Hydrogen embrittlement mechanisms in metals

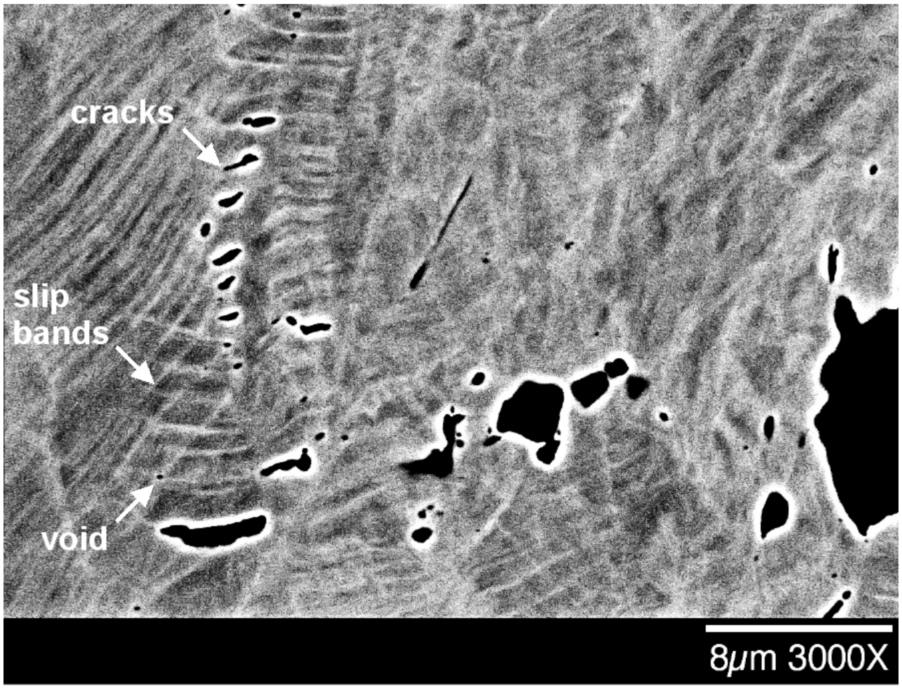

Figure 1. Backscattered electron image from crack growth specimen of stainless steel exposed to hydrogen gas. The image reveals a link between hydrogen-enhanced deformation and cracking.

Hydrogen embrittlement modeling can help ensure structural integrity of hydrogen fuel containers

High-pressure storage is a critical component of the emerging infrastructure for using hydrogen gas as an energy source. One of the key materials issues in storage is hydrogen embrittlement of metals. That happens when metal structures are subjected to concurrent mechanical loading and hydrogen gas exposure, causing the metal to become more susceptible to cracking. Embrittlement is enabled by the ability of hydrogen molecules to dissociate into hydrogen atoms on metal surfaces, which then diffuse into the metal. Hydrogen embrittlement has been explained through several mechanisms involving interactions between the atomic hydrogen and the host metal.

One of the hydrogen-metal interactions associated with embrittlement is hydrogen-enhanced localized plasticity. Compelling evidence from both experiments and modeling demonstrates that hydrogen can facilitate the motion of dislocations and promote slip planarity. However, the link between enhanced deformation and fracture has not been well established.

Sandia researchers conducted crack growth experiments on stainless steels exposed to hydrogen gas to gain insight into how hydrogen-enhanced plasticity can lead to fracture. Post-test examinations using high-magnification backscattered electron imaging (see figure) revealed that voids nucleated at intersecting slip bands and then evolved into cracks, which propagated along the slip bands. Previous results for this stainless steel demonstrated that slip bands were promoted by the presence of hydrogen. Such detailed evidence for the sequence of localized deformation, void formation at intersecting slip bands, and cracking along the slip bands has not been previously reported for full-size crack growth specimens exposed to hydrogen gas.

Ultimately, the motivation for understanding the detailed mechanisms of hydrogen embrittlement is to develop predictive models, and the framework and input parameters must be based on the real physics of deformation and fracture. Hydrogen embrittlement models can aid in designing resistant materials and assessing structural integrity, which will become more important as infrastructure is developed to support the use of hydrogen as a fuel.

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Hydrogen Effects on Materials Laboratory

Sandia National Laboratories has been working on structural design for hydrogen gas containment and hydrogen embrittlement of materials for over 40 years. The Hydrogen Effects on Materials Laboratory is a unique laboratory for measuring mechanical properties of materials exposed to high-pressure hydrogen gas. It has been maintained since the late 1970s and is being expanded. The laboratory has three primary capabilities, which are distinguished by the capabilities for conducting crack growth experiments *in situ* at hydrogen gas pressures exceeding 100 MPa:

- Exposing materials to high-pressure hydrogen gas at pressures up to 140 MPa and temperatures up to 300 ºC. This capability is used to dissolve high concentrations of hydrogen in mechanical test specimens, which are tested *ex situ* and provide data on the effect of high hydrogen concentrations on material properties.
- Testing fracture mechanics specimens that are concurrently exposed to high-pressure hydrogen gas and statically loaded under constant displacement. These *in situ* tests can be conducted in hydrogen gas pressures up to 200 MPa at room temperature and up to 140 MPa at temperatures ranging from -75 ºC to 175 °C. The tests provide data on the crack propagation threshold and crack propagation rates of materials.
- Testing fracture mechanics specimens that are concurrently exposed to high-pressure hydrogen gas and dynamically loaded. These *in situ* tests can be conducted in hydrogen gas pressures up to 140 MPa at room temperature and provide data on the fracture toughness and fatigue crack propagation rates of materials.

Sandia has tested a variety of structural materials in high-pressure hydrogen gas, which have yielded material property data used in structural design for hydrogen gas containment and provided insights into the mechanisms of hydrogen embrittlement. Sandia is actively involved in projects connected to the development of hydrogen energy infrastructure; in particular, providing input on material properties and material testing protocols for codes and standards.

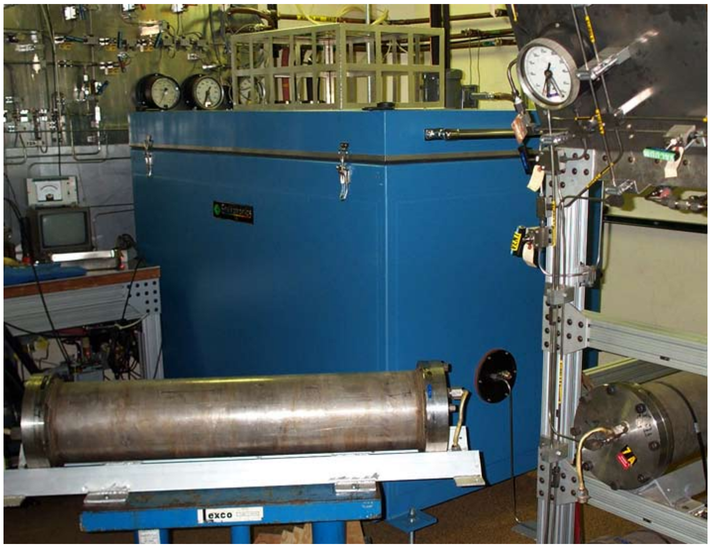

Figure 2. Laboratory for conducting tests on materials in high-pressure hydrogen gas.

Publications

"Technical Reference for Hydrogen Compatibility of Materials", B.P. Somerday and C. San Marchi, Eds., www.ca.sandia.gov/matlsTechRef.

"Effects of High-Pressure Gaseous Hydrogen on Structural Metals", C. San Marchi and B.P. Somerday, SAE 2007 World Congress, Detroit, MI, 2007.

"Mechanical Properties of Super Duplex Stainless Steel 2507 After Gas Phase Thermal Precharging with Hydrogen," C. San Marchi, B.P. Somerday, J. Zelinski, X. Tang, and G.H. Schiroky, submitted to *Metallurgical and Materials Transactions* A, 2007.

"Permeability, Solubility and Diffusivity of Hydrogen Isotopes in Stainless Steels at High Gas Pressures," C. San Marchi, B.P. Somerday, and S.L. Robinson, *International Journal of Hydrogen Energy*, vol. 32, pp. 100-116, 2007.

"Hydrogen Effects on Dislocation Activity in Austenitic Stainless Steel," K.A. Nibur, D.F. Bahr, and B.P. Somerday, *Acta Materialia*, vol. 54, pp. 2677-2684, 2006.

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