2011 DOE Hydrogen and Fuel Cells Program Review

Integrity of Steel Welds in High-Pressure Hydrogen Environment

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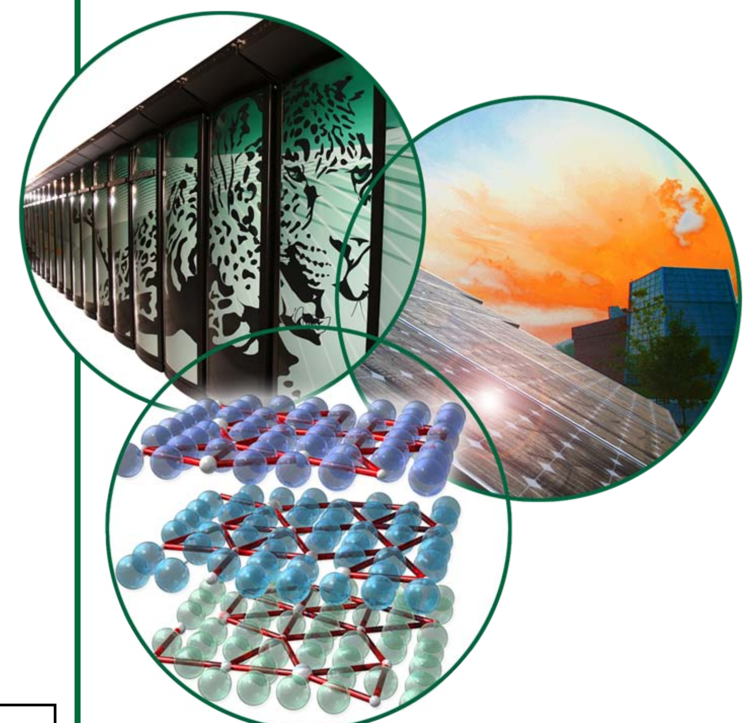
Project ID # PD049



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U.S. DEPARTMENT OF ENERGY

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Overview

Timeline

- Project start date: Mar. 2004
- Project end date: Sep. 2012*
- Percent complete: *90%*

Budget

- Total project funding
  - DOE share: $1,327K
  - Contractor share: Not Applicable
- Funding received in FY10: $150K
- Funding for FY11: $150K

* Project continuation and direction determined annually by DOE

Barriers

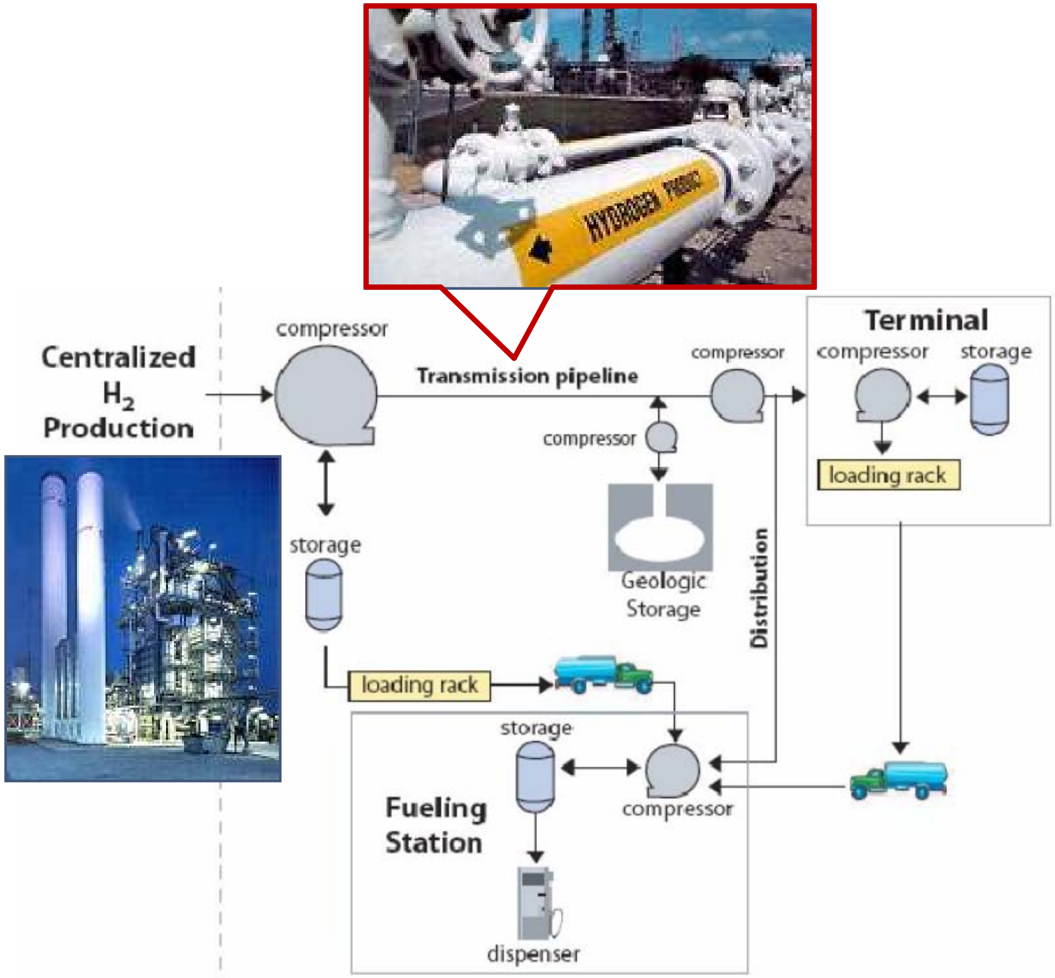
- Barriers addressed
  - **D.** High Capital Cost and Hydrogen Embrittlement of Pipelines
  - **K.** Safety, Codes and Standards, Permitting

Partners

- Project lead
  - ORNL (Oak Ridge National Laboratory)
- Interactions / collaborations
  - Savannah River National Lab
  - University of Illinois
  - Praxair
  - MegaStir Technologies
  - ESAB
  - DOT and ASME

Details in Slide 20

Relevance – Hydrogen Delivery



Gaseous hydrogen delivery pathway

Figure adapted from Hydrogen Delivery, in Multi-Year Research, Development and Demonstration Plan, 2007.

- **1,200 miles of H_2 pipelines currently operating in the U.S.**
- **New pipelines under construction by major gas suppliers**
- **Current joining technology for steel pipes:**
  - **Creating microstructure that is susceptible to hydrogen embrittlement**
  - **Labor-intensive and costly**

Ref.: Hydrogen Delivery, Multi-Year Plan, 2007.

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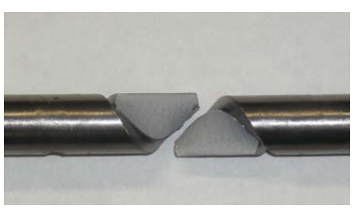
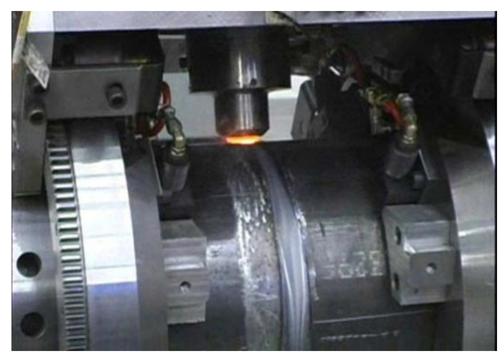
Relevance – Project Objectives

- Overarching goal of project:
  - Improve resistance to hydrogen embrittlement (HE) in pipeline steel welds
  - Reduce welding-related construction cost
- Specific objectives during the current project year:
  - Validate the fracture toughness testing methodology for pipeline steel welds in high-pressure hydrogen environment
  - Demonstrate the effectiveness of friction stir welding for improving resistance of pipeline steel welds to hydrogen embrittlement





Overall Technical Approach

- Understand H_2 transport behavior in base metal steels and welds
  - Measurement and modeling of H_2 permeation and diffusion under high pressure (up to 5,000 psi)
  - Effect of steel composition, microstructure, and sample surface conditions
- Generate weld property data for fracture-mechanics based pipeline design
  - Tensile test for relative ranking of weld microstructure susceptibility to hydrogen embrittlement
  - Spiral notch torsion test for determining fracture toughness degradation in steel welds
- Develop welding technology for steel pipelines for H_2 delivery
  - Solid-state friction stir welding for improved mechanical property and reduced cost

Focuses of the current project year

Technical Accomplishments and Progress

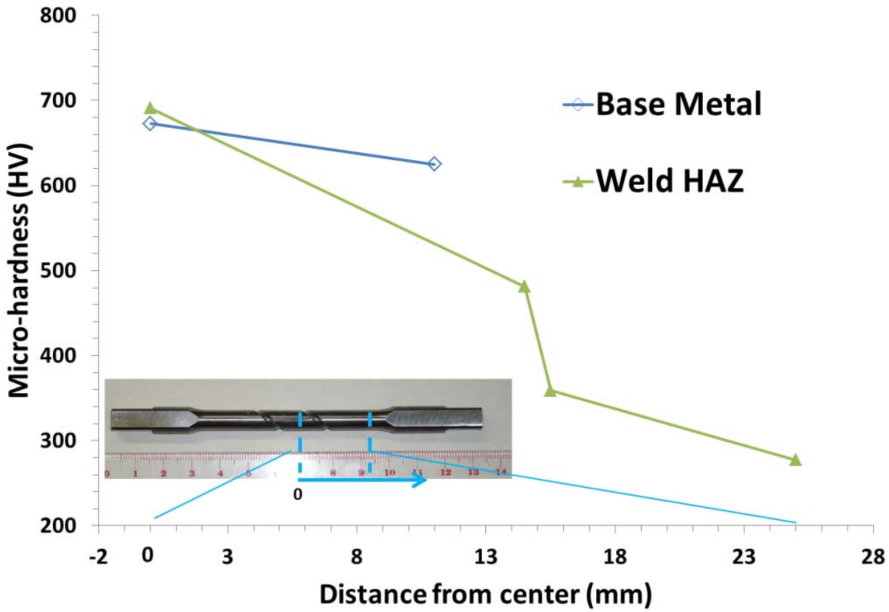
- Quantitative understanding of hydrogen embrittlement in pipeline steel welds based on *in-situ* testing methods:
  – Spiral notch torsion test (SNTT) for fracture toughness
  – Multi-notch tension test for microstructure susceptibility
- Friction stir welding for improving resistance of steel welds to hydrogen embrittlement
- Improving capability of testing equipment
  – A hydrogen charging system capable of steadily supplying or varying H_2 pressure up to 10,000 psi

Validation of *in-situ* Fracture Toughness Testing in High-Pressure H_2

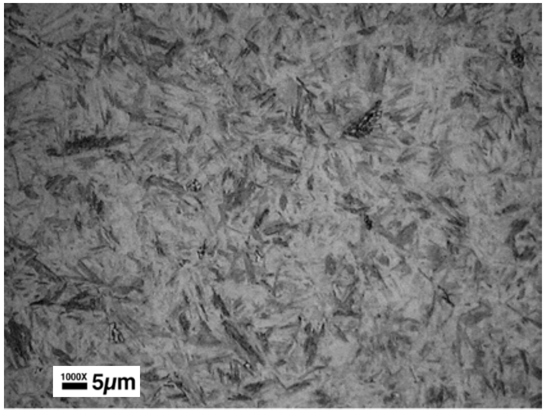
Testing matrix

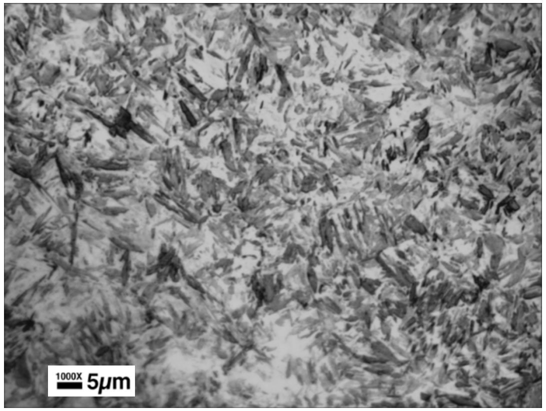
- Fracture toughness testing method
  - Spiral notch torsion test
- Testing specimens
  - Base metal of AISI 4340 high-strength steel
  - Simulated heat-affected zone (HAZ) of 4340 steel weld
- Testing environments:
  - Room temperature
  - Gaseous hydrogen at 1,900 psi pressure
  - Air

Microstructure and Hardness in 4340 Base Steel & Weld Heat-Affected Zone

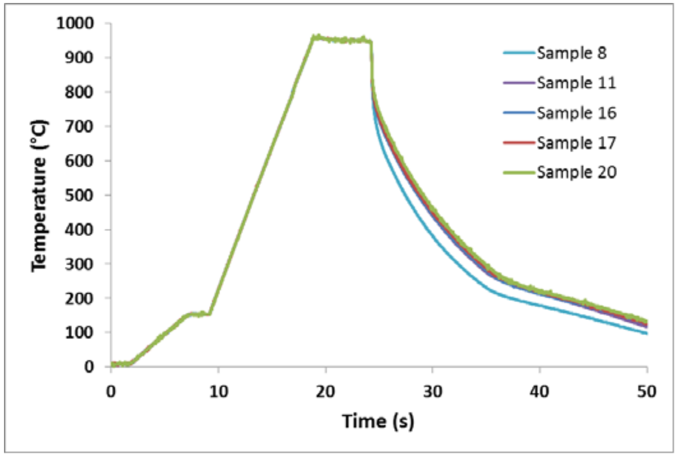


- Base metal prepared by:
  - Heat treated at 850 °C for one hour and oil-quenched to room temperature
- Simulated weld HAZ prepared using a Gleeble® thermal-mechanical system:
  - Heated to 950 °C at a rate of 10 °C/s, held at 950 °C for 5 s, and quenched to room temperature using helium gas
  - Temperature profiles mimicking those encountered in welding

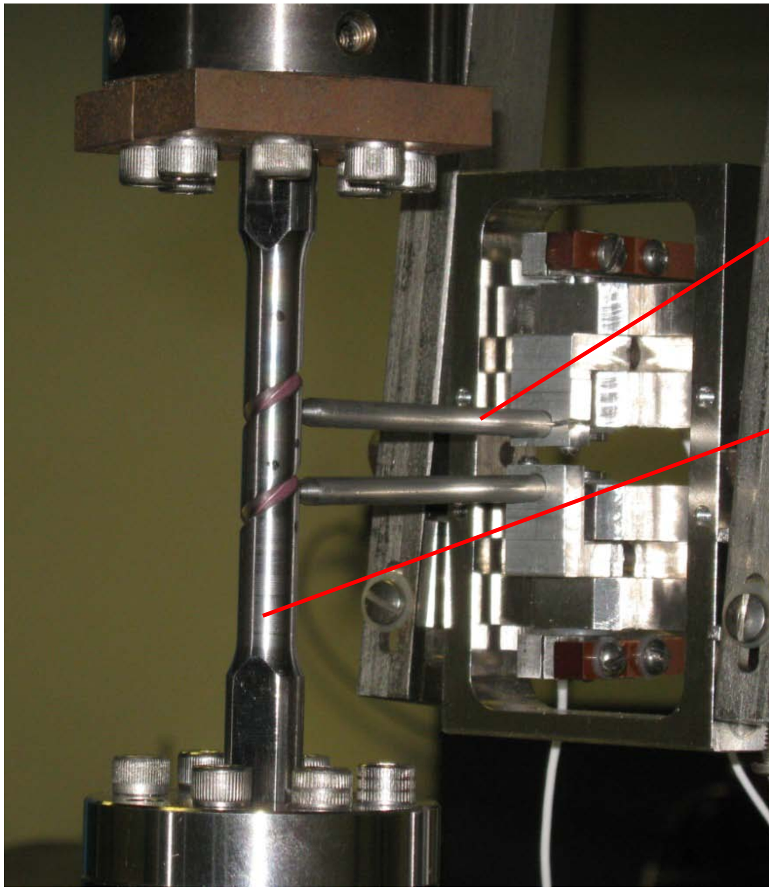


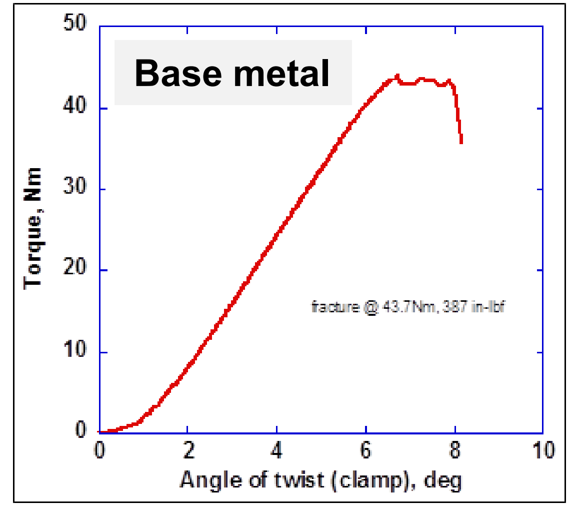


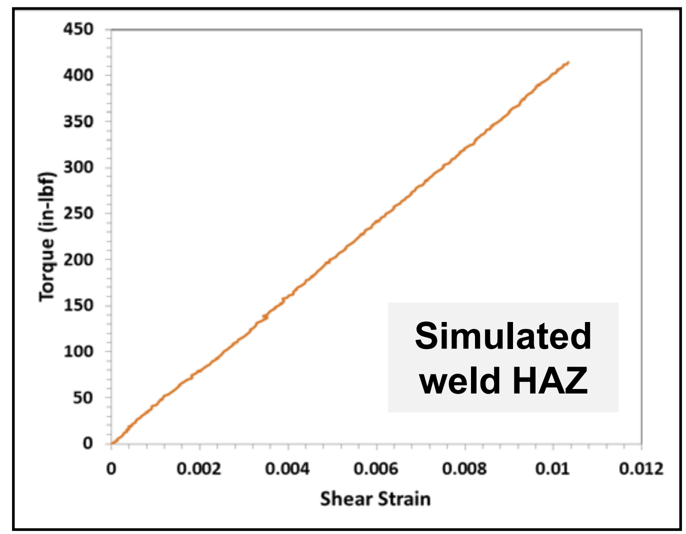
Martensitic microstructure observed at the specimen center (Left: base metal; Right: simulated weld HAZ)



Baseline Fracture Toughness Data in Air using SNTT



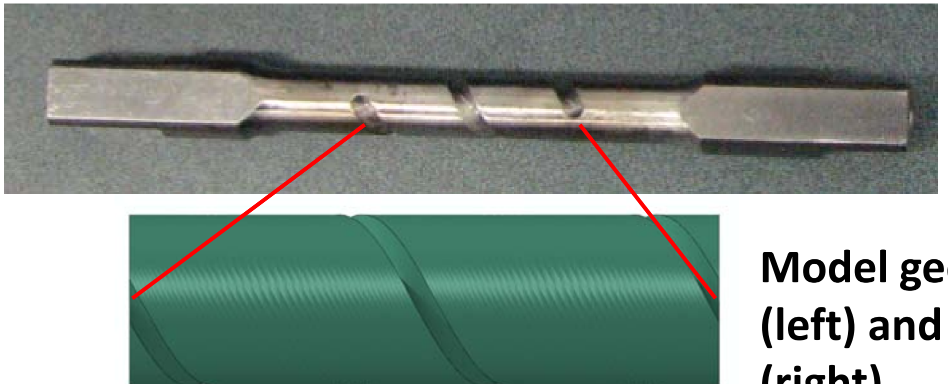




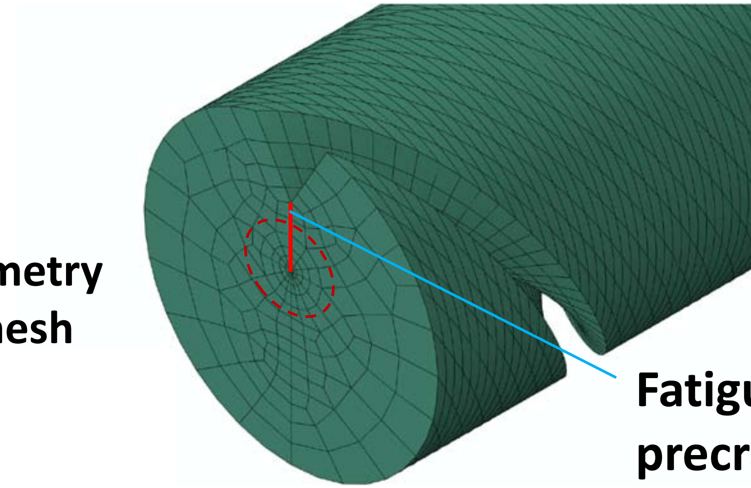
During testing, a torque is applied at the ends of the sample subjecting the entire sample to pure shear forces.

Before testing, both specimens were prepared by cyclic fatigue to introduce sharp crack-tips.

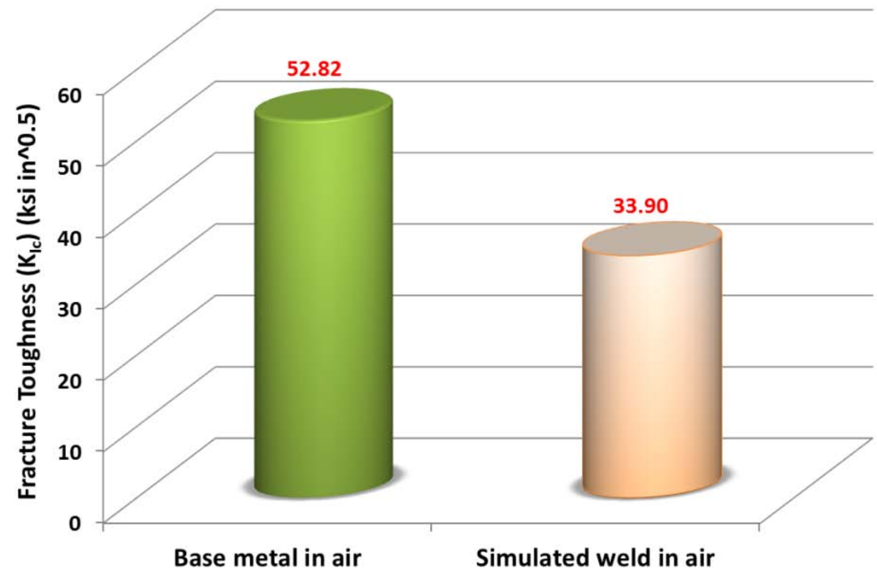
Finite Element Analysis for Determining Toughness by Converting Measured Data



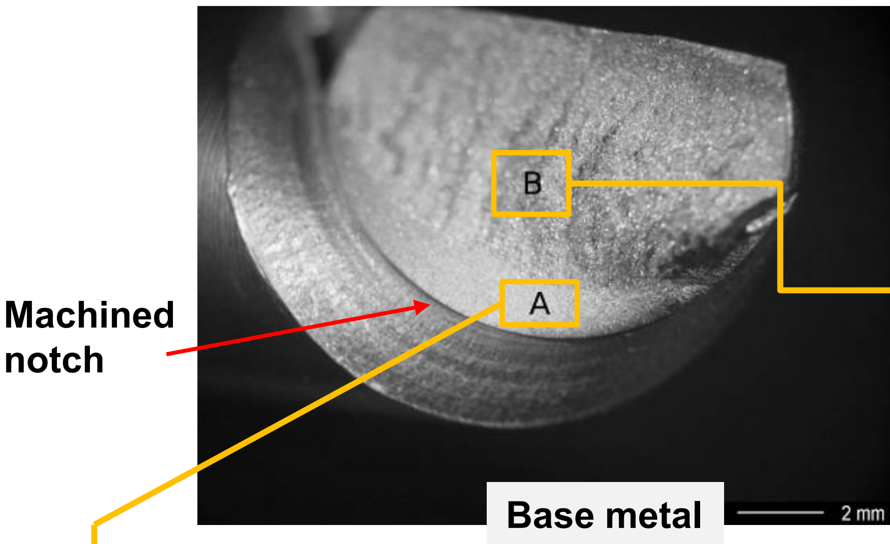
Model geometry (left) and mesh (right)

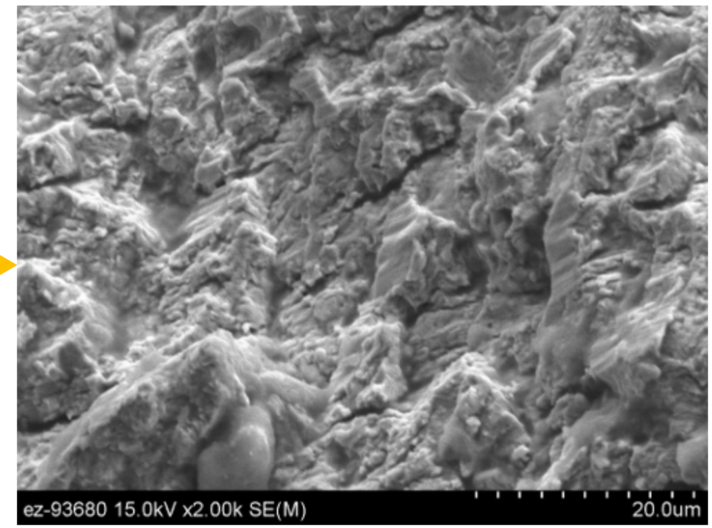


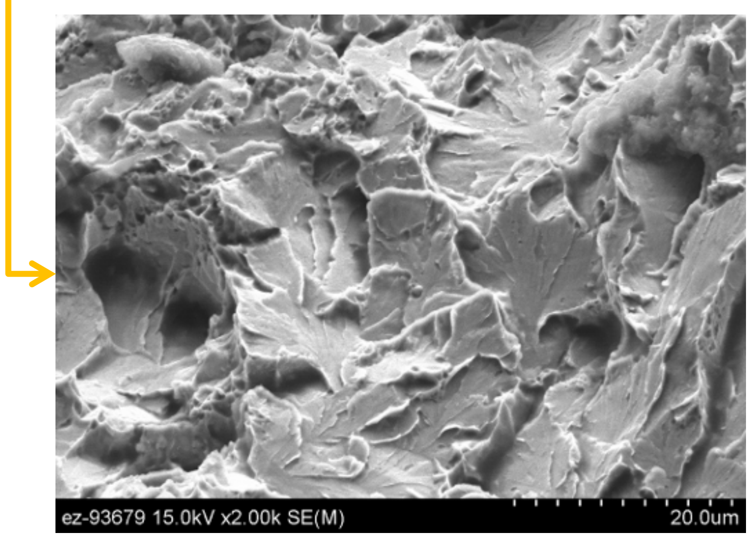
- **Special meshing**
  - Rings of elements centered on the crack tip line to facilitate the contour integral calculation
  - Element: 20-node quadratic brick
- **Mechanical properties**
  - Young's modulus = 205 GPa
  - Poisson's ratio = 0.29



Two Zones observed on Fracture Surface of Sample tested in Air







B. Fracture due to final monotonic loading

- Significant amount of cleavage, indicating brittle feature

A. Precrack zone due to cyclic fatigue

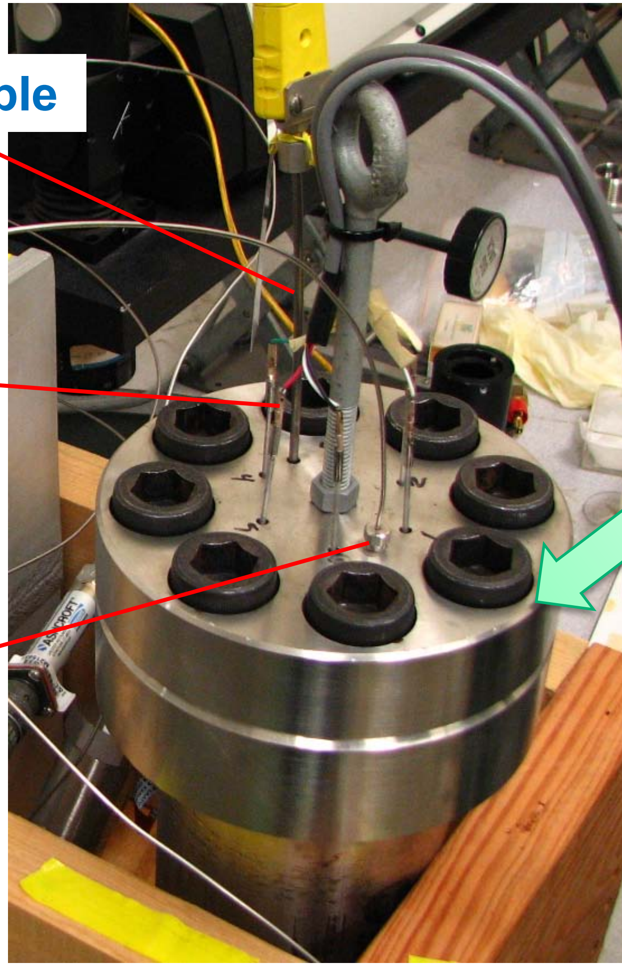
- Fairly smooth fracture surface
- Transgranular fracture

Fracture Toughness Testing in High-Pressure Hydrogen

Thermo-couple

Wires for strain gages

H_2 port for charging / discharging



Autoclave containing high-pressure H_2

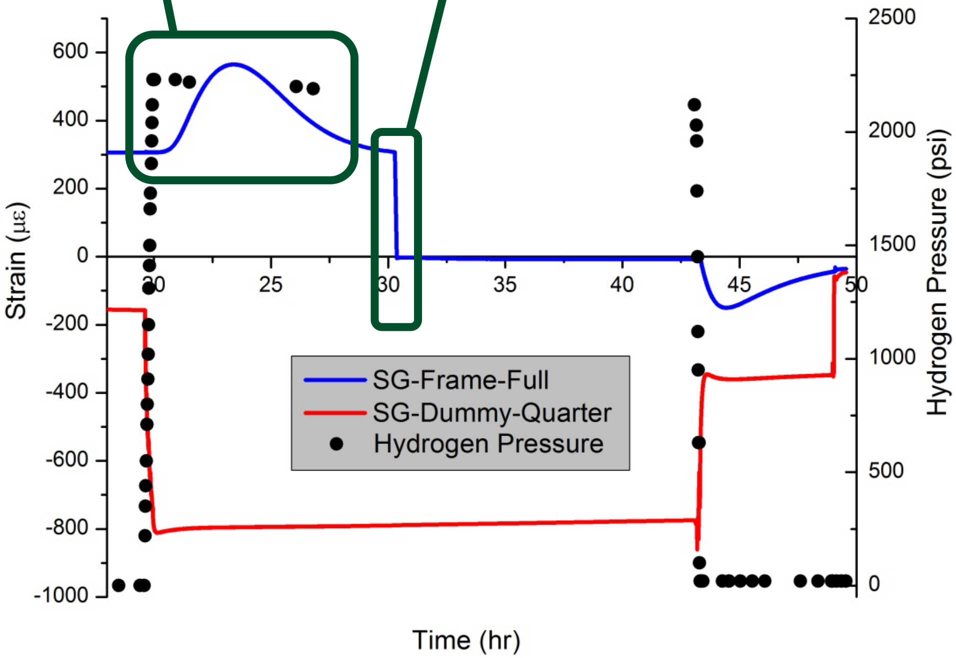
Load frame for torsion

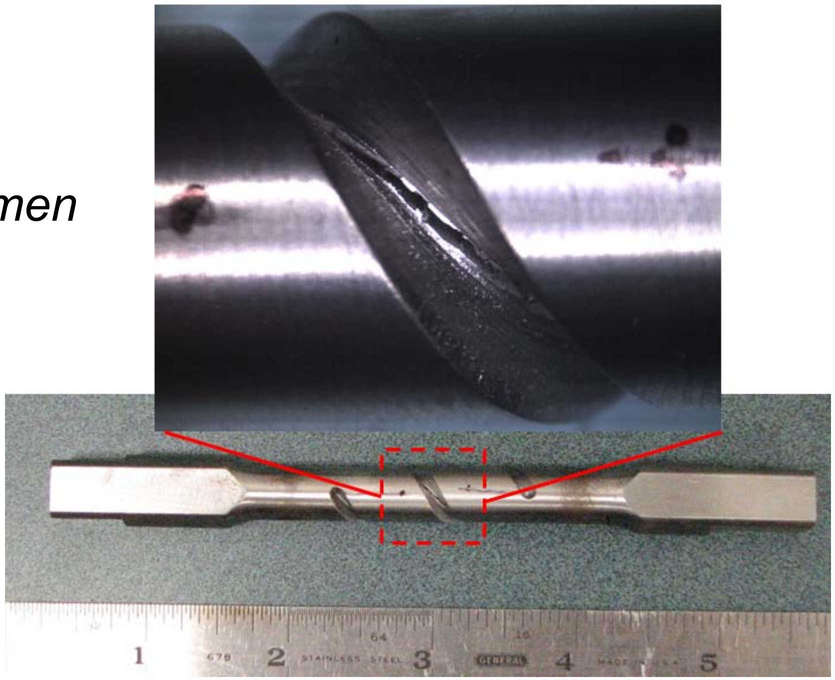
Specimen

In the test, the entire load frame with pre-stressed specimen is placed inside the autoclave.

Stain Gage Readings for Fracture when Testing in Hydrogen

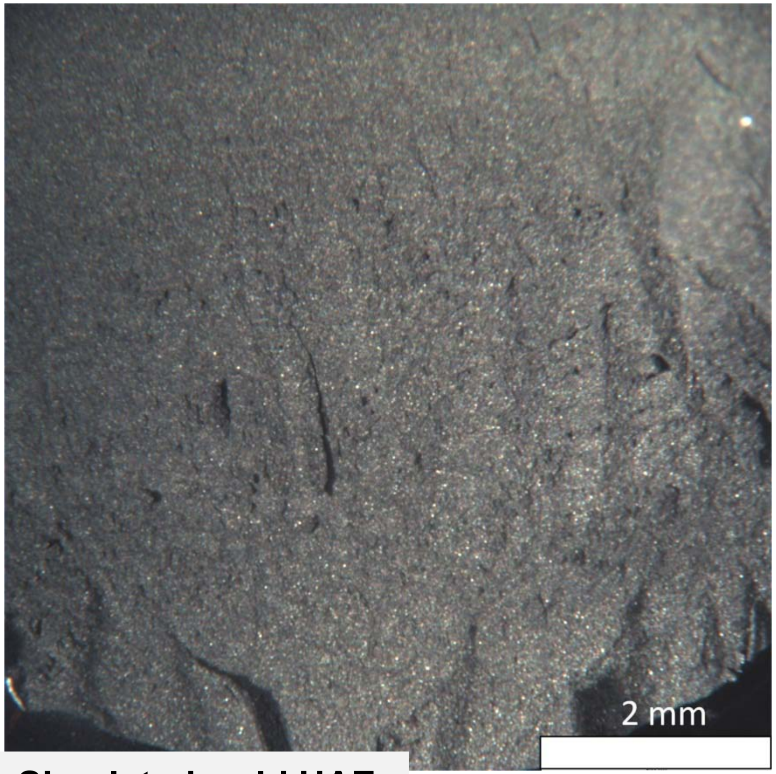
- *Initial rise and eventual stabilization in strain gage readings due to the interaction of H_2 and strain gage*
- *Sudden drop in readings indicating the fracture of specimen*





Cracked specimen after exposure to hydrogen (pressure = 1,900 psi)

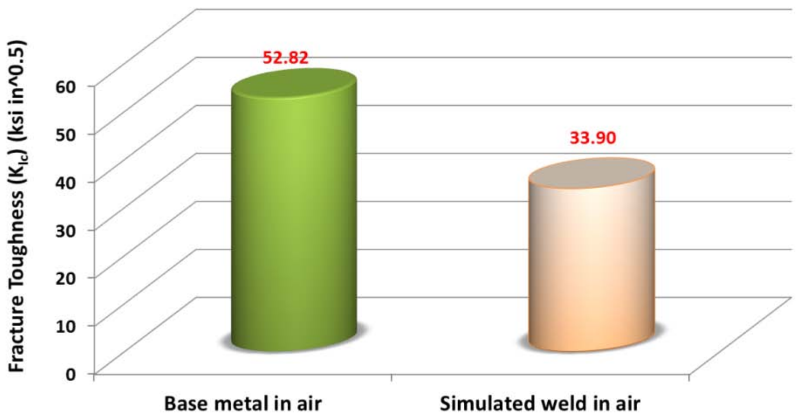
Fracture Surface of Sample tested in 1,900 psi Hydrogen (Preliminary Result)



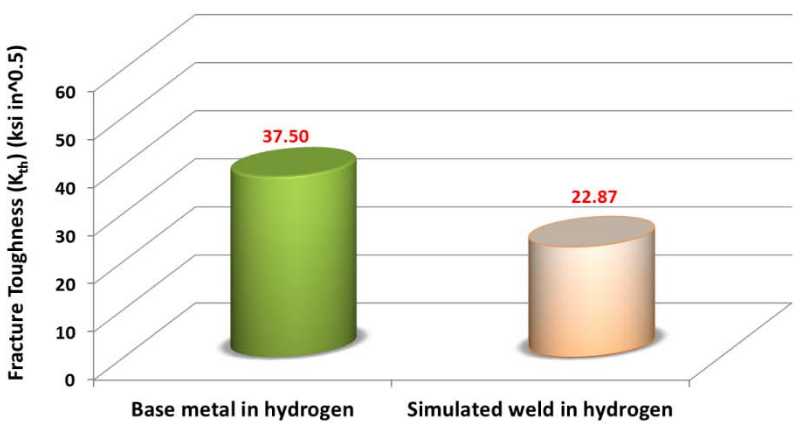
Simulated weld HAZ

Ongoing effort to characterize the fracture surface for signature of hydrogen embrittlement using high-magnification scanning electron microscopy (SEM)

Degradation of Fracture Toughness when exposed to High-Pressure H_2



Testing in ambient air



Testing in 1,900 psi H_2

- **Effect of hydrogen embrittlement:**
  - **Base metal: 36% drop in fracture toughness in H_2**
  - **Simulated weld HAZ: 39% drop in fracture toughness H_2**

Notes:

- *Specimens tested in air were prepared by cyclic fatigue to introduce sharp crack tips.*
- *Specimens tested in H_2 were not cyclic fatigued.*
- *Effort is ongoing to test specimens with fatigue precrack in H_2.*

Consistency with Literature Data

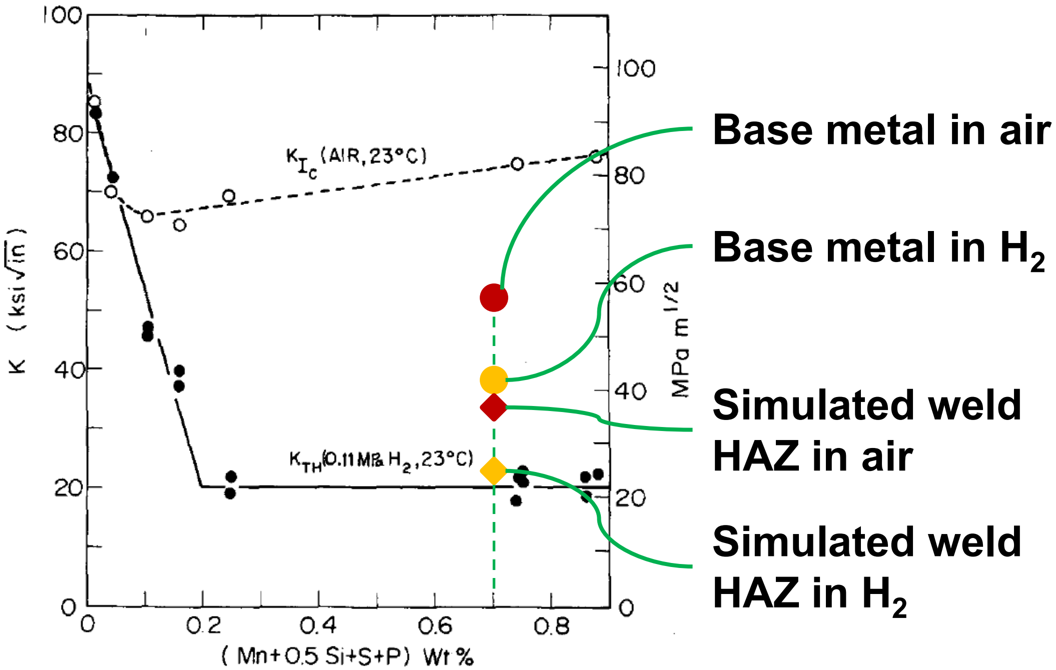
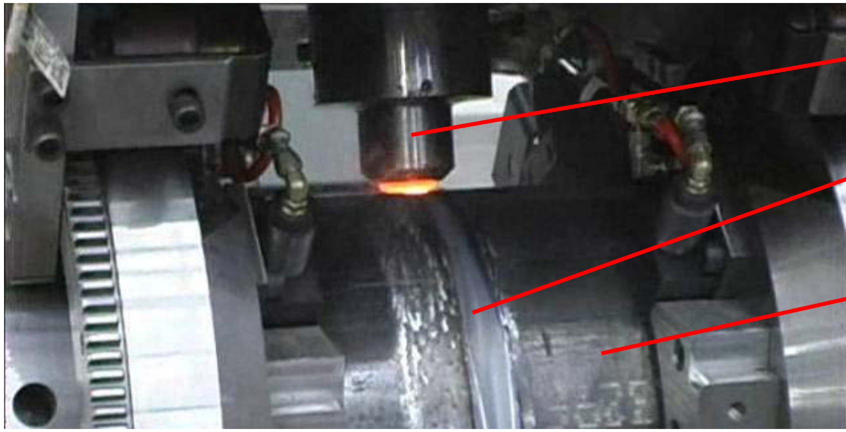


Figure adapted from N. Bandyopadhyay, et al., 1983.

Chemistry of AISI 4340 steel used in the current study (by wt%)				
C	Mn	P	S	Si
0.30	0.55	0.015	0.015	0.25
Cr	Mo	Cu	Ni	Al
1.01	0.22	0.13	0.11	0.025

	Literature data	Current study
Heat treatment	Tempering for one hour in vacuum in the range 100 to 525 °C after quenching	No tempering after quenching
Material	Base metal only	Base metal and simulated weld heat-affected zone
H_2 pressure	16 psi	1,900 psi

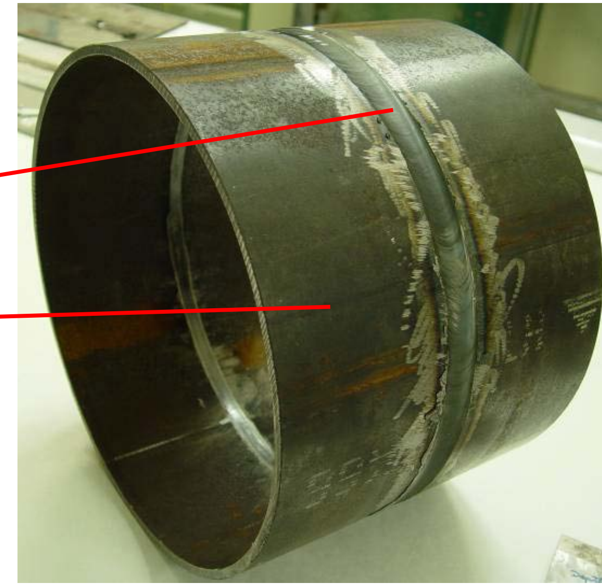
Unique Property of Friction Stir Welded X65 Steel Pipe

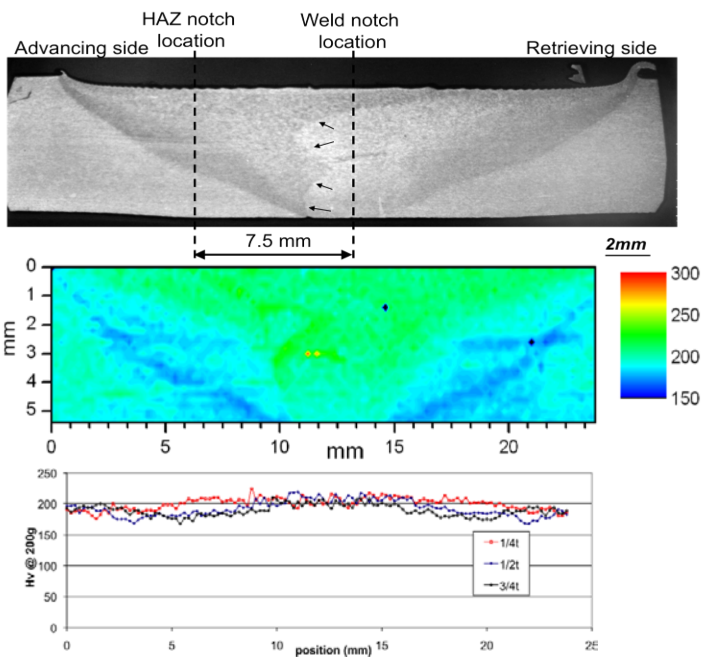


Welding tool

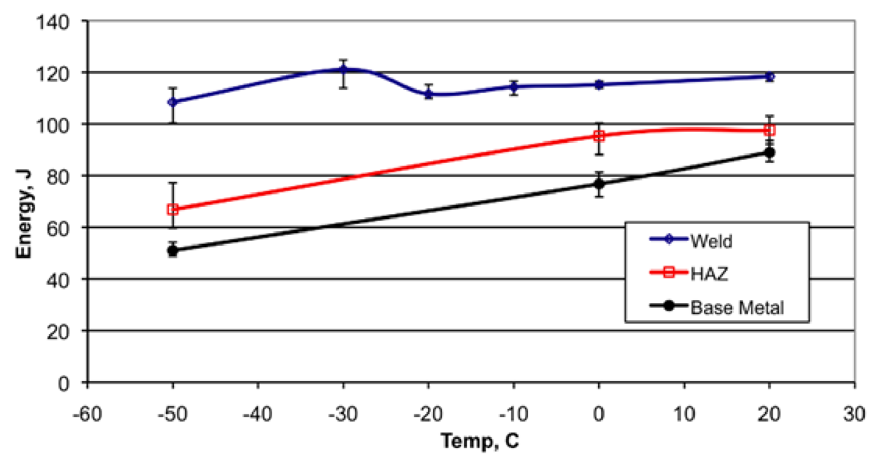
Weld

Pipe



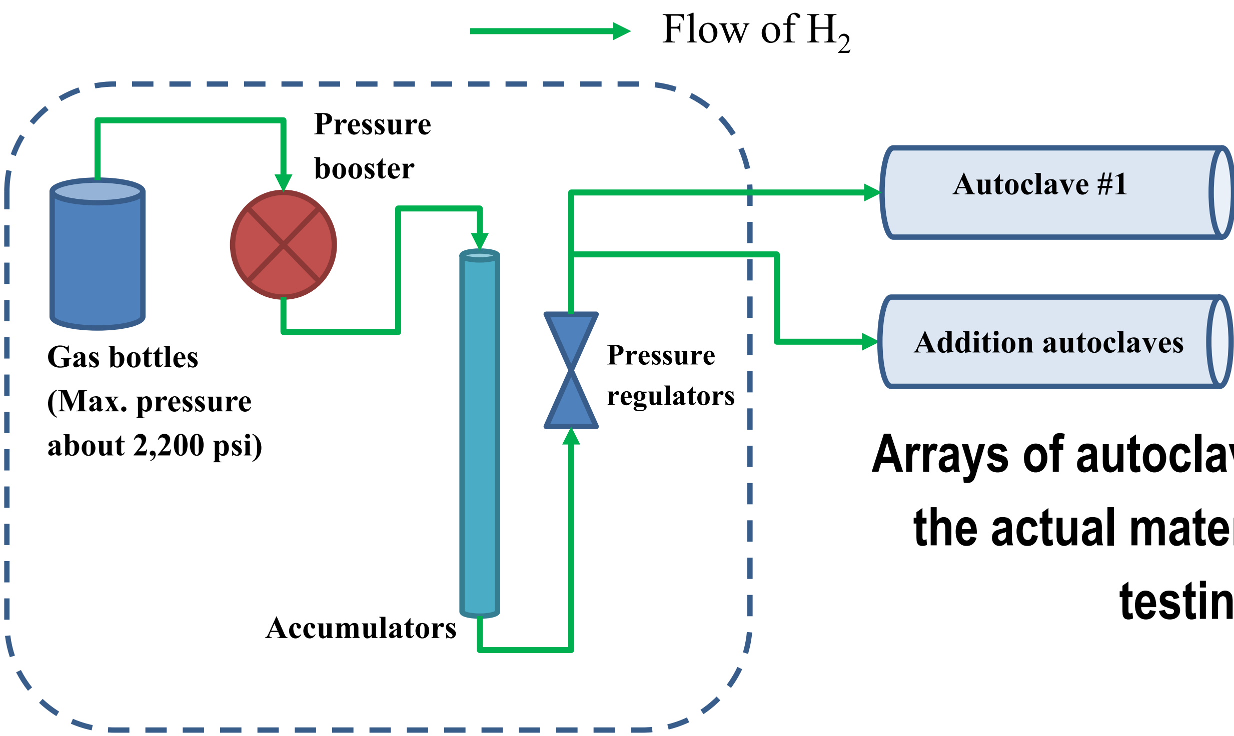


Uniform distribution of hardness in weld



Testing in air demonstrated superior weld mechanical properties attained by friction stir welding

Improving Capability of Testing Equipment: High-Pressure H_2 Charging System



Arrays of autoclaves for conducting the actual material compatibility testing in H_2

High-pressure H_2 charging system capable of maintaining or varying pressure up to 10,000 psi

Proposed Future Work

- Remaining of the current project year
  - Complete the assembly of hydrogen charging system that is capable of supplying pressure up to 10,000 psi
  - Acquire baseline arc weld of X65 steel pipe
  - Demonstrate the improved hydrogen embrittlement resistance attained in friction stir welded X65 steel pipe
- Potential follow-on work in FY2012 and beyond
  - Apply the unique testing methods and apparatus (tension and torsion) to study hydrogen embrittlement in other important engineering materials

Collaborations and Interactions

Savannah River National Lab	*Hydrogen permeation*
University of Illinois	*Mechanism of hydrogen embrittlement*
Praxair (Industry partner)	*Degradation of mechanical properties due to hydrogen embrittlement*
MegaStir Technologies (Industry partner)	*Friction stir welding*
ESAB (Industry partner)	*Friction stir welding*
DOT Pipeline and Hazardous Materials Safety Administration (PHMSA)	*Pipeline integrity for alternative fuels transmission*
ASME B31.13 (Codes and Standards)	*Hydrogen piping and pipelines*

Project Summary

Relevance:	Improve fundamental understanding of weld performance necessary for ensuring safety and reliability of hydrogen transmission pipelines
Approach:	Develop and apply unique weld property testing techniques and advanced joining process for pipeline steels
Technical Accomplishments and Progress in the current Project Year:	• Demonstrated the in-situ fracture toughness testing method for steel welds exposed to high-pressure hydrogen • Several ongoing efforts (see future research below)
Technology Transfer / Collaborations	• Close partnership with national lab, university and industry • Active interaction with DOT and ASME • Presentations and publications
Proposed Future Research:	• Demonstrate the improved hydrogen embrittlement resistance in friction stir welded X65 steel pipe • Complete the assembly of high-pressure hydrogen charging system

Acknowledgements

- **Project Sponsor:** DOE Fuel Cell Technologies Program
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