Materials Solutions for Hydrogen Delivery in Pipelines

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Project Team

SECAT (KY)	Project Manager
Oregon Steel Mills (OR)	Steel Pipe Producer
Columbia Gas of Kentucky (KY)	NG transporter
Schott North America (PA)	Glass coatings supplier
Chemical Composite Coatings (GA)	Composites coatings
Advanced Technology Corp. (TN)	ABI technology provider
ASME (NY)	Codes and Standards
DGS Metallurgical Solutions (OR)	Steel consulting
University of Illinois (IL)	Basic embrittlement studies
Oak Ridge National Laboratory (TN)	Applied research

Objective and Deliverables

Objective:

- Develop materials technologies to minimize embrittlement of steels used for high-pressure transport of hydrogen

Deliverables:

- Identify steel compositions and processes suitable for construction of new pipeline infrastructure
- Develop barrier coatings for minimizing hydrogen permeation in pipelines and associated processes
- Understand the economics of implementing new technologies

Key Technical Barriers

- Hydrogen embrittlement of steels and welds exposed to high pressure H_2 is **not well understood**
- Effect of metallurgical variables such as alloying element additions and microstructures of steels are **not known**
- Effectiveness of metallic and non-metallic coatings on minimizing H_2 embrittlement at high pressures has **not been studied**
- Economics of technological solutions to remediate the effect of hydrogen embrittlement has **not been quantified**

Major Tasks

Task 1: Evaluate high-pressure hydrogen embrittlement characteristics of steels

Task 2: Develop and/or identify alternate steels

Task 3: Develop coatings to minimize dissolution and penetration of hydrogen

Task 4: Evaluate the hydrogen embrittlement in steels coated with selected coatings

Task 5: Perform economic analyses and incorporate knowledge into codes and standards

Progress To Date

a) **Four (4) commercial pipeline steels have been down-selected**

- Baseline microstructure and mechanical property data have been characterized

- Two (2) traditional screening tests have been explored

- ***In-situ* ABI test has been developed**

- Processing techniques developed for glassy coatings

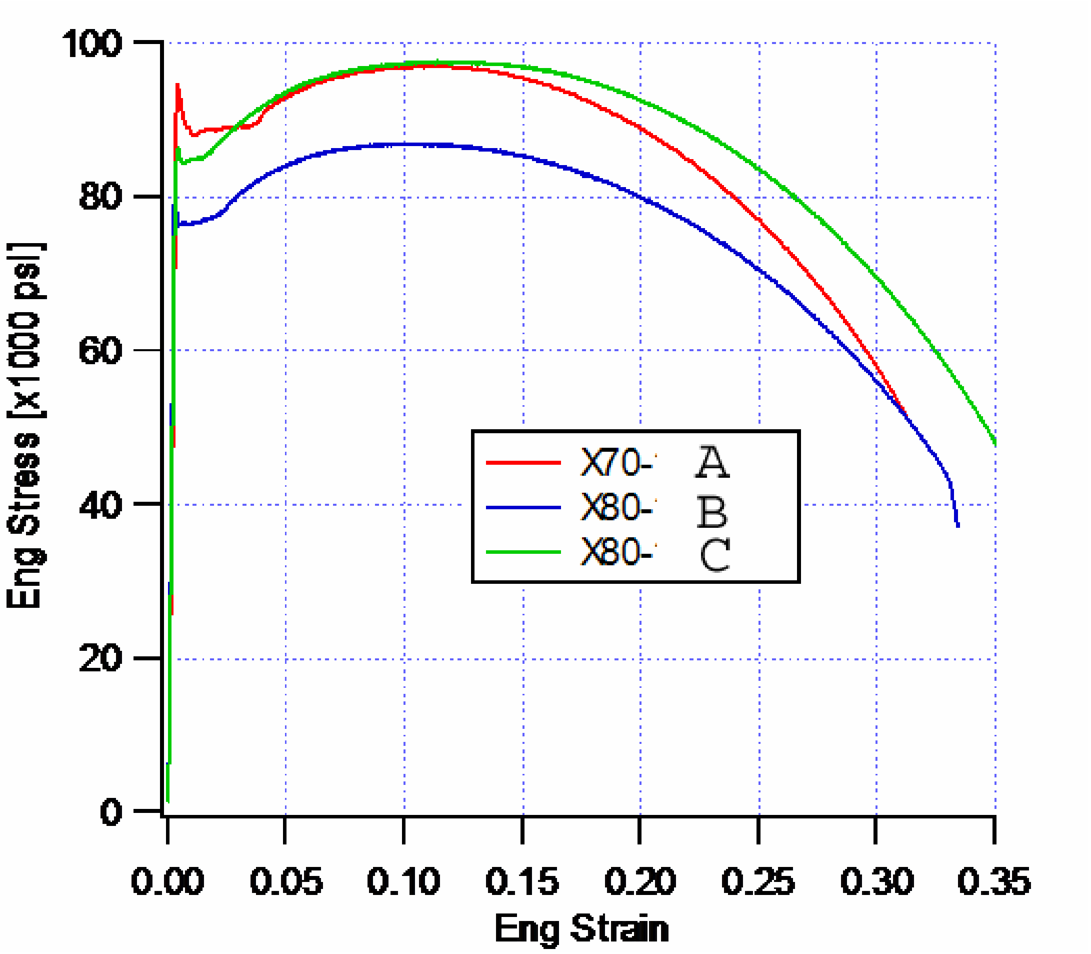
- **Down-selected composition has been coated for properties and microstructural analyses**

Down-selected Steel Compositions

Grade	Code	Carbon	Comment
X70 Std	A	0.08	Baseline
X70/X80	B	0.05	Potentially Good
X70/X80	C	0.04	Potentially Good
X52/X60 HIC	D	0.03	Potentially Best

Baseline Properties of Steels Using Traditional Tensile Tests

(No hydrogen)



ABI Measured Mechanical Properties of Selected Steels

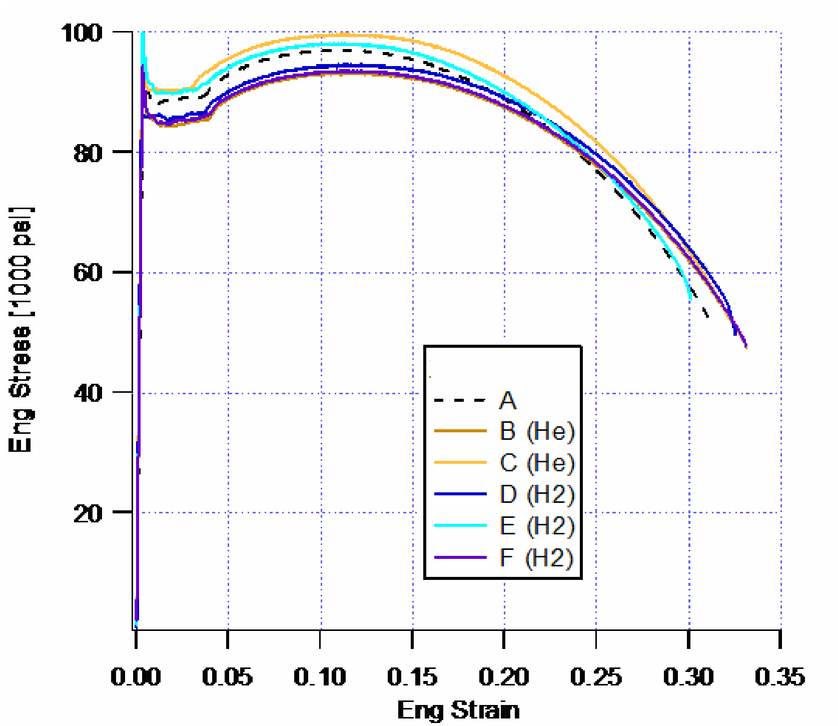
Sample ID	YS	Calc. Eng.	Calc. Unif.	YS/UTS
All API Plate Samples	(ksi)	UTS	Ductility	Ratio
		(ksi)	(%)	
API X70, A-1	82.8	102.3	7.9	0.81
API X70, A-2	82.3	101.3	7.8	0.81
API X70, A-3	81.4	100.9	8.0	0.81
API X80, B-1	74.9	93.4	8.1	0.80
API X80, B-2	75.0	94.7	8.3	0.79
API X80, B-3	77.4	94.3	7.6	0.82
API X80, C-1	86.4	104.8	7.5	0.82
API X80, C-2	84.8	104.5	7.9	0.81
API X80, C-3	86.2	105.9	7.6	0.81

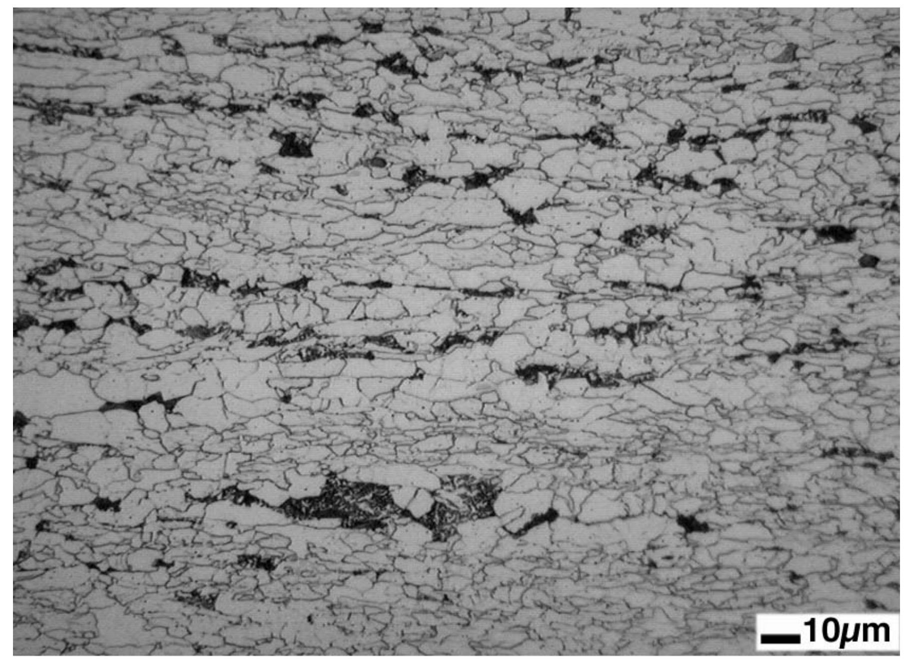
Screening Tests for Hydrogen Induced Embrittlement

- Two traditional tests
  - *Ex-situ* tensile testing (Sandia)
  - NACE HIC testing (Oregon Steel)

- Automated Ball Indentation test
  - *In-situ* testing in 2000 psi hydrogen (Advanced Technology Corporation)

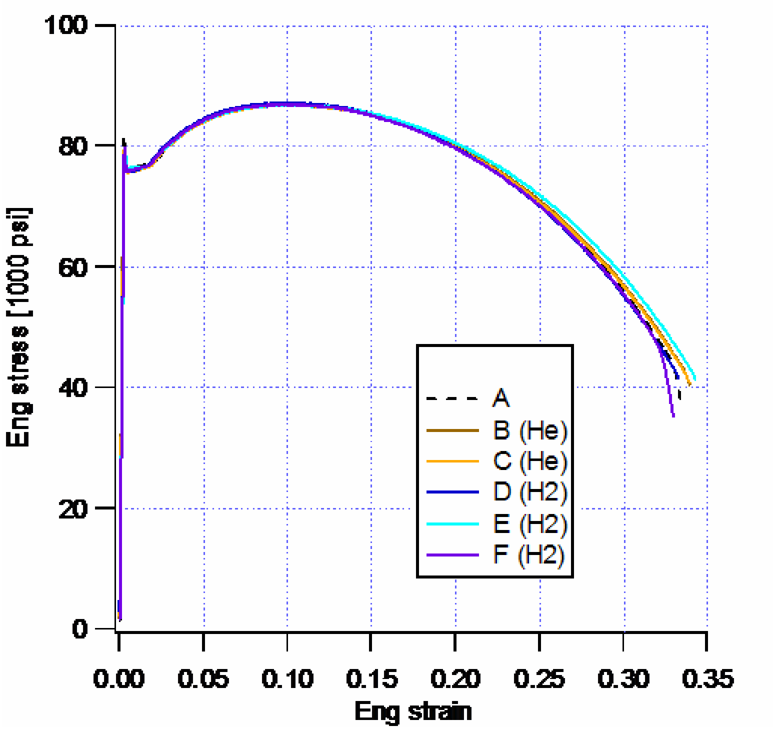
Effect of Hydrogen on the Mechanical Properties of Steel A

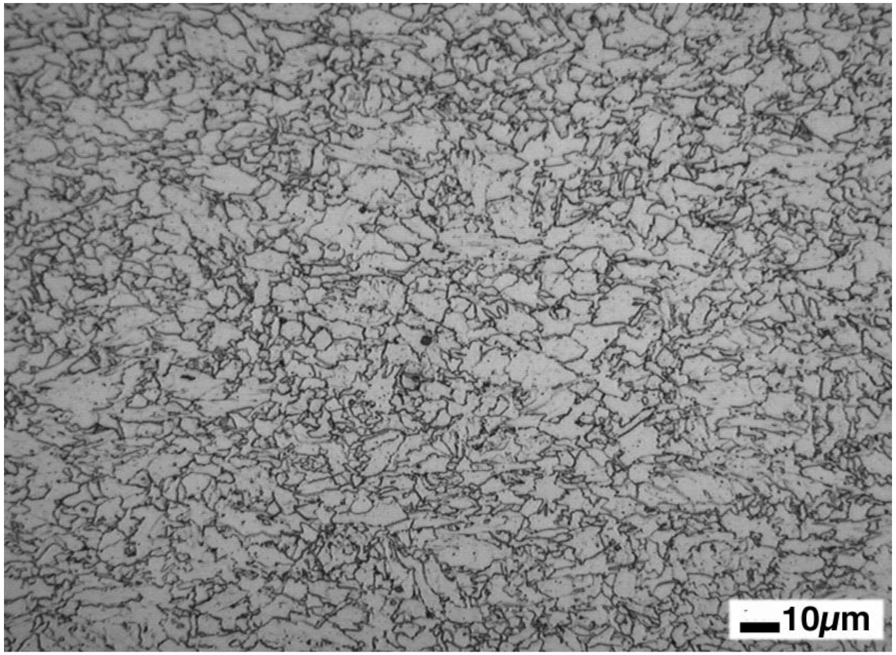




Ferrite + Pearlite

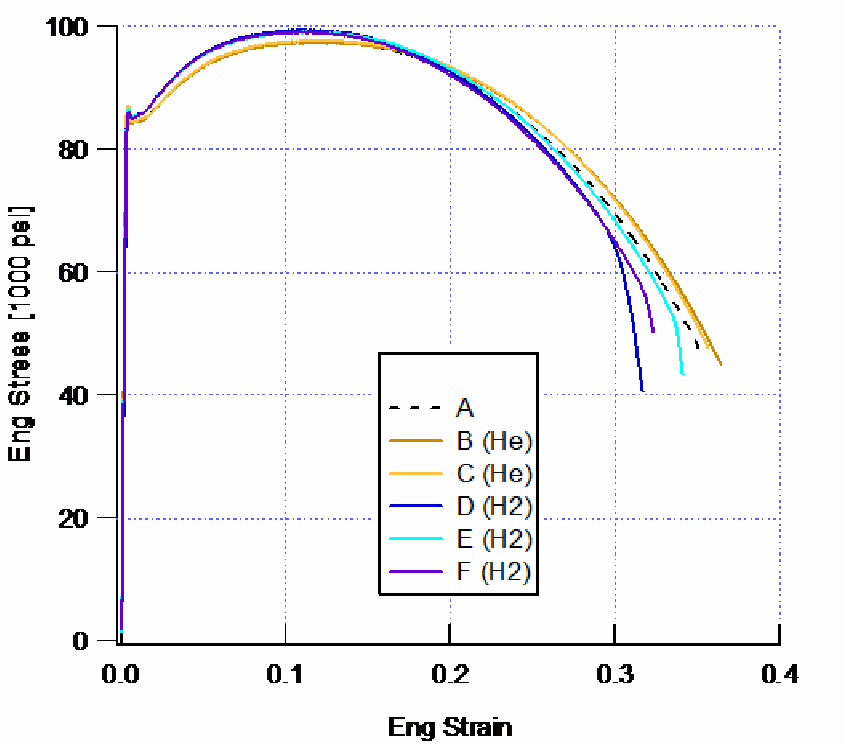
Effect of Hydrogen on the Mechanical Properties of Steel B

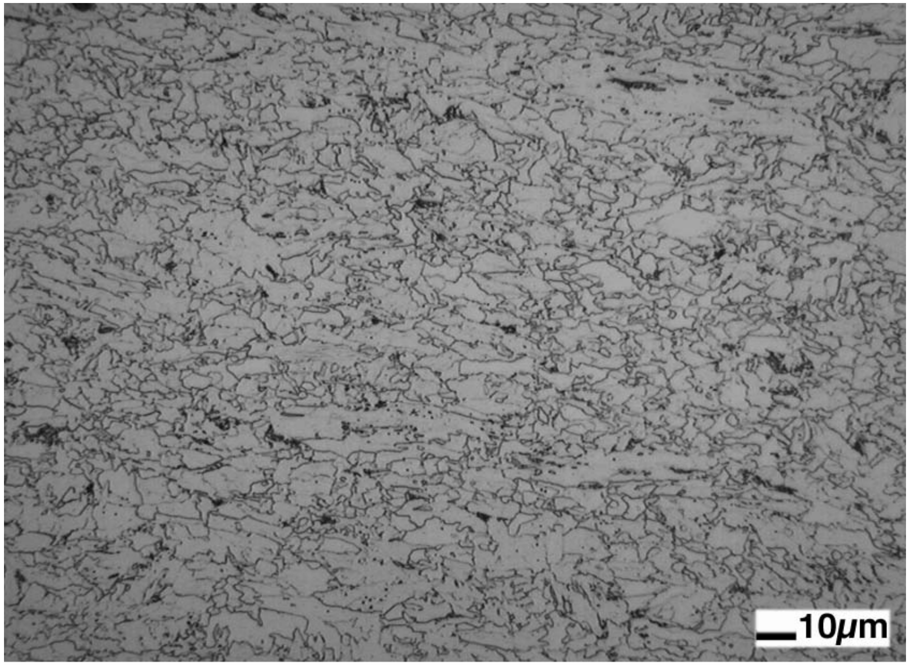




Ferrite + Acicular Ferrite

Effect of Hydrogen on the Mechanical Properties of Steel C





Ferrite/acicular ferrite + pearlite

NACE Hydrogen Induced Cracking (HIC) Test

- Evaluates resistance of pipeline and pressure vessel plate steels to Hydrogen Induced Cracking (HIC) caused by hydrogen adsorption
- Cracks developed ALONG the rolling direction are evaluated
- UNSTRESSED test specimens are immersed in one of two H_2S containing solutions for 96 hours
- Test provides reproducible environments for distinguishing susceptibility to HIC in a relatively SHORT TIME

NACE HIC Testing of Selected Pipeline Steels

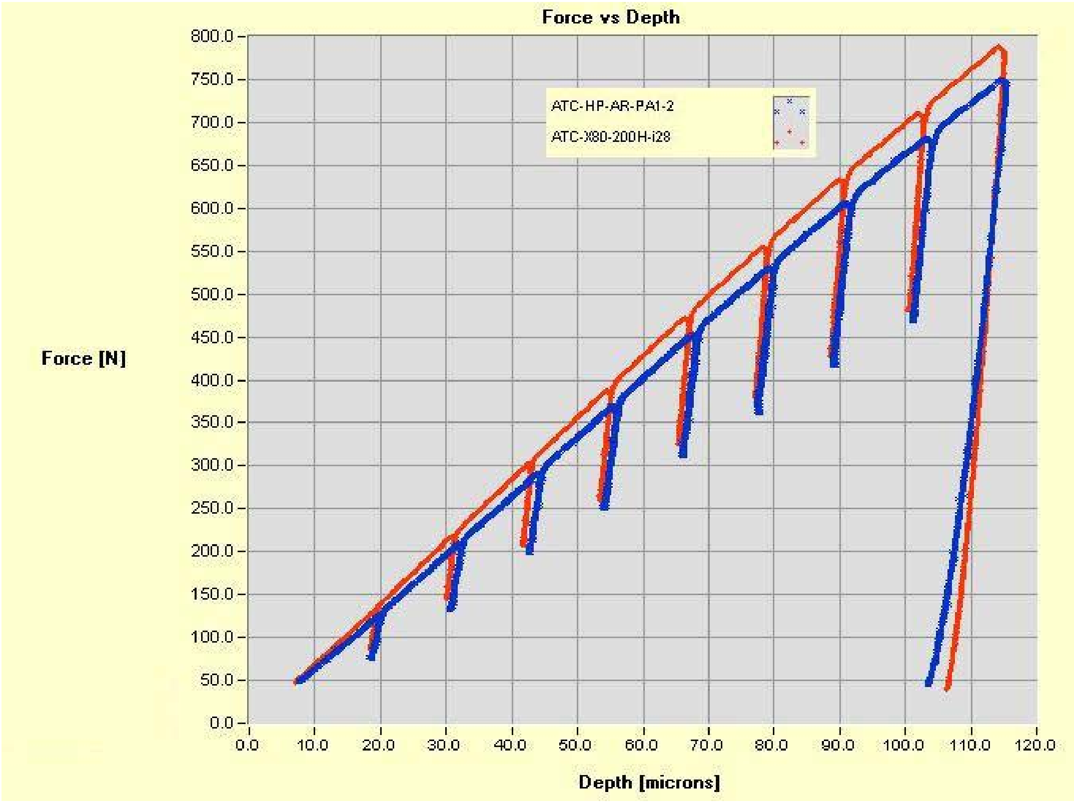
Alloy	Crack Length Ratio (%)	Crack Sensitivity Ratio (%)	Crack Thickness Ratio (%)
A	11.8	0	0.1
B	0.4	0	0
C	0	0	0
D	0	0	0

Lower numbers are desirable

In-Situ SSM Testing System:

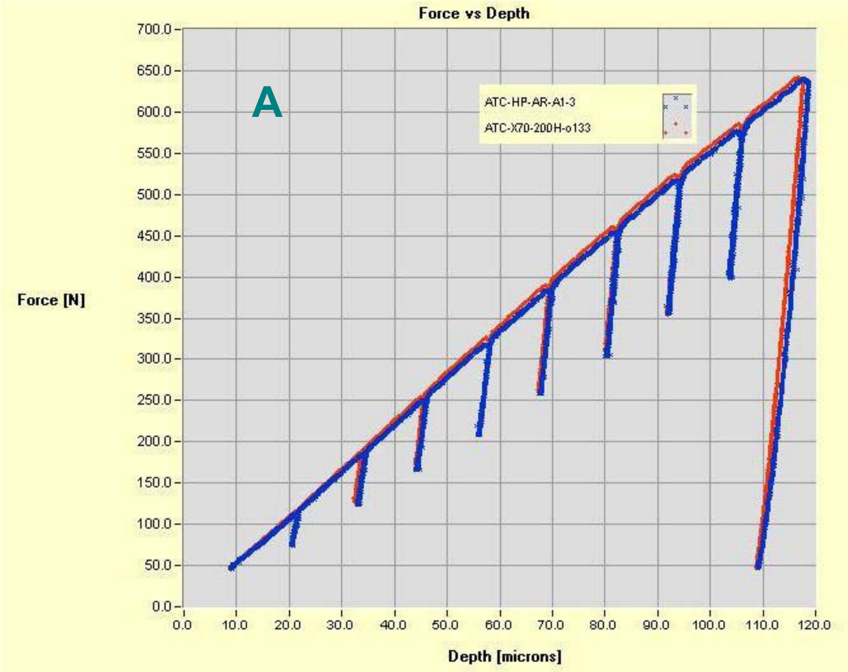
Advanced Technology Corporation

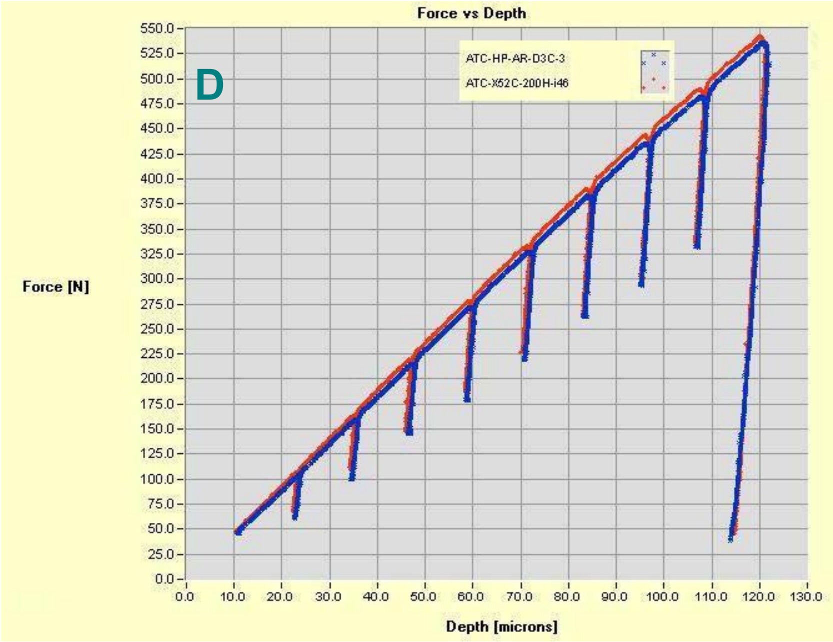
ABI tests on an X-80 Steel from Praxair Showed Significant Changes in Properties



- **Traditional fracture toughness tests (Praxair) show 49% reduction in fracture toughness**

Effects of 200 h exposure to 2,000 psi hydrogen on ABI data of downselected steels





No significant changes were observed

Lessons Learned for Future Testing

- Mechanical testing will be carried *in-situ* in high pressure hydrogen atmosphere

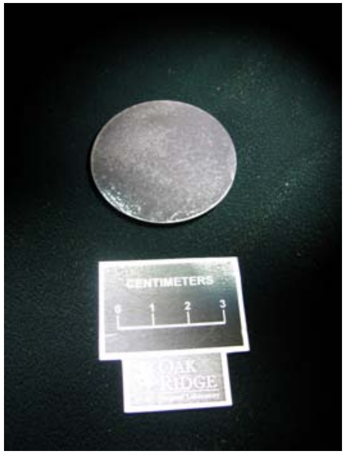
- ABI tests are promising but need to be performed for longer times for comparison with traditional tests

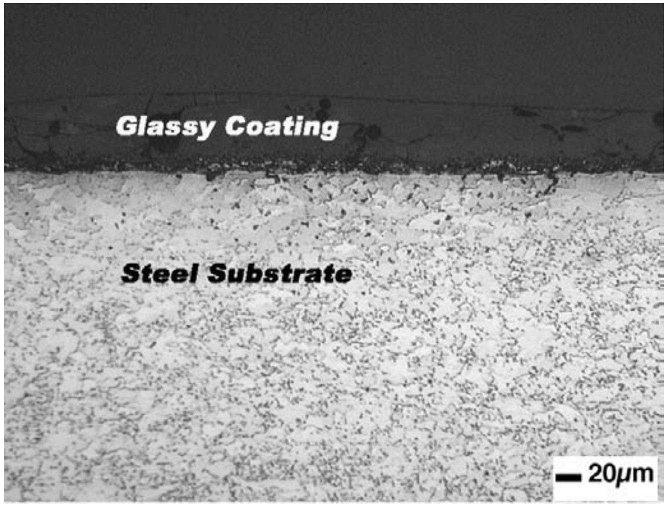
System for *in-situ* Testing in High Pressure Hydrogen

- Several modifications are being implemented in response to Pipeline Working Group consensus on test procedures
  - Gas collection after test is being enabled
  - Load range has been increased to enable use of larger cross-sectional area
  - Accessible strain rates will be lowered to 10^{-6} /sec from the current 10^{-4} /sec

Glassy Coating on Pipeline Steel (Schott/ORNL)

- Designed and produced precursors for 5 customized glass compositions
- Evaluated low-cost approaches to coat the inside of steel tubes
- Tested compatibility of glass coatings with steel substrate
- Coated downselected steel with glassy coating

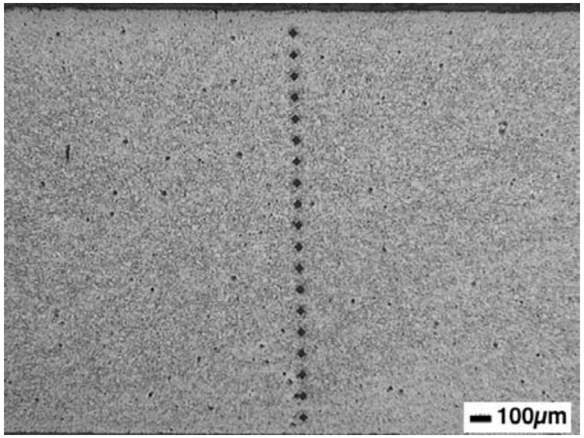


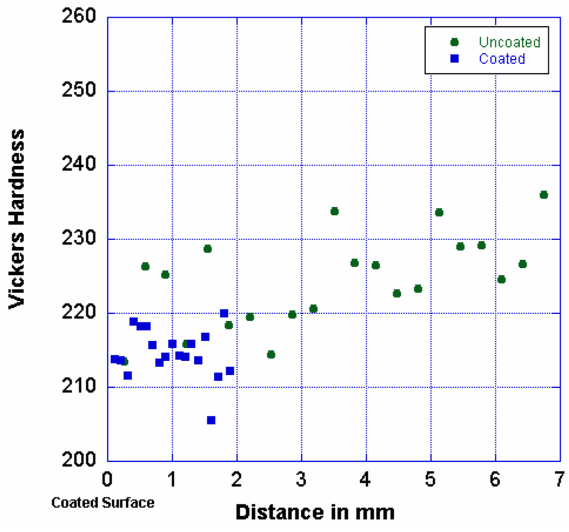


Effect of Coating Process on Steel Substrate Properties

- Microhardness measurements were made in the thickness direction in cross-sections of coated and uncoated samples

- A small (~5%) decrease in hardness was noticed in coated specimens

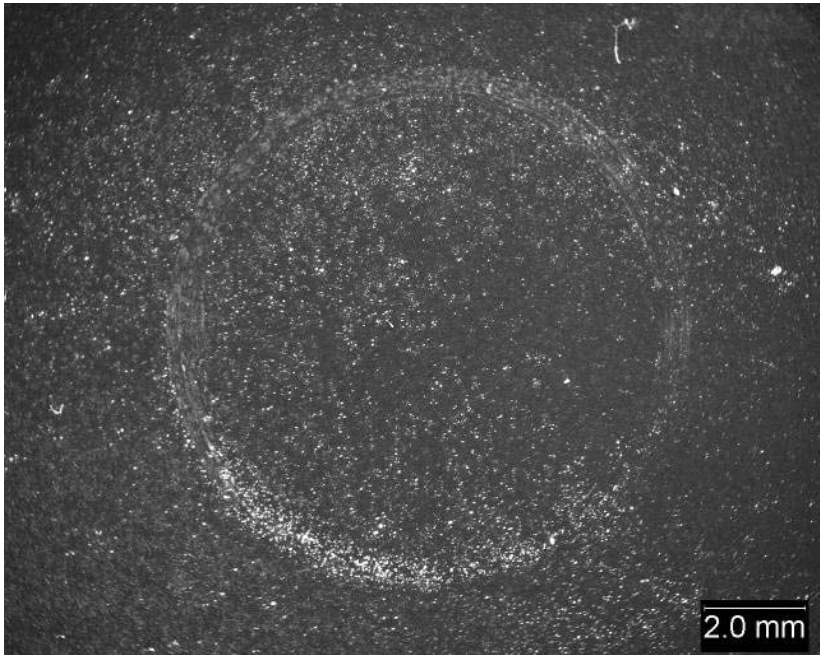




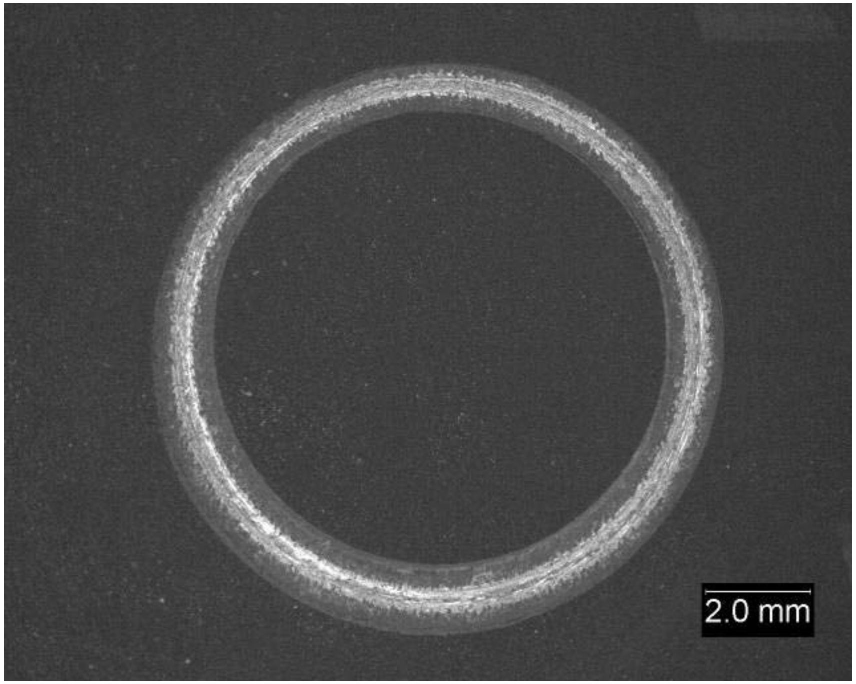
Friction and Wear Properties of Glassy Coatings Characterized

- Wear properties of coatings were evaluated to understand effect of “pigs”
- Coating shows excellent adhesion to substrate with no spalling or cracking even at high loads
- Wear rate is proportional to the applied load
- Wear-rate of the coating is slightly larger than that of the steel substrate.

Wear Tracks at Low and High Loads Show Coating Integrity



1 N Load



5 N Load

Future Work

- **Steels**
  - Complete measurement of mechanical properties *in-situ* and compare with *in-situ* ABI tests
  - Complete microstructural characterization of down-selected steels before and after exposure to hydrogen to understand the effect of microstructure on embrittlement
- **Coatings**
  - Characterize permeability of coated samples
  - Evaluate embrittlement characteristics of coated steels
- **Economic Analysis**
  - Recommend steel and coating systems for implementation
  - Evaluate economic impact of suggested materials systems

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