Materials Solutions for Hydrogen Delivery in Pipelines

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September 26, 2007

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Project Team

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Project Manager
Steel Pipe Producer
NG transporter
Glass coatings supplier
Composites coatings
ABI technology provider
Codes and Standards
Steel consulting
Basic embrittlement studies
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

<table>
<thead>
<tr>
<th>Grade</th>
<th>Code</th>
<th>Carbon</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>X70 Std</td>
<td>A</td>
<td>0.08</td>
<td>Baseline</td>
</tr>
<tr>
<td>X70/X80</td>
<td>B</td>
<td>0.05</td>
<td>Potentially Good</td>
</tr>
<tr>
<td>X70/X80</td>
<td>C</td>
<td>0.04</td>
<td>Potentially Good</td>
</tr>
<tr>
<td>X52/X60 HIC</td>
<td>D</td>
<td>0.03</td>
<td>Potentially Best</td>
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</table>
Baseline Properties of Steels Using Traditional Tensile Tests

(No hydrogen)
# ABI Measured Mechanical Properties of Selected Steels

<table>
<thead>
<tr>
<th>Sample ID</th>
<th>YS</th>
<th>Calc. Eng.</th>
<th>Calc. Unif.</th>
<th>YS/UTS</th>
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</thead>
<tbody>
<tr>
<td><strong>All API Plate Samples</strong></td>
<td>(ksi)</td>
<td>UTS (ksi)</td>
<td>Ductility (%)</td>
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</tr>
<tr>
<td>API X70, A-1</td>
<td>82.8</td>
<td>102.3</td>
<td>7.9</td>
<td>0.81</td>
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<td>API X70, A-2</td>
<td>82.3</td>
<td>101.3</td>
<td>7.8</td>
<td>0.81</td>
</tr>
<tr>
<td>API X70, A-3</td>
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<td>100.9</td>
<td>8.0</td>
<td>0.81</td>
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<td>API X80, B-1</td>
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<td>93.4</td>
<td>8.1</td>
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<tr>
<td>API X80, B-2</td>
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<td>0.79</td>
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<td>94.3</td>
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<td>0.82</td>
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<tr>
<td>API X80, C-1</td>
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<td>104.8</td>
<td>7.5</td>
<td>0.82</td>
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<tr>
<td>API X80, C-2</td>
<td>84.8</td>
<td>104.5</td>
<td>7.9</td>
<td>0.81</td>
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<tr>
<td>API X80, C-3</td>
<td>86.2</td>
<td>105.9</td>
<td>7.6</td>
<td>0.81</td>
</tr>
</tbody>
</table>
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 $\text{H}_2\text{S}$ 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

<table>
<thead>
<tr>
<th>Alloy</th>
<th>Crack Length Ratio (%)</th>
<th>Crack Sensitivity Ratio (%)</th>
<th>Crack Thickness Ratio (%)</th>
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</thead>
<tbody>
<tr>
<td>A</td>
<td>11.8</td>
<td>0</td>
<td>0.1</td>
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<tr>
<td>B</td>
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<td>0</td>
<td>0</td>
</tr>
<tr>
<td>C</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>D</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

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 \textit{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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