeline steels
- **Technical Accomplishments and Progress in FY 2010:** Demonstrate that the fracture toughness of weld HAZ can be effectively evaluated using the spiral notch torsion test
- **Technology Transfer/Collaborations:**
  - Close partnership with MegaStir, ESAB and other industry companies
  - Presentations, publications and invention disclosures
  - Active interaction with Department of Transportation (DOT) PHMSA
- **Proposed Future Research:**
  - Apply SNTT to evaluate fracture toughness of weld HAZ in H<sub>2</sub>
  - Perform comparative test of HE for X52 welds and X100 welds
  - Complete microstructure characterization