2010 DOE Hydrogen Program Review

Project ID#: PD049

H_2 Permeability and Integrity of Steel Welds

Zhili Feng (PI), Wei Zhang, and Jy-An Wang

Poster presenter: Wei Zhang

Oak Ridge National Laboratory

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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

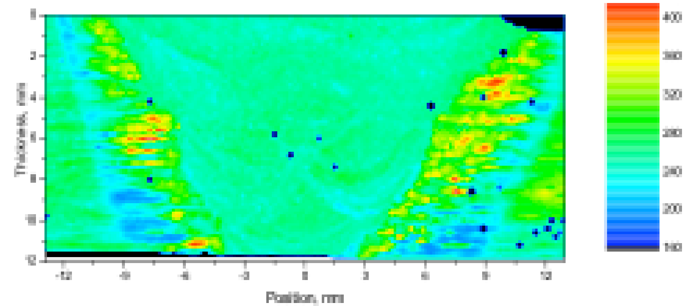
- High capital cost and hydrogen embrittlement (HE) of steel pipelines
  - Preventive measures for HE and permeation
  - Improved joining methods to reduce cost and mitigate HE
- Safety, codes and standards

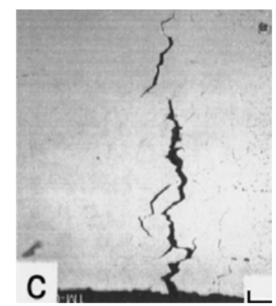
Partners

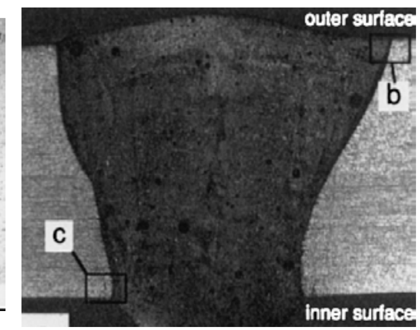
- Oak Ridge National Laboratory
- Savannah River National Laboratory
- University of Illinois
- Praxair
- MegaStir Technologies
- ESAB
- Edison Welding Institute

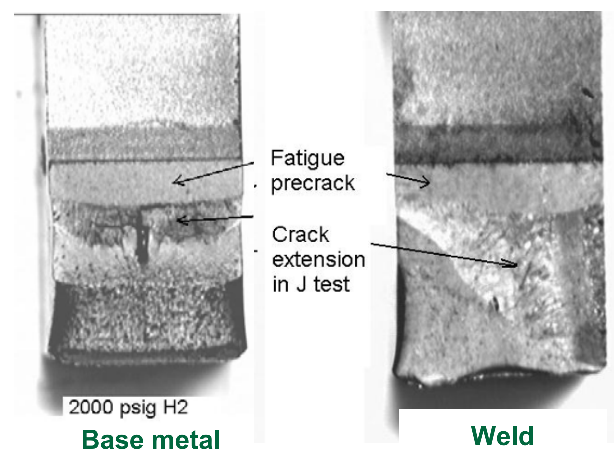
Relevance to DOE H_2 Production and Delivery Program

- 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









K. Xu: ASTM G1 Hydrogen Embrittlement Workshop, 2005.

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

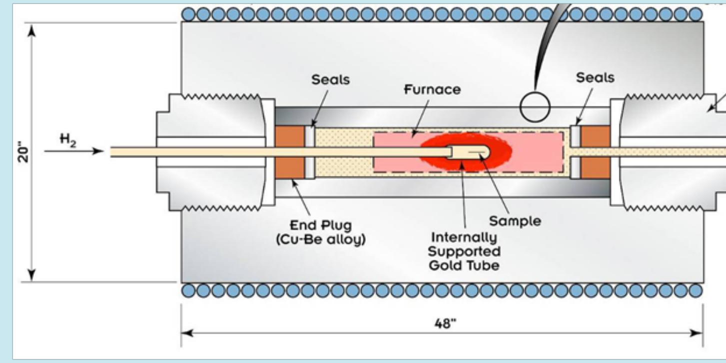
Barrier	Project impact
Preventive measures for HE & permeation	• Measurement and modeling of high-pressure hydrogen permeation and diffusion • Development and validation of tests for measuring weld property degradation in high-pressure H_2
Improved joining methods to reduce cost and mitigate HE	• Development of solid-state friction stir welding process for welding of steel pipes

Overall technical approach

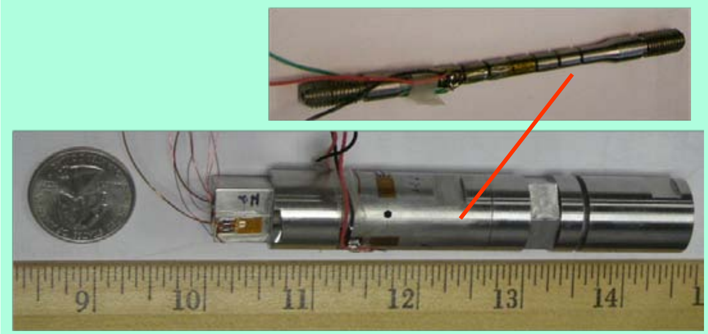
- Understand hydrogen transport behavior in base steels and welds
  - High pressure (up to 5,000 psi) hydrogen permeation and diffusion measurement and modeling
  - Effect of steel composition and microstructure
  - Effect of surface conditions
- Determine mechanical property degradation in weld region
  - 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 <u>base steel</u> 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

Oak Ridge National Laboratory

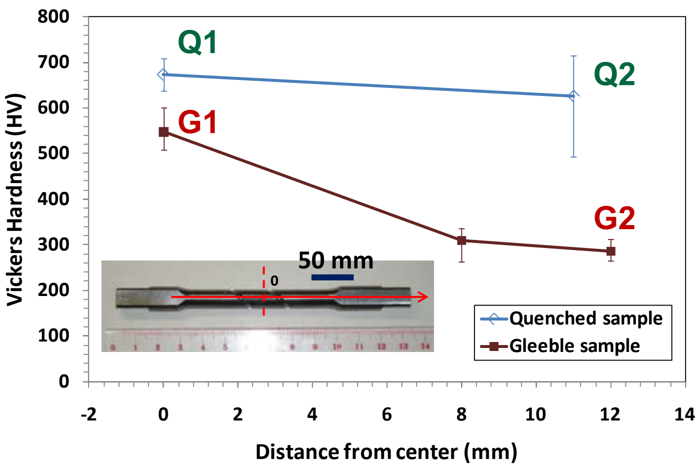
Technical Accomplishments:

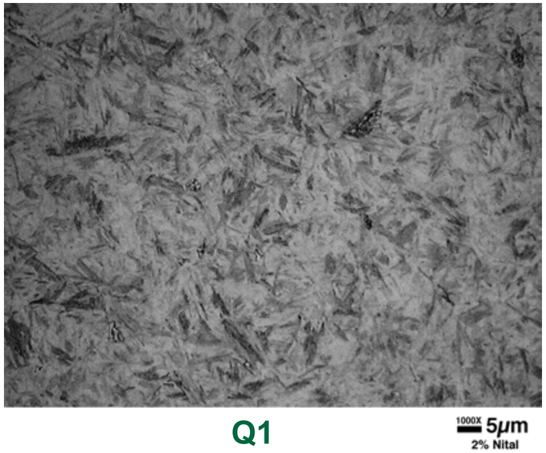
Effect of microstructure distribution on fracture toughness

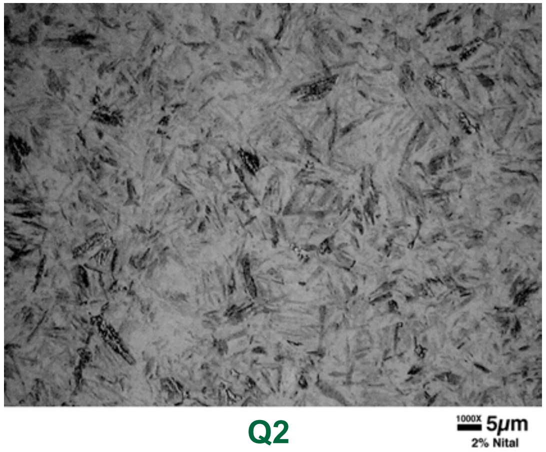
- Preparation of two groups of fracture toughness samples via different heat treatment
  - For procedure development purpose, AISI 4340 high strength steel was chosen since it is sensitive to HE.
- First group designed to introduce non-uniform microstructure similar to that encountered in a weld heat-affected zone (HAZ)
  - Using Gleeble system, samples were heated to 850 ^{o}C at a rate of 10 ^{o}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 ^{o}C, held at this temperature for one hour, and oil-quenched to room temperature.

Technical Accomplishments:

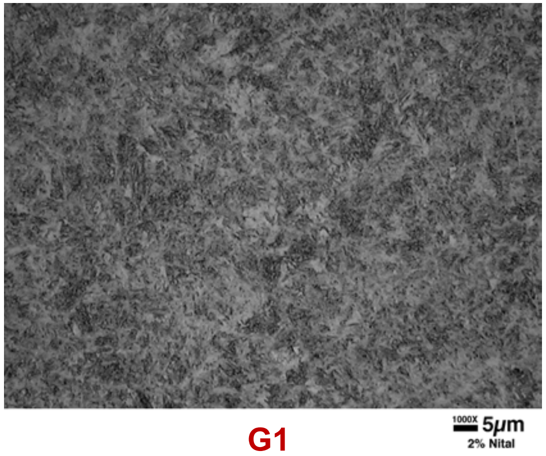
Distribution of hardness & microstructure in sample axial direction



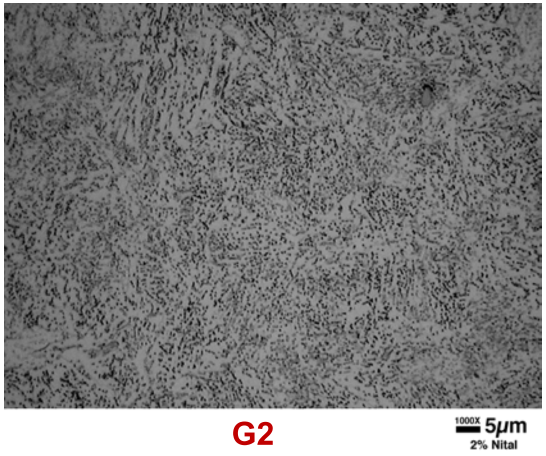




Predominantly martensite



Mixture of bainite and martensite

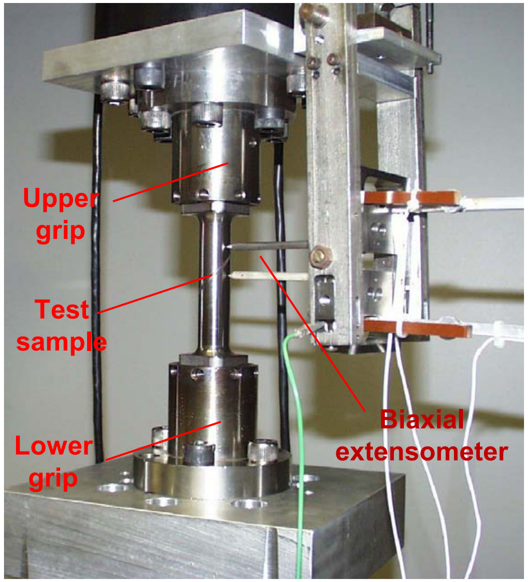


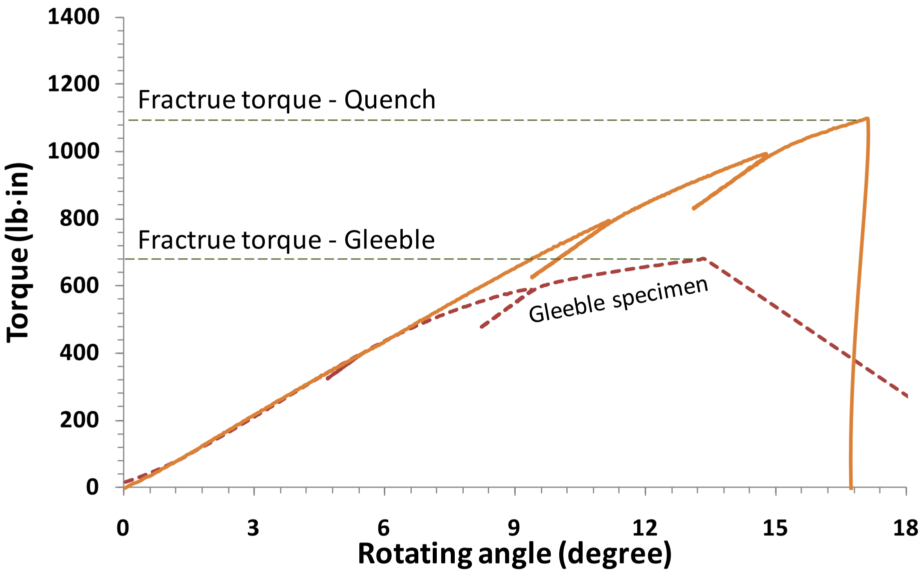
Bainite

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

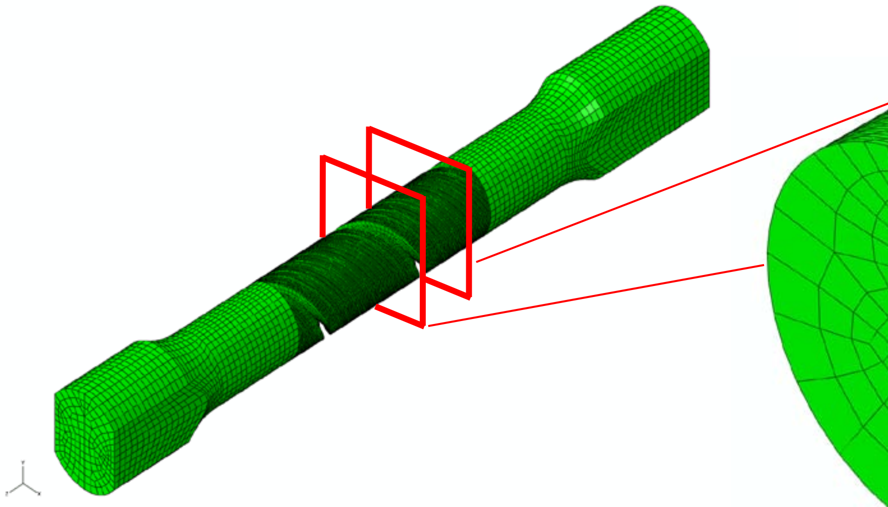


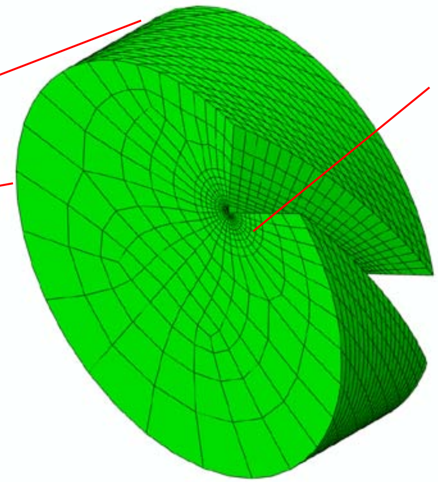


- Quenched sample with uniform microstructure distribution
  - Torque increased almost linearly with rotation angle
  - Sample fractured abruptly at torque = 124 kN·m (1,100 lb·in)
- Gleeble sample with non-uniform microstructure distribution
  - Significant non-linearity especially at high torque
  - 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

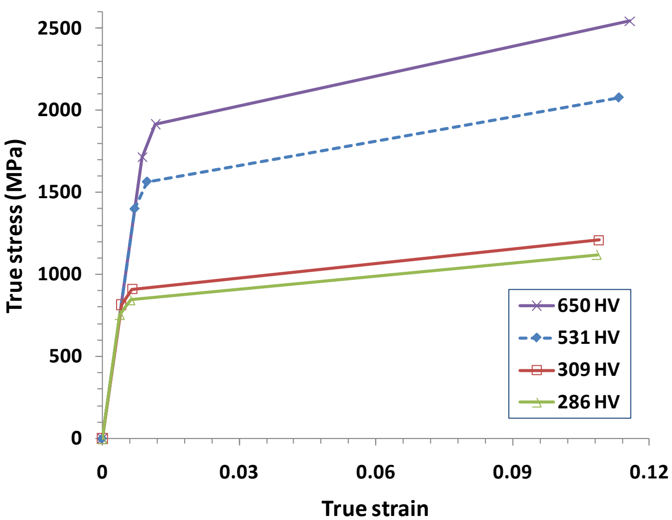
Technical Accomplishments:

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

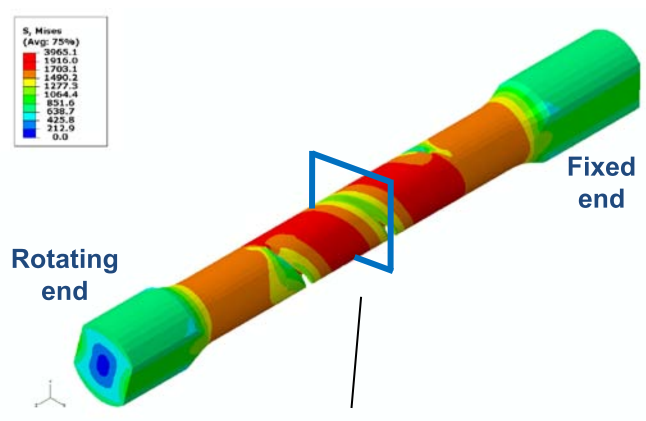


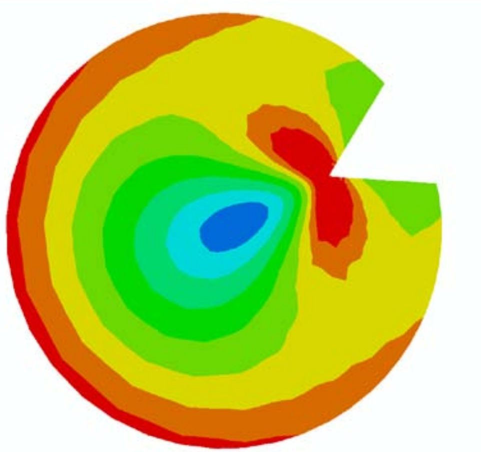
Mechanical property

- 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

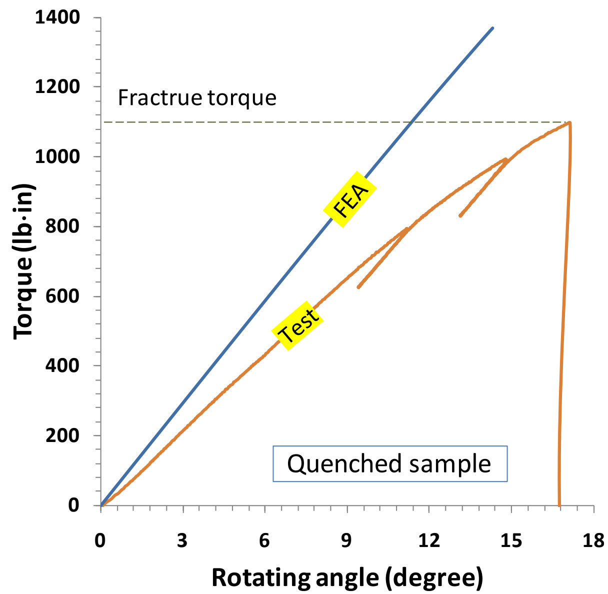
Technical Accomplishments:

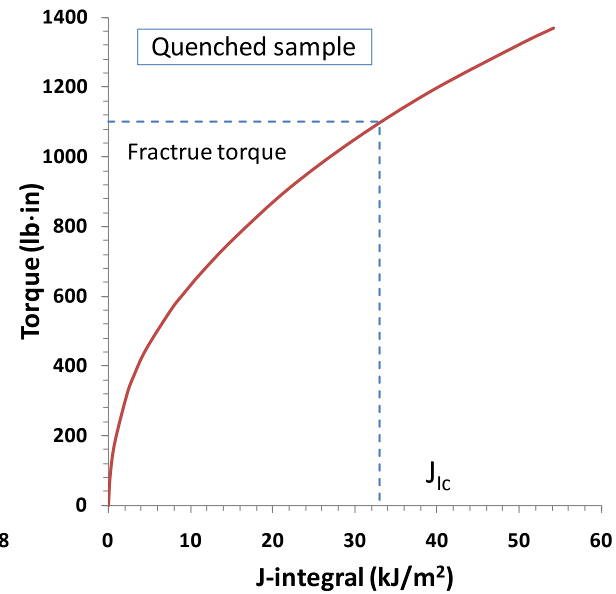
Uniform microstructure – Mechanical behavior and fracture toughness





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:

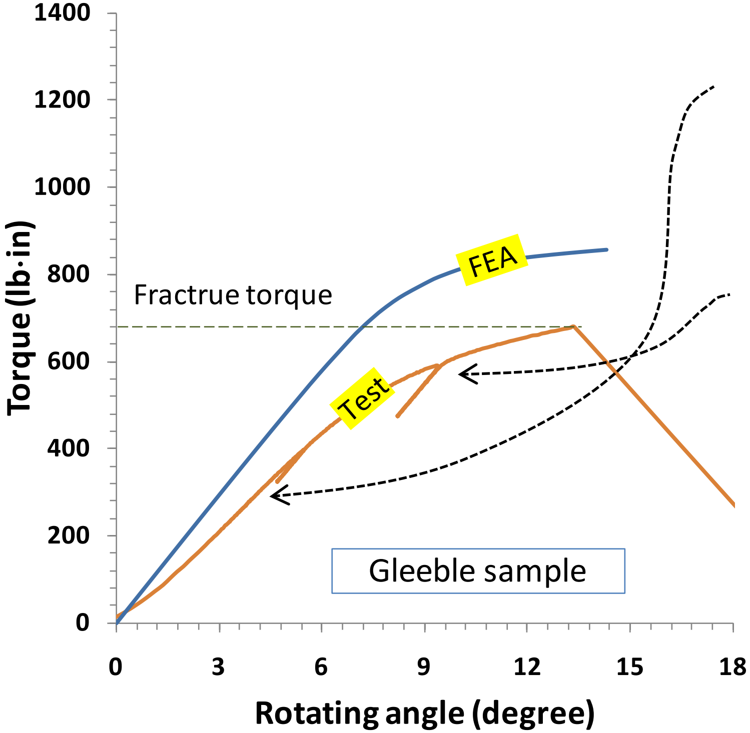
$$84.1\ \text{MPa}\cdot\sqrt{m}\quad (76.5\ \text{ksi}\cdot\sqrt{in}\ )$$

K_{Ic} from compact tension: 67 to 86 $\text{ksi}\cdot\sqrt{in}$

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

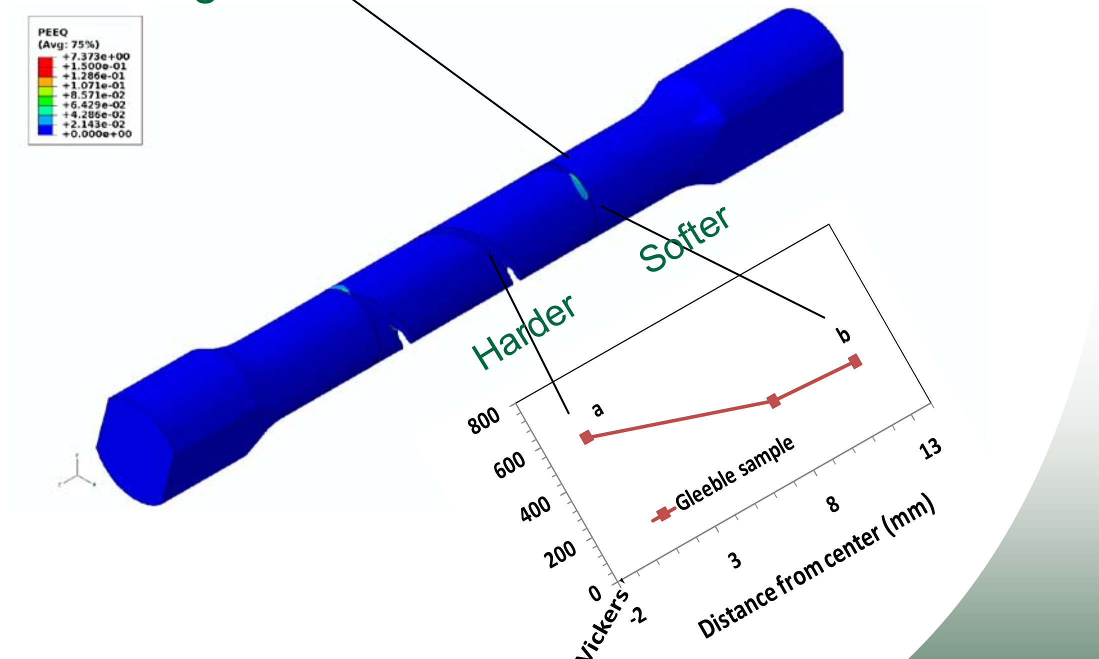
Technical Accomplishments:

Non-uniform microstructure – Mechanical behavior



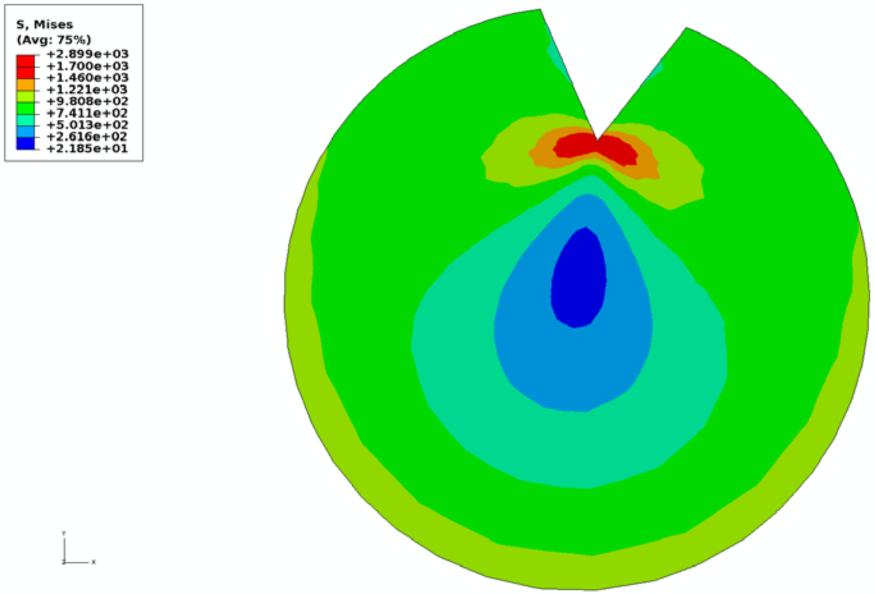
- As the applied torsion load increases from zero, the stress in the sample rises till the soft (low hardness) region starts to yield.

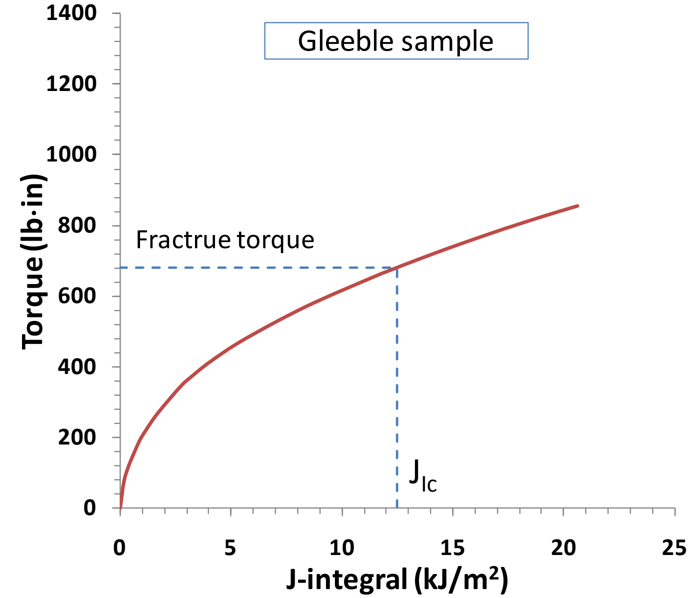
- Once yielding occurs, the stress rise begins to level off & more plastic strain accumulates in the soft region.



Technical Accomplishments:

Non-uniform microstructure – fracture toughness

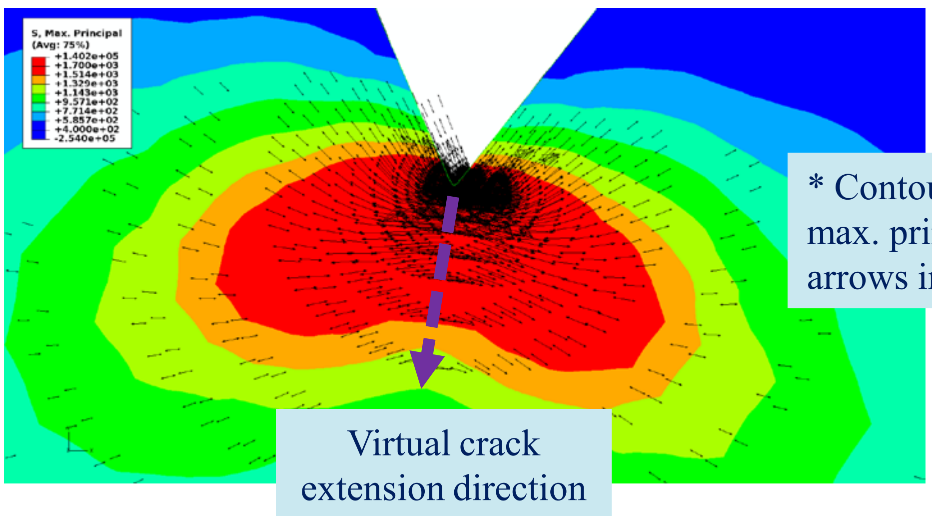




* K_{Ic} of 4340 steel *weld HAZ*:

$$51.8\ \text{MPa}\cdot\sqrt{m}\ \ (47.1\ \text{ksi}\cdot\sqrt{in}\ )$$

i.e., 62% of that of base metal



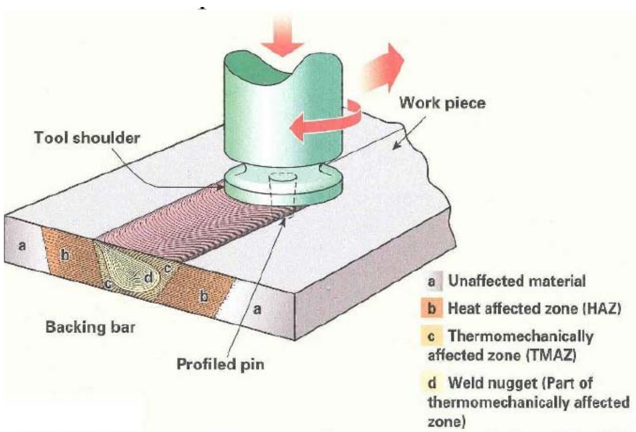
* Contours show the values of max. principle stress, while arrows indicate the directions.

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

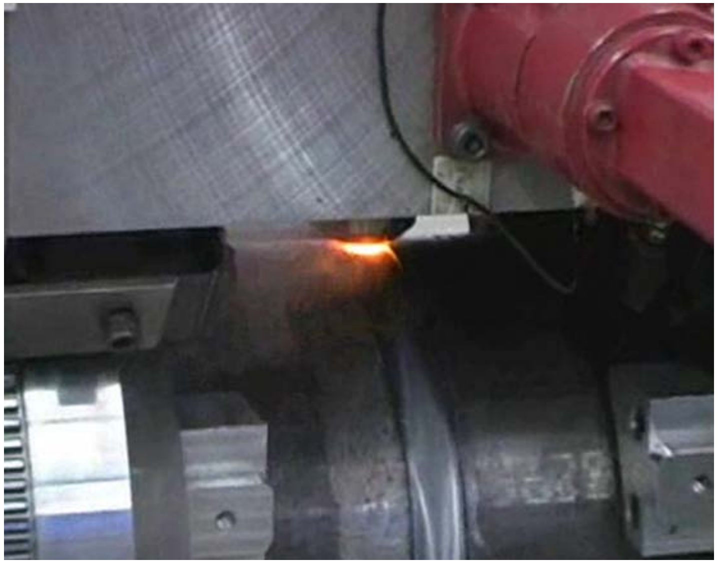
Collaborations

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.



Sketch provided by TWI



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_2
  - Perform comparative test of HE for X52 welds and X100 welds
  - Complete microstructure characterization