III.19 Hydrogen Embrittlement of Pipelines: Fundamentals, Experiments, Modeling

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Objectives

- Mechanistic understanding of hydrogen embrittlement in pipeline steels in order to devise fracture criteria for safe and reliable pipeline operation under hydrogen pressures of at least 15 MPa and loading conditions both static and cyclic.
- Explore methods of mitigation of hydrogen-induced failures through inhibiting species (e.g., water vapor) or regenerative coatings (e.g., surface oxidation).
- Explore suitable steel microstructures to provide safe and reliable hydrogen transport at reduced capital cost.
- Assess hydrogen compatibility of the existing natural gas pipeline system for transporting hydrogen.

Technical Barriers

This project addresses the following technical barriers from the Hydrogen Delivery section of the DOE Hydrogen, Fuel Cells and Infrastructure Technologies Program Multi-Year Research, Development and Demonstration Plan (HFCIT Multi-Year RD&D Plan):

(D) High Capital Cost and Hydrogen Embrittlement of Pipelines

(G) Storage Tank Materials and Costs

(K) Safety, Codes and Standards, Permitting

Technical Targets

This project is conducting fundamental studies of hydrogen embrittlement of materials using both numerical simulations and experimental observations of the degradation mechanisms. Based on the understanding of the degradation mechanisms the project's goal is to assess the reliability of the existing natural gas pipeline infrastructure when used for hydrogen transport, suggest possible new hydrogen-compatible material microstructures for hydrogen delivery, and propose technologies (e.g. regenerative coatings) to remediate hydrogen-induced degradation. These studies meet the following DOE technical Targets for Hydrogen Delivery as mentioned in Table 3.2.2 of the HFCIT Multi-Year RD&D Plan:

- *Pipelines: Transmission*–Total capital investment will be optimized through pipeline engineering design that avoids conservatism. This requires the development of failure criteria to address the hydrogen effect on material degradation (2012 target).
- *Pipelines: Distribution*–Same cost optimization as above (2012 target).
- *Pipelines: Transmission and Distribution*–Reliability relative to H_2 embrittlement concerns and integrity, third party damage, or other issues causing cracks or failures. The project's goal is to develop fracture criteria with predictive capabilities against hydrogen-induced degradation (2017 target). It is emphasized that hydrogen pipelines currently in service operate in the absence of design criteria against hydrogen-induced failure.
- *Off-Board Gaseous Hydrogen Storage Tanks (Tank cost and volumetric capacity)*–Same cost optimization as in *Pipelines: Transmission* above. Current pressure vessel design criteria are overly conservative by applying conservative safety factors on the applied stress to address subcritical cracking. Design criteria addressing the hydrogen effect on material safety and reliability will allow for higher storage pressures to be considered (2010 target).

Accomplishments

- Began using focused ion beam (FIB) machining to lift-out sections from fracture surfaces along with transmission electron microscopy (TEM) analysis of the extracted thin foils to reveal the nature and identify the characteristic details of the degradation mechanisms.

- Characterized the microstructure of pipeline steels through optical analysis, scanning electron microscopy (SEM), and TEM, and identified particle composition through energy dispersive spectroscopy for: a) laboratory specimens from Air Liquide, Air Products, and Kinder-Morgan industrial pipelines; b) new microalloyed, low-carbon steels from Oregon Steel Mills (OSM) provided by DGS Metallurgical Solutions, Inc.
- Measured the macroscopic flow characteristics of the new microalloyed, low-carbon steels, possibly hydrogen compatible.
- Determined the hydrogen permeability of steels from OSM and Kinder-Morgan.
- Developed a thermodynamic theory of hydrogen-induced decohesion that was used to model and simulate hydrogen-induced subcritical cracking.
- Developed modeling and simulation capabilities of transient hydrogen transport accounting for the mechanical deformation of the pipeline microstructure. Predictions have been made of a) fracture initiation through void nucleation at inclusions, and b) threshold stress intensities associated with subcritical crack growth.
- Determined the intensity of the hydrostatic constraint ahead of an axial crack on the inside surface. Laboratory specimen type (hydrostatic constraint guidelines) has been identified to investigate fracture processes in a real-life pipeline.

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Introduction

Hydrogen is a ubiquitous element that enters materials from many different sources. It almost always has a deleterious effect on material properties. The goal of the project is to develop and verify a lifetime prediction methodology for failure of materials used in pipeline systems and welds exposed to high-pressure gaseous environments. Development and validation of such predictive capability and strategies to avoid material degradation is of paramount importance to the rapid assessment of the suitability of using the current pipeline distribution system for hydrogen transport and of the susceptibility of new alloys tailored for use in hydrogen related applications.

Through our hydrogen permeation rig, we measured the permeability of steel samples from industrial pipelines (Kinder-Morgan) and some new possibly hydrogen-compatible microalloyed, low-carbon steels provided by OSM. We used electron microscopy techniques to characterize the microstructure of these steels. Such characterization is important for the identification of the hydrogen trapping states in the material. We began using FIB machining to to lift out sections from the fracture surfaces in order to understand whether hydrogen-induced fracture follows a cleavage plane or a slip plane. We carried out finite element calculations of transient hydrogen transport simulating hydrogen uptake and transport through an axial crack on the inside surface of a pipeline, and determined through constraint fracture mechanics that the single edge notch tension specimen is the appropriate laboratory specimen for the study of the fracture resistance of a pipeline. We studied the hydrogen effect on void nucleation at inclusions and calculated the hydrogen-induced reduction of the fracture toughness of pipeline steels containing MnS inclusions (natural gas pipeline steels). Further, we established the methodology to calculate threshold stress intensities for subcritical cracking which is of paramount importance to assessing whether a crack on the inside surface of a pipeline shall remain subcritical.

Approach

Our approach integrates mechanical property testing at the microscale, microstructural analyses and TEM observations of the deformation processes of materials at the micro- and nano-scale, first principle calculations of interfacial cohesion at the atomic scale, and finite element modeling and simulation at the micro- and macro-level.

In order to come up with fracture criteria for safe pipeline operation under hydrogen pressures of at least 15.0 MPa, we investigate the interaction of hydrogen transient transport kinetics with material elastoplastic deformation ahead of an axial crack either on the inside or the outside surface of a pipeline. Understanding of this interaction requires the determination of the elastic and flow characteristics of pipeline materials in the presence of hydrogen, and the measurement of the hydrogen adsorption, permeability, and bulk diffusion characteristics, such as the nature and strength of microstructural trapping sites for hydrogen. These experimental data are used in finite element simulations of the hydrogen distribution ahead of a crack tip in an effort to understand the transient and steady-state hydrogen population profiles. In addition, we use FIB machining to lift out sections from the fracture surfaces to explore and identify the nature of the hydrogen-induced fracture processes/events.

To quantitatively describe the hydrogen effect on internal material cohesion as a function of the hydrogen concentration under transient hydrogen conditions, we devised a thermodynamic theory of decohesion at internal material interfaces such as grain boundaries, precipitate/matrix, and second-phase/matrix interfaces. First-principles calculations of the hydrogen effect on these interfaces (see 2008 annual progress report), which constitute potential fracture initiation sites, are used to calibrate the parameters of the thermodynamic theory such as the ratio of the reversible work of separation in the presence of hydrogen to that in the absence of hydrogen. The first-principles calculation results and the thermodynamics-based description of material cohesion provide hydrogen-dependent traction-separation laws. The combined information for the fracture mechanisms from the experiments and hydrogen concentration profiles from the simulations will help to establish the regime of critical hydrogen concentrations and critical elapsed time for a crack to remain stable under high hydrogen pressure. Quantitatively this will be assessed through the development of engineering fracture criteria in terms of macroscopic parameters.

Results

Identification and Characterization of the Fracture Mechanisms

Optical and SEM analyses show that hydrogen-induced fractures are distinctly different from the cold fast fractures in the compact tension specimens in the absence of hydrogen. In addition, the new microalloyed, low alloy carbon steels from the OSM exhibit fracture surfaces which are not characteristic (see Figure 1 for D type steel; a typical low carbon [0.03% by wt] Mn-Si-single microalloy API/Grade X60, a predominantly ferrite microstructure with some pearlite) of the ductile mode of fracture expected for pipeline steels (existing natural gas pipelines).

To understand the fracture processes, we use TEM studies of samples taken from just below the fracture surface by the lift-out technique using FIB machining. The FIB lift-out technique is generally used on flat polished surfaces, but we have recently developed a means of lifting out samples directly from a rough fracture surface. Figure 1 shows the location of the top edge of the FIB sample with respect to the fracture surface. From the fracture surface of a compact tension specimen, trenches can be milled directly into the fracture surface and a thin membrane sampling perpendicular to the fracture surface can be lifted out, Figure 2.

Prior to the TEM examination, the lifted-out sample is thinned to electron transparency (Figure 2f). Microstructural features such as a grain boundaries and secondary phases such as carbides immediately below the fracture surface can be identified. Also,

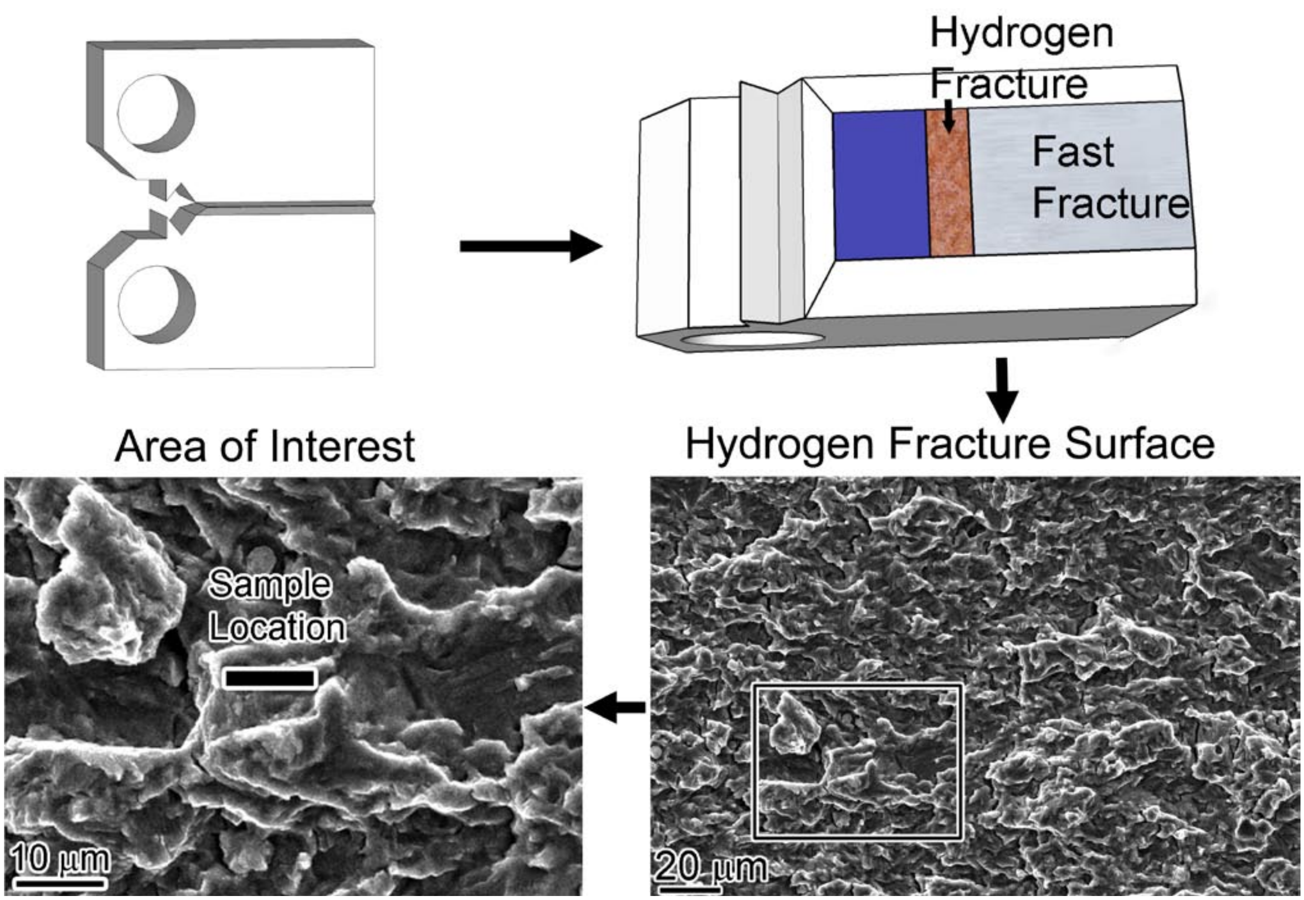

FIGURE 1. Location of FIB lift-out sample from fracture surface of a compact tension specimen of D steel fractured in hydrogen at Sandia National Laboratories.

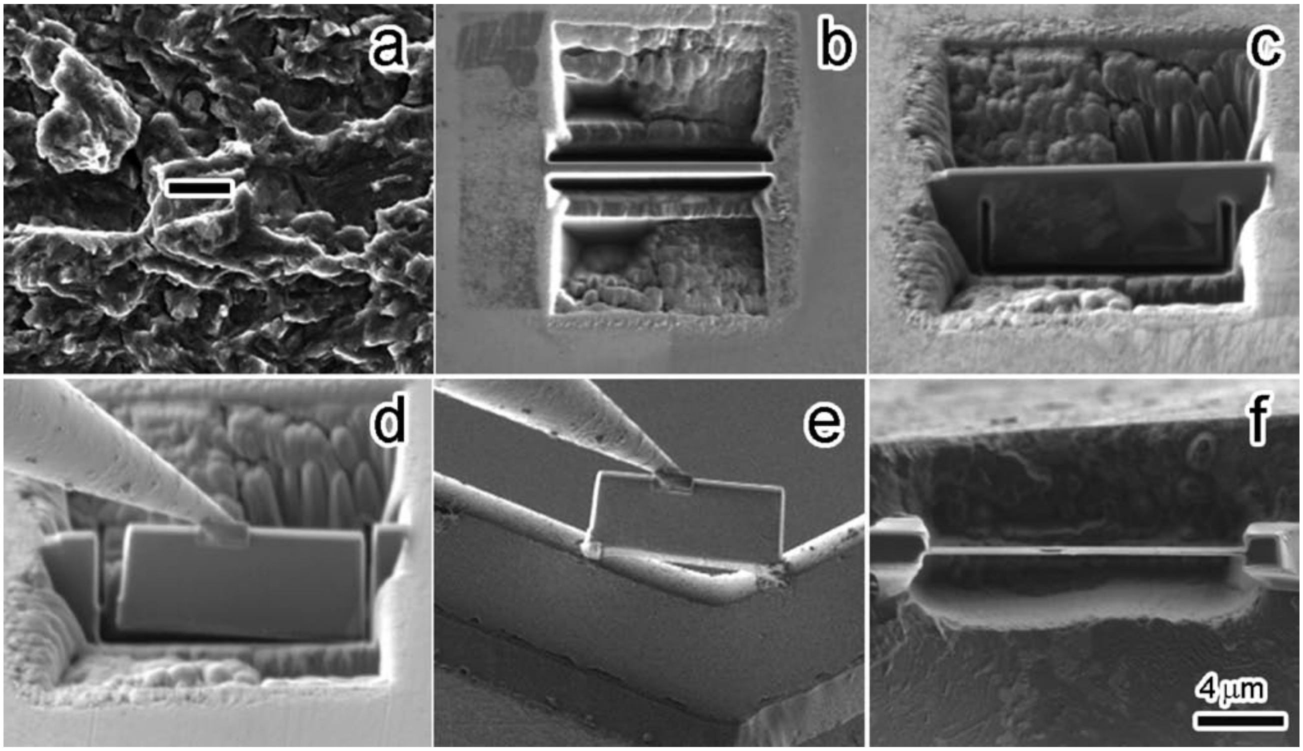

FIGURE 2. FIB lift out process: a) area of interest is located and a platinum strip is deposited; b) trenches are milled on either side of the platinum strip; c) a u-cut is made; d) micromanipulator is attached to the sample, and sample is cut free; e) sample is attached to a copper grid; f) sample is thinned to electron transparency.

evidence of plasticity such as dislocation structures immediately below the fracture surface can be observed and identified. The goal is to discover the nature of the fracture mechanisms of pipeline steels in a hydrogen environment.

Characterization and identification of the hydrogen/induced fracture processes/events is required for all objectives of the project.

Permeation Measurements and Microstructural Characterization

As described in previous annual progress reports, we continue using our permeation device to carry out permeation measurements for the D type steel provided by OSM – a typical low carbon (0.03% by wt) Mn-Si-single microralloy API/Grade X60, a predominantly ferrite microstructure with some pearlite. This alloy was found to perform very well in sour natural gas service. Microstructural characterization of this steel is also underway.

The design of the permeation experimental apparatus and the related hydrogen permeation measurements meet all objectives of the project.

Micro- and Macro-Modeling and Simulation

We used our hydrogen-transport/material-deformation simulation tool (see 2008 annual progress report) to carry out numerical simulations for the prediction of the macroscopic response of materials in the presence of hydrogen. In particular, we simulated the hydrogen effect on i) subcritical crack growth by intergranular failure. The calculated threshold stress intensity factor is a material parameter that can be used to design components against hydrogen-induced brittle fracture; ii) on void nucleation at inclusions followed by subsequent crack propagation. This scenario pertains to microstructures of medium/low strength steels used in the current natural gas pipelines; iii) issues of transferability between laboratory specimen fracture toughness results and real-life pipeline response. Highlights of all three simulation cases are as follows:

i) *Subcritical crack growth by grain boundary decohesion*: Conducting slow crack growth experiment with wedge opening load (WOL) specimens (Figure 3a) of alloy IN903, Moody *et al.* [1,2] observed that at hydrogen gas pressures larger than 45 MPa material cracks propagate intergranularly (Figures 3b,c). To simulate the mechanics of sustained-load cracking in a gaseous hydrogen environment, we used the thermodynamic theory of interfacial decohesion

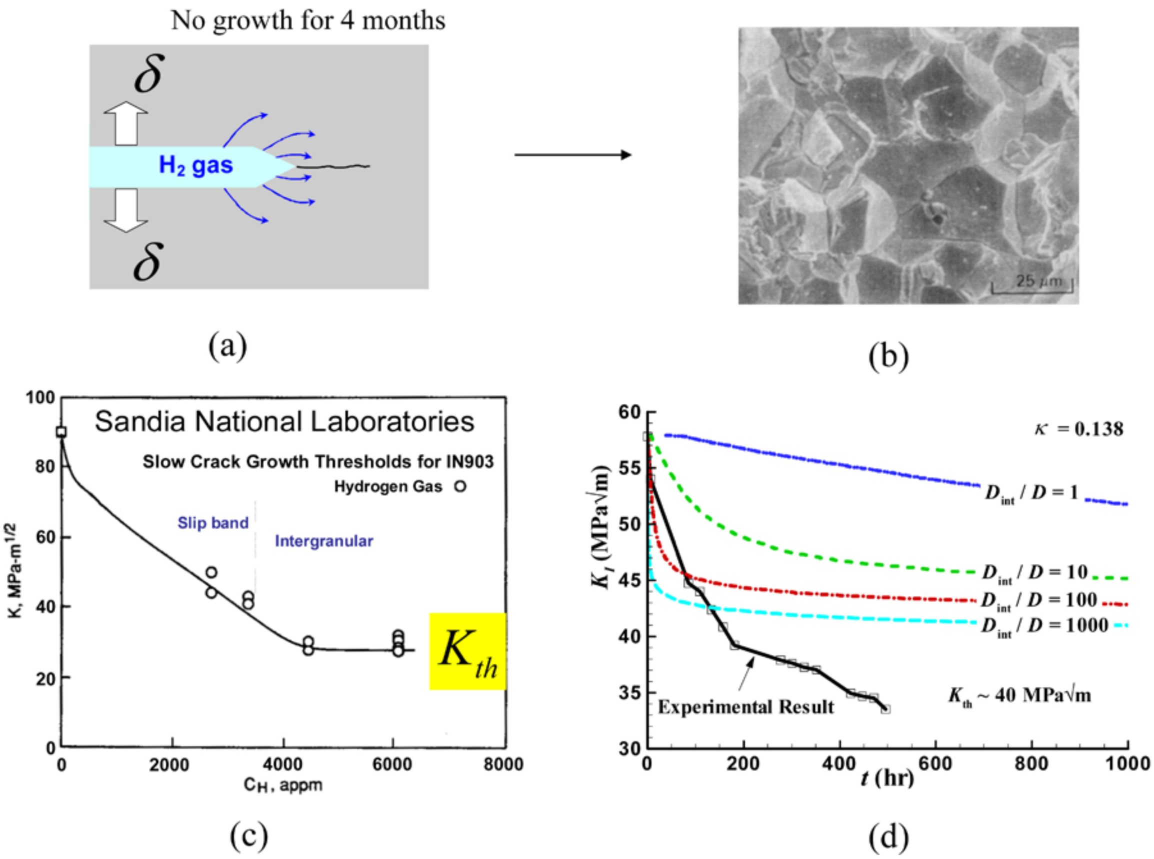

FIGURE 3. Hydrogen-induced subcritical crack growth in alloy IN903: a) schematic of the WOL specimen used in the experiments; b) micrograph showing intergranular cracking at high hydrogen gas pressure; c) experimentally measured threshold stress intensity factor as a function of hydrogen concentration in the specimen in equilibrium with the hydrogen gas; d). simulation predictions of threshold stress intensity factor vs. time at various magnitudes of the interfacial diffusion coefficient. The parameters $k = 0.138$ denotes the ratio of the cohesive energy of hydrogen-saturated grain boundary to the cohesive energy of the hydrogen-free grain boundary.

of Mishin *et al*. [3] to model intergranular crack propagation in alloy IN903.

According to Mishin *et al*. [3], the grain boundary cohesion is characterized by a traction-separation law phrased as

$$\sigma(c_{\text{int}}, q) = \frac{27}{4}\sigma_{\max}\left[1 + (\kappa - 1)c_{\text{int}}/c_c\right]q(1-q)^2, \qquad (1)$$

where $\sigma_{\max}$ is the cohesive stress in the absence of hydrogen, c_{int} is the grain boundary hydrogen concentration in hydrogen atoms per metal atom, c_c is the concentration when the grain boundary is saturated, κ is the ratio of the cohesive energy of the saturated boundary to the cohesive energy of the hydrogen free boundary, and $q = \delta/\delta_c$ is non-dimensionalized separation with δ_c being the critical separation for complete failure of the grain boundary.

For the transient hydrogen transport problem, we assumed that hydrogen diffuses through the bulk material [4] while it diffuses along the separating grain-boundary interface during crack propagation. Hydrogen transport along the grain-boundary interface is motivated by the gradient of the chemical potential μ_{int} of hydrogen which is given [3] by

$$\mu_{\text{int}} = N_A(\varepsilon_B - \varepsilon_A)/c_c + \frac{N_A\left(\varphi_B^0 - \varphi_A^0\right)}{c_c}\left[4(1-q)^3 - 3(1-q)^4\right] + R\Theta \ln\frac{c_{\text{int}}}{\beta_{\text{int}} - c_{\text{int}}}, \qquad (2)$$

where N_A denotes Avogadro's number, ε_A and ε_B are respectively twice the surface energy of the material with no hydrogen and under saturation c_c, φ_A^0 and φ_B^0 are the cohesive energies of the grain boundary with no hydrogen and under saturation respectively in the absence of stress, β_{int} denotes the number of available sites for hydrogen occupancy per host atom on the grain boundary, $R = 8.314$ J/mol K is the universal gas constant, and Θ is the temperature.

The values of the parameters in Eq. (1) used in the calculations are reported in the work of Dadfarnia *et al*. [5]. In particular, the parameter κ was taken equal to 0.138 indicating a maximum cohesive energy reduction by hydrogen of 86%. Such a reduction also accounts for the amount of plastic dissipation upon decohesion. The diffusion coefficient of hydrogen through the normal interstitial sites (NILS) of the bulk material surrounding the propagating crack was taken $D = 1.66 \times 10^{-15}$ m^2/s [5] for room temperature at 295 K.

As hydrogen diffuses through the separating grain boundaries and the normal interstitial lattice sites (NILS) sites in the bulk material, there is a continuous exchange of hydrogen on the boundaries and in the adjacent grains such that continuity of the chemical potential of hydrogen is maintained. This provides the coupling between concurrent hydrogen transport through the matrix and along the grain boundaries. We solved the coupled bulk-diffusion/grain-boundary diffusion and material deformation problems as in the work of Liang and Sofronis [6].

Figure 3d shows the simulation results for the subcritical crack growth observed in the experiments of Moody *et al*. [1,2] in 207 MPa hydrogen gas. Simulations were carried out for various values of the grain boundary diffusion coefficient D_{int} for hydrogen. Whereas the assumed magnitude of the diffusion coefficient along the grain boundary affects the time at which the crack is arrested, it has no effect on the distance the crack travels. The calculated threshold stress intensity K_{th} is about 40 MPa$\sqrt{\text{m}}$; the experimentally measured value is 33.5 MPa$\sqrt{\text{m}}$ (Figure 3c).

ii) *Hydrogen-induced void coalescence and crack initiation*: We studied crack/inclusion interactions under small scale yielding conditions by considering multiple circular debonded inclusions located on the axis of symmetry ahead of a crack, as shown in Figure 4a, in the presence of hydrogen. We assumed that the inclusions are completely debonded (from the manufacturing process) and hydrogen can diffuse along the matrix/inclusion interface. In particular, we studied the cases of inclusions with volume fractions $f_0 = 0.001$, 0.0025, and 0.00875. We switched on hydrogen uptake through the crack faces while at the same time we began loading the domain at a constant stress intensity factor rate $K_I = 1.0$ MPa$\sqrt{\text{m}}$/s.

Hydrogen induced softening was modeled as in the work of Dadfarnia *et al*. [7] in which the flow stress of the material was considered to decrease linearly with the amount of hydrogen trapped at dislocations. The numerical simulations were carried out for the C type steel whose material properties are reported in previous annual progress reports. On the crack faces a concentration $C_0 = 2.659 \times 10^{22}$ H atoms/m^3 (= 3.142×10^{-7} H atoms per solvent atom) in equilibrium with gas pressure of 15 MPa was prescribed.

We considered that crack initiation took place when the void nearest to the crack tip coalesced with the crack tip. Coalescence occurs when the size of the ligament between the crack tip and the void is reduced to half its size in the undeformed state [8]. We found that hydrogen reduces the fracture toughness measured in terms of J_{IC} by about 30% at small initial void volume fraction ($f_0 = 0.001$ and 0.0025) and by 22% at $f_0 = 0.00875$. In the absence of hydrogen and at the smallest initial void volume fraction ($f_0 = 0.001$), the void closest to the crack tip experiences a significant growth in size as shown in Figure 4b while the rest of the voids do not grow significantly, a crack growth mechanism that is controlled by a single void. On the other hand, at the largest initial void volume fraction $f_0 = 0.00875$, crack growth is governed by a multiple-void growth mechanism, i.e., all three voids start growing almost simultaneously upon the application of the load at almost the same rate. In general, hydrogen increases the void growth rate irrespective of the initial void volume fraction and intensifies plastic flow localization (Figure 4c).

iii) *Tranferability of fracture toughness results from laboratory specimens to the real-life pipeline*: In our previous annual progress reports, we presented the hydrogen concentration fields close to the crack tip of an axial pipeline crack. The pipeline was loaded mechanically by the hydrogen pressure exerted on the inside surface and the crack flanks while hydrogen diffused toward the outside surface. We termed the associated solution to the hydrogen transport problem

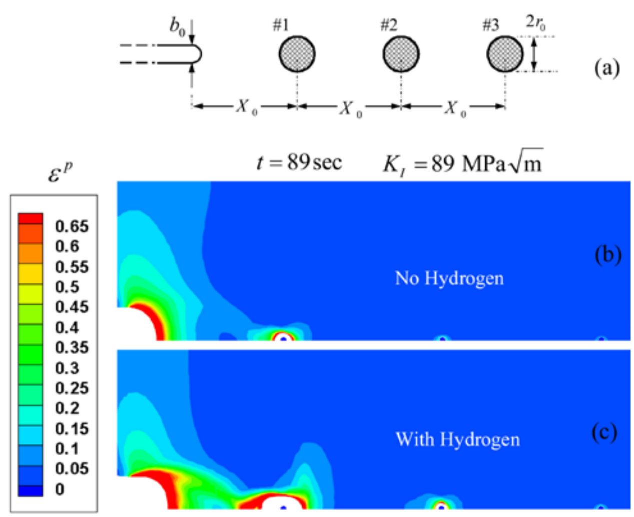

FIGURE 4. a) Model schematic used to investigate the behavior of debonded MnS inclusions in the neighborhood of a crack tip under small scale yielding conditions for a medium strength steel; b) void growth in the absence of hydrogen; c) void growth and plastic flow localization close to the crack tip in the presence of hydrogen-induced softening. In both cases (b) and (c) the remote stress intensity factor is $K_I = 89$ MPa$\sqrt{\text{m}}$ and 89 s have passed from the application of the load. Hydrogen uptake was by diffusion through the crack faces.

as the full-field solution. We demonstrated that this full-field solution close to the crack tip can also be described by a modified boundary layer formulation using the *T*-stress the pipeline crack experiences.

Prompted by these results, we solved the initial/boundary value problem of transient hydrogen diffusion coupled with material elastoplasticity directly in a single edge notch tension specimen with a shallow crack loaded by remote tension. We chose the dimensions of the specimen and the applied tension stress such that the stress intensity factor K_I and *T*-stress are the same as for the axial crack in the pipeline under a given hydrogen pressure. The numerical simulations indicate that the associated stresses and deformation are almost identical. With regard to the steady-state hydrogen concentration profiles there is only a 2% difference between the full-field and the single edge notch tension specimen solutions at the location of the peak NILS hydrogen concentration. In addition, we found that the results close to the crack tip are not affected by the remote hydrogen boundary conditions, that is, impermeable vs. an outgassing outside surface.

The simulations described in this section are essential prerequisites toward meeting all objectives of our project.

First-Principles Assessment of Hydrogen Effects on Interfacial Cohesion

Ab initio density-functional-theory calculations can reveal directly the key bonding and surface-energy effects (grain boundary, free surface, or interphase boundaries) that control interfacial cohesion in the presence of hydrogen solute atoms.

We are continuing our work to quantitatively characterize the cohesive properties of the MnS/ferrite matrix interface. The objective here is to characterize the magnitude of the component of the cohesive stress normal to the interface and whether the component tangential to the interface is negligible either due to manufacturing process effects (cooling from high temperature to ambient) or due to hydrogen accumulated at the interface.

The issue here is that in steel pipelines for the existing natural gas system sulfides and large particles provide fracture initiation sites (all project objectives).

Conclusions and Future Directions

- Hydrogen transport simulations have been carried in which material deformation is coupled to hydrogen-induced degradation in the form of grain boundary decohesion or hydrogen-accelerated void growth, respectively, for subcritical crack growth or rising load fracture toughness.
- We demonstrated that the single edge notch tension specimen can be used to experimentally measure the fracture resistance of materials as affected by hydrogen. The specimen exhibits the same constraint characteristics as cracks in real-life pipelines.
- A permeation measurement apparatus has been built and tested. Identification of the diffusion characteristics (e.g. permeability, solubility, trap strength and density) of existing and new pipeline steel microstructures is carried out with increasing membrane thickness to isolate and understand potential surface adsorption related effects.
- We completely characterized almost all materials provided by DGS Metallurgical Solutions Inc. and sample specimens taken from hydrogen pipelines operated by Air Liquide.
- We use ab initio calculation results to calibrate thermodynamic models of interfacial decohesion needed for finite element simulations of the hydrogen effect at the macroscale.
- In collaboration with Sandia National Laboratories, we carry out fracture testing along with FIB, SEM, and TEM studies to identify the failure mechanisms and associated microstructural features in the presence of hydrogen.
- Once the fracture testing results become available and the hydrogen-induced fracture mechanisms in pipeline steels are understood, we plan to integrate ab-initio calculation results through the thermodynamic theory of decohesion with finite element simulations at the continuum level in order to establish fracture criteria for pipeline safe operation.
- We continue our collaboration with the National Institute for Hydrogen Industrial Use and Storage (HYDROGENIUS) of Japan.

Special Recognitions & Awards/Patents Issued

1. P. Sofronis visited Japan from June 9 to June 25, 2006 as a fellow of the Japan Society for the Promotion of Science (JSPS) to collaborate on research related to hydrogen material compatibility.

2. P. Sofronis and I. Robertson were invited speakers at the *International Hydrogen Energy Development Fora* organized by HYDROGENIUS at Fukuoka, Japan on January 31 – February 1, 2007, February 4–8, 2008, February 4–6, 2009.

3. P. Sofronis has been elected a fellow of the American Society of Mechanical Engineers (ASME) for his contributions to the field of hydrogen embrittlement.

4. I. Robertson was an invited keynote speaker at the 7th International Conference on the Effects of Hydrogen on Materials, Grant Teton National Park, Jackson Lake Lodge, Wyoming, September 7–10, 2008.

FY 2009 Publications/Presentations

Publications

1. Robertson, I.M., Sofronis, P., and Birnbaum, H.K. (In print) Hydrogen effects on plasticity, an invited review article to be published in the series on *Dislocations in Solids.*

2. Dadfarnia, M., Sofronis, P., Somerday, B.P., Liu, J.B., Johnson, D.D., Robertson, I.M. (In Print) Modeling issues on hydrogen-induced intergranular cracking under sustained loading, *Proceedings of the International Conference on the Effects of Hydrogen on Materials*, Jackson Lake Lodge, Wyoming, Sept. 7–10, 2008.

3. Gerberich, W.W., Stauffer, D.D., and Sofronis, P. (In Print) A coexistent view of hydrogen effects on mechanical behavior of crystals: HELP and HEDE, *Proceedings of the International Conference on the Effects of Hydrogen on Materials*, Jackson Lake Lodge, Wyoming, Sept. 7–10, 2008.

4. Dadfarnia, M., P. Sofronis, B. Somerday, I. Robertson (2009) Effect of Remote Hydrogen Boundary Conditions on the Near Crack-tip Hydrogen Concentration Profiles in a Cracked Pipeline, In: *Materials Innovations in an Emerging Hydrogen Economy*, G.G. Wicks and J. Simon, editors, The American Ceramic Society, Ceramic Transactions, Volume 202, pp. 187-199.

5. Dadfarnia, M., Somerday, B.P., Sofronis, P., Robertson, I.M., Stalheim, D. (2009) Interaction of Hydrogen Transport and Material Elastoplasticity in Pipeline Steels, ASME *Journal of Pressure Vessel and Technology*, 131, 041404-13.

6. Sofronis, P., Dadfarnia, M., Novak, P., Yuan, R., Somerday, B., Robertson, I.M., Ritchie, R.O., Kanezaki, T., Murakami, Y. (2009) A Combined Applied Mechanics/ materials Science Approach Toward Quantifying the Role of Hydrogen on Material Degradation. In: Proc. *12th Intl. Conf. on Fracture*, Ottawa, Canada, CD-ROM.

7. Dadfarnia, M., Sofronis, P., Somerday, B.P., Robertson, I.M. (2008) On the small scale character of the stress and hydrogen concentration fields at the tip of an axial crack in steel pipeline: effect of hydrogen-induced softening on void growth, *International Journal of Materials Research (Formerly Z. Metallkd.)*, 99, 557-570.

8. Dadfarnia, M., Somerday, B.P., Sofronis, P., Robertson, I.M. (2008) Hydrogen/Plasticity Interactions at an Axial Crack in Pipeline Steel, *Journal of ASTM International (JAI)*. Vol. 5(6), Paper ID JAI101531, www.astm.org (Published online in June 2008).

9. Liu, J.B. and Johnson, D.D. (2009) bcc-to-hcp Transformation Pathways in Iron versus Hydrostatic Pressure: Coupled Shuffle and Shear Modes, *Phys. Rev. B*, published online in the April 2009 issue of Physical Review B (Vol.79, No.13) http://link.aps.org/abstract/PRB/v79/e134113.

10. Liang, Y., Ahn, D.C., Sofronis, P., Dodds, R. and Bammann, D. (2008) Effect of Hydrogen Trapping on Void Growth and Coalescence in Metals and Alloys, *Mechanics of Materials*, 40, 115-132.

Presentations

1. Robertson, I. (2008, keynote) Revealing the Fundamental Processes Controlling Hydrogen Embrittlement," International Symposium on the *Effects of Hydrogen on Materials*, Grant Teton National Park, Jackson Lake Lodge, Wyoming, September 7-10, 2008.

2. Sofronis, P. (2008, invited) A Combined Applied Mechanics/Materials Science Approach Toward Understanding the Role of Hydrogen on Material Degradation in Low and High Strength Steels. *ExxonMobil Research and Engineering Company*, Annandale, New Jersey, April 23.

3. Dadfarnia, M. Sofronis, P., Somerday, B., Biao, J., Johnson, D. (2008) Modeling Hydrogen-Induced Sustained-Load Cracking by Intergranular Failure. International Symposium on the *Effects of Hydrogen on Materials*, Grant Teton National Park, Jackson Lake Lodge, Wyoming, September 7–10.

4. Sofronis, P. (2009, invited) Materials for the Hydrogen Economy: Embrittlement and Remediation. *Society of Engineering Science*, 45th Annual Technical Meeting, Urbana, Illinois, October 13–15.

5. Dadfarnia, M.A Methodology for Studying Hydrogen Embrittlement in a Steel Pipeline. *Society of Engineering Science*, 45th Annual Technical Meeting, Society of Engineering Science, Urbana, Illinois, October 13–15, 2009.

6. Sofronis, P. (2009, invited) On the Design of Steel Pipelines against Hydrogen Embrittlement. *Third International Hydrogen Energy Development Forum*, Hotel Okura, Fukuoka, Japan, Feb. 4.

7. Ritchie, R.O. and Sofronis, P. (2009, invited) Micro-Mechanical Modeling of Hydrogen-Induced Brittle Fracture. *Third International Hydrogen Energy Development Forum*, Hotel Okura, Fukuoka, Japan, Feb. 4.

8. Sofronis, P. (2009, invited) Assessing the Hydrogen Effect on Fracture: valid Fracture Testing. *International* HYDROGENIUS *Symposium on Hydrogen-Materials-Interaction*, Kyushu University, Fukuoka, Japan, Feb. 5.

9. Robertson, I.M. (2009, invited) "Hydrogen and Grain Boundaries," *International* HYDROGENIUS *Symposium on Hydrogen-Materials-Interaction*, Kyushu University, Fukuoka, Japan, Feb. 5, 2009.

References

1. Moody, N.R., Perra, M.W., and Robinson, S.L. (1988) Hydrogen Pressure and Crack Tip Stress Effects on Slow Crack Growth Thresholds in an Iron-Based Supperalloy. *Scripta Metallurgica*, 22(8), pp. 1261-1266.

2. Moody, N.R., Perra, M.W., and Robinson, S.L. (1990) Hydrogen-Induced Cracking in an Iron-Based Superalloy. *Hydrogen Effects on Material Behavior*: Proceedings of the 4th International Conference on Effect of Hydrogen on Behavior of Materials, N.R. Moody and Anthony W. Thompson, eds., TMS, Warrendale, PA, pp. 625-635.

3. Mishin, Y., Sofronis, P., and Bassani, J.L. (2002) Thermodynamic and Kinetic Aspects of Interfacial Decohesion. *Acta Materialia*, 50(14), pp. 3609-3622.

4. Taha, A., and Sofronis, P. (2001) A Micromechanics Approach to the Study of Hydrogen Transport and Embrittlement. *Engineering Fracture Mechanics*, 68(6), pp. 803-837.

5. Dadfarnia, M., Sofronis, P., Somerday, B.P., Robertson, I.M., Biao, J., and Johnson, D.D. (2009) Modeling Issues on Hydrogen-Induced Intergranular Cracking Under Sustained Load. *Effect of Hydrogen on Materials*: Proceedings of 2008 International Hydrogen Conference, Grand Teton National Park, Wyoming, USA.

6. Liang, Y., and Sofronis, P. (2003) Micromechanics and Numerical Modelling of the Hydrogen-Particle-Matrix Interactions in Nickel-Base Alloys. *Modelling and Simulation in Materials Science and Engineering*, 11(4), pp. 523-551.

7. Dadfarnia, M., Sofronis, P., Somerday, B.P., Robertson, I.M. (2008) On the small scale character of the stress and hydrogen concentration fields at the tip of an axial crack in steel pipeline: effect of hydrogen-induced softening on void growth, *International Journal of Materials Research* (*Formerly Z. Metallkd.*), 99, 557-570.

8. Tvergaard, V., and Hutchinson, J.W. (2002) Two Mechanisms of Ductile Fracture: Void by Void Growth Versus Multiple Void Interaction," *International Journal of Solids and Structures*, 39(13-14), pp. 3581-3597.