III.1 Fatigue Performance of High-Strength Pipeline Steels and Their Welds in Hydrogen Gas Service

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Project Start Date: October 1, 2015
Project End Date: September 30, 2018

Overall Objectives

- Enable the use of high strength steel hydrogen pipelines, as significant cost savings can result by implementing high strength steels as compared to lower strength pipes.
  - Determine whether girth welds in high-strength steel pipe exhibit fatigue performance similar to lower-strength steels in high-pressure hydrogen gas.
  - Identify pathways for developing high-strength pipeline steels by establishing the relationship between microstructure constituents and hydrogen-accelerated fatigue crack growth (HA-FCG).

Fiscal Year (FY) 2017 Objectives

- Complete fabrication of specimens from graded-microstructure high-strength steels for HA-FCG measurements. (SNL)
- Complete the draft of a peer-reviewed journal article on HA-FCG results for a current-practice arc weld in X100 steel. (SNL)
- Complete a minimum of three HA-FCG measurements on graded-microstructure high-strength steels at constant H_2 pressure, load-cycle frequency, and mean stress. (SNL)
- Incorporate a calibrated phenomenological model of X100 base metal into the framework of a physics-based model for validation of the physics-based model. (NIST)
- Analyze results of Gleeble™ tests to identify relationship between microstructure constituents and HA-FCG to inform development of lab-scale steel and NIST predictive model. (SNL, ORNL)
- Fabricate friction-stir weld in X100 steel. (ORNL)

Technical Barriers

This project addresses the following technical barriers from the Hydrogen Delivery section of the Fuel Cell Technologies Office Multi-Year Research, Development, and Demonstration Plan.

(D) High As-Installed Cost of Pipelines

(K) Safety, Codes and Standards

Technical Targets

This project impacts the following technical targets for hydrogen delivery components (Table 3.2.4 of the Fuel Cell Technologies Office Multi-Year Research, Development, and Demonstration Plan) related to pipelines for gaseous hydrogen delivery.

- Total capital investment: $695,000/mile (FY 2020)
- Transmission pressure: 100 bar (FY 2020)
- Lifetime: 50 years (FY 2020)

Design codes such as the America Society of Mechanical Engineers (ASME) B31.12 [1] contain structural integrity models which enable safety assessment of low strength steel pipelines subjected to pressure cycling. Currently there are prescribed safety factors specifically for hydrogen service (i.e., materials performance factors) to accommodate the potential for hydrogen embrittlement. These materials performance factors are a function of the specified minimum yield strength (SMYS) for the steel. Consequently, allowable stresses are significantly more restricted for high strength steel pipe compared to low strength, yet recent testing performed at both SNL and NIST [2–4] have shown similar fatigue performance of steel pipelines over a large range of SMYS. However, such conservative allowable stresses allowed in the current code nullify any cost savings that would be afforded by high strength steels. Direct reductions in capital costs would be realized if higher strength steels with thinner wall pipe thicknesses were permitted.

FY 2017 Accomplishments

- Completed triplicate fatigue crack growth rate (FCGR) tests on the base metal, weld and heat affected zone (HAZ) of a commercially available X100 girth welded pipeline steel in 21 MPa H_2 gas.
- Paper published on X52 friction stir weld: J.A. Ronevich, B.P. Somerday, Z. Feng, "Hydrogen accelerated fatigue crack growth of friction stir welded X52 steel pipe," *Int. J. of Hydrogen Energy*, Vol. 42, (7), 2017, pp. 4259–4268.
- Completed draft manuscript in collaboration with University of California, Davis entitled, "Residual stress effects on fatigue crack growth rates of X100 steel welds in high pressure hydrogen gas," to be submitted to *Engineering Fracture Mechanics.*
- Fabricated and extracted test coupons from three high strength alternative consumable welds for testing in hydrogen gas to provide comprehensive study on high strength welds.
- Determined pathway to quantify and correct for residual stresses in welds and HAZ in high strength materials to allow direct comparisons of fatigue performance of different microstructures.
- Initiated microstructure investigation and grain size distribution on X100 base materials and welds.
- Implemented calibration of plasticity-fatigue in ABAQUS framework.

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INTRODUCTION

Steel pipelines represent an economical means of transporting gaseous hydrogen over long distances; however, it is well known that these carbon-manganese steels are susceptible to hydrogen degradation. Current steel pipelines codes (e.g., ASME B31.12 [1]) place limitations on allowable stresses based on the SMYS of the material. These material performance factors reflect the general trend that hydrogen embrittlement can be more severe in high-strength steels. However, recent testing [2–4] of pipeline steels with a range of SMYS from 358 MPa to 689 MPa have not exhibited this trend and suggest that hydrogen assisted fatigue crack growth may not increase with strength. The conservative allowable stresses currently permitted in the code remove the cost savings that would be realized if higher strength steel pipelines were permitted. In pipeline applications without material performance factors, wall thickness is inversely proportional to steel strength; therefore, higher strength steels can reduce material and installation costs [5].

This project focuses on developing a pathway to enable the use of high-strength steel pipes. One means to accomplishing this goal is to assess the fatigue performance of high-strength steel pipelines in high pressure hydrogen gas. The fatigue crack growth rate (da/dN) versus stress-intensity factory range (ΔK) relationship is a necessary input to structural integrity models applied to steel hydrogen pipelines. One specific assessment methodology for steel hydrogen pipelines is published in ASME B31.12 code [1] which requires testing of the base metal, weld, and heat-affected zone. One of the gaps is the fatigue performance of high strength steel welds and whether the behavior will follow the same trends that the base metal exhibited over the SMYS range. As the performance of the steel base metals or welds may vary as function of microstructure, development of physics-based relationships between FCGRs and microstructure would greatly enhance the structural integrity models and drastically reduce the test burdening required to qualify materials for hydrogen use. The relationships between microstructures, contained in high-strength steels and welds, and hydrogen-assisted fatigue are evaluated in this study.

APPROACH

The objectives for this project are the following: (1) demonstrate that girth welds in high-strength steel pipe exhibit fatigue performance similar to lower-strength steels in high-pressure hydrogen gas and (2) identify pathways for development of high-strength pipeline steels by establishing the relationship between microstructure constituents and HA-FCG. Based on these project objectives, the technical tasks are designed to furnish innovative high-strength steel products for evaluation and to measure performance metrics for these high-strength steel products (i.e., fatigue crack growth rates in hydrogen gas) with high reliability. Completion of these tasks will assist in reaching the goal of this work: the deployment of steel pipe with reduced wall thickness, which can lower costs for hydrogen pipeline installation.

RESULTS

Fatigue crack growth rate testing was completed in 21 MPa H_2 gas on a commercially available X100 welded steel pipe with testing focused on the base metal, weld, and HAZ. The results from triplicate tests are shown in Figure 1a along with a test performed in air for comparison. Residual stresses were measured in collaboration with University of California, Davis to aid in decoupling the effects of residual stress from microstructural sensitivity to hydrogen degradation. The residual stresses were quantified and the FCGR curves were corrected as shown in Figure 1b. Due to the repeatability in the triplicate tests, only one curve for the weld, HAZ, and base metal were corrected. As can

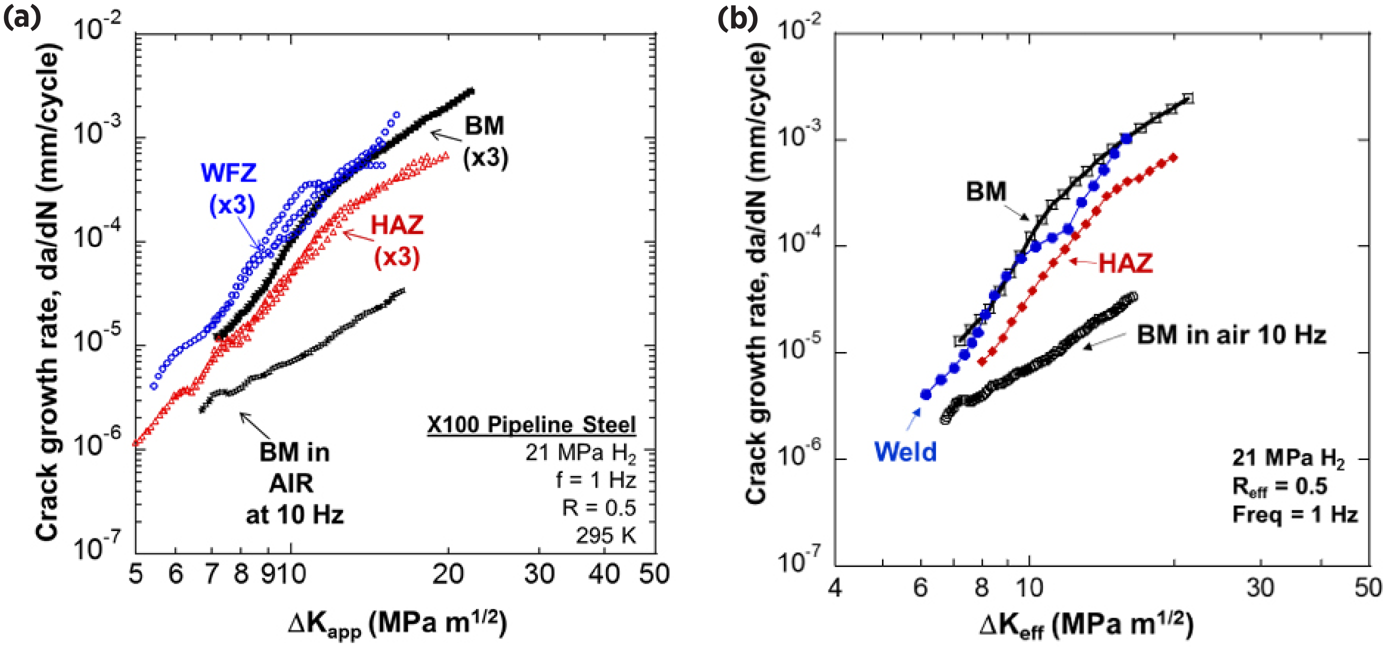

FIGURE 1. (a) Fatigue crack growth rate (da/dN versus ΔK_{app}) curves for X100A base metal (BM), weld fusion zone (WFZ), and heat affected zone (HAZ) tested in 21 MPa H_2 gas. Test performed in air at 10 Hz is shown for comparison. (b) Fatigue crack growth rates corrected for residual stress and plotted versus ΔK_{eff}.

be observed in Figures 1a and 1b, the base metal exhibits negligible difference between ΔK_{app} and ΔK_{eff}, whereas the weld and HAZ exhibit a notable difference between the ΔK_{app} and ΔK_{eff}. The removal of residual stress effects shifts the weld FCGR curve to comparable or even slightly lower FCGRs than the base metal. The HAZ data appears to have a similar shift to the right resulting in lower da/dN for a given ΔK_{eff}. This result is important as it demonstrates that residual stresses can have significant and measureable effects on fatigue crack growth rates.

In an effort to gain a more comprehensive understanding of high strength steel welds, ORNL fabricated three additional welds using different consumables from the same X100 base metal. Figures 2a, 2b, and 2c show the three welds labeled W1, W3, and W4, respectively, along with hardness maps. W1 and W3 were fabricated using commercial filler metals and W4 was fabricated with a weld wire developed by ORNL which was designed to be resistant to hydrogen embrittlement. Testing is planned of these welds in hydrogen from the fourth quarter of FY 2017 to the first quarter of FY 2018.

In order to enable a detailed study of the relationship between microstructure and hydrogen-assisted fatigue crack growth, a novel approach was developed to produce laboratory controlled microstructures using a Gleeble™ at ORNL. X80 steel coupons were subjected to non-uniform heating to produce a gradient microstructure in the axial direction. This facilitated extraction of computed tomography (CT) test coupons in which constant ΔK tests could be performed across the gradient microstructure allowing assessment of a wide range of microstructures in only a few test specimens. This is demonstrated in Figure 3a in which the CT specimen is extracted in an orientation that facilitates extension of the crack across the gradient microstructure. One challenge that was encountered during the fatigue testing was that the crack arrested due to compressive residual stresses as shown in Figure 3b. Although not directly measured, the magnitude of the residual stress in this CT test coupon convolutes a clear comparison of microstructure and da/dN. ORNL is fabricating additional Gleeble™ specimens with a less severe temperature gradient to mitigate residual stresses, thereby improving probability of comparing microstructure and fatigue crack growth rates in H_2 gas.

In collaboration with the U.S. Department of Transportation, NIST and Colorado School of Mines have derived a constitutive, phenomenological model that can predict HA-FCG in pipeline steels as a function of hydrogen pressure and specimen strain [7]. This model was developed through a combination of mathematical modeling and calibration with experimental results. Tensile data of X100 were used to extrapolate relationships that correlate strain (a measurable, physical parameter of steel) to applied stress (e.g. due to pressure cycling in a pipeline). Figure 4 shows some ABAQUS finite element model results of an X100 steel in which tensile experimental data were used to calibrate fully reversed loading in the model. These relationships were then incorporated into standard engineering models

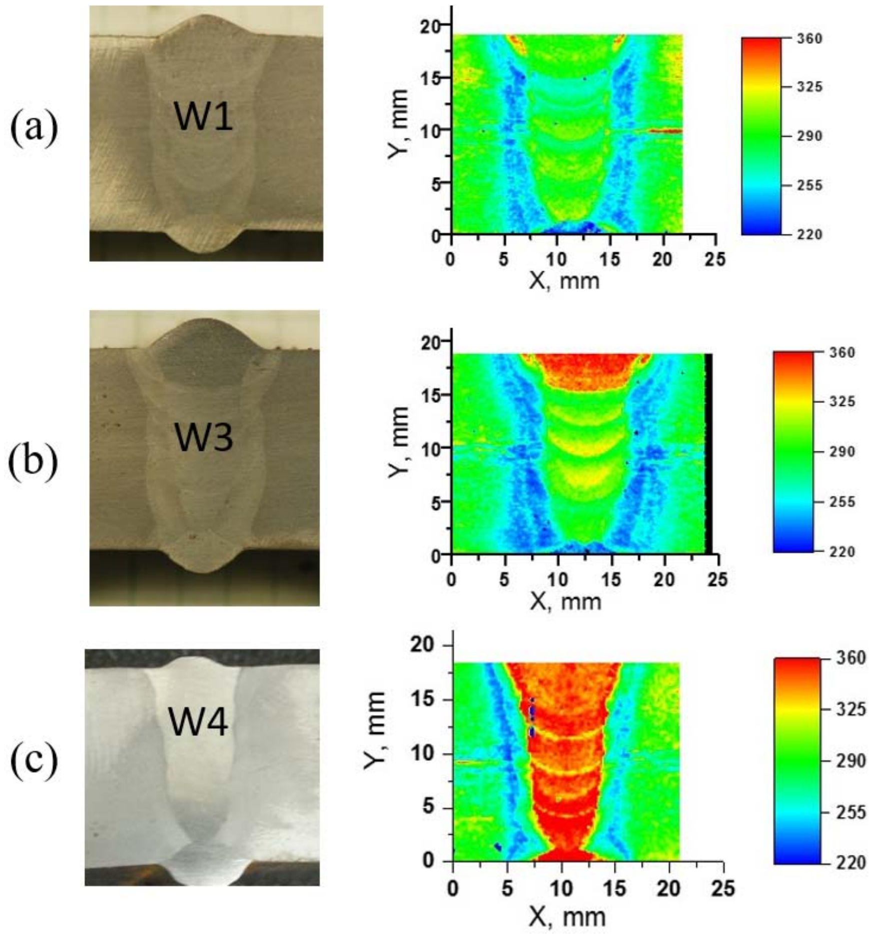

FIGURE 2. Fabricated alternative consumable welds: W1, W3, and W4, with corresponding microhardness maps.

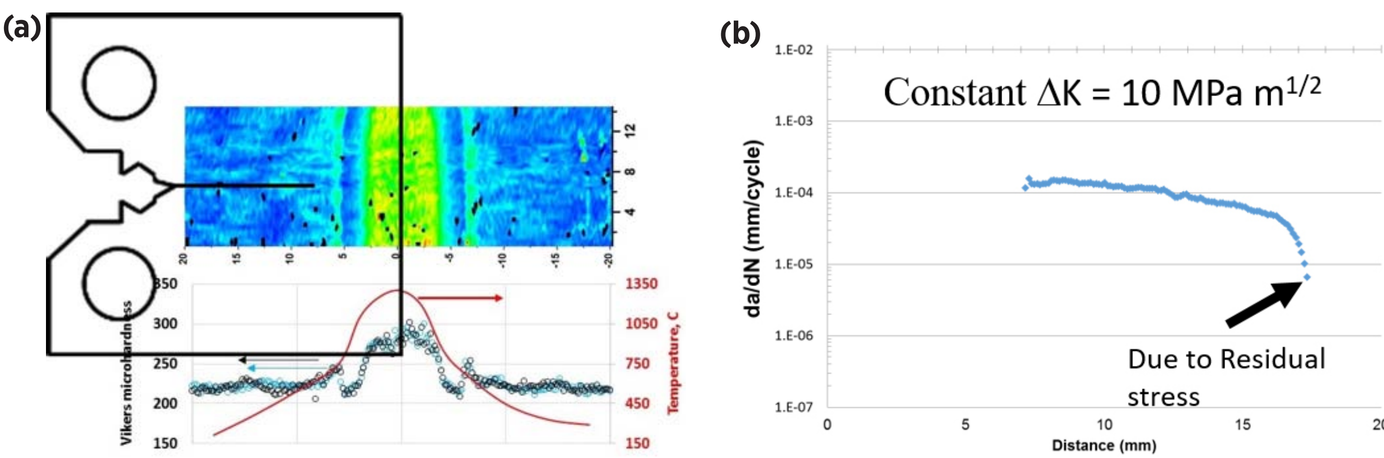

FIGURE 3. (a) CT specimen overlaid on hardness map of Gleeble™ coupon indicating gradient hardness that crack extension should encounter. (b) FCGR during a constant ΔK test as a function of position in 21 MPa H_2 gas. Fatigue crack was arrested near higher hardness area due to compressive residual stresses.

of damage from both mechanical loading and hydrogen effects to derive a constitutive model that predicts HA-FCG in CT specimens as a function of hydrogen pressure and cycle frequency [8]. The constitutive model is currently being calibrated to additional microstructures of steel used in pressure vessels, and incorporated into a finite element

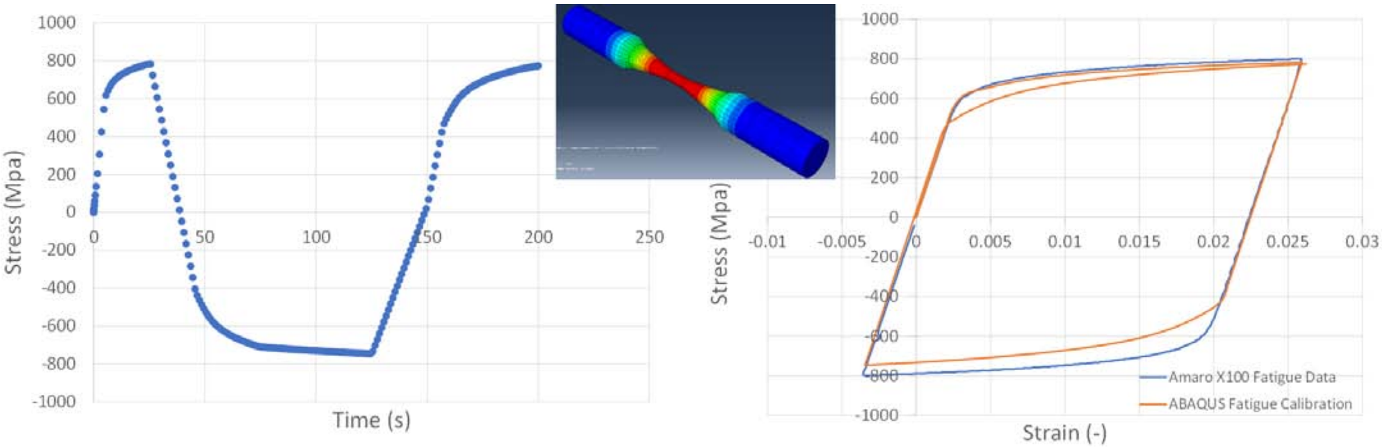

FIGURE 4. ABAQUS finite element calibration of X100 pipeline steel experiencing fully reversed load. Model predicts stress-strain response by use of Mises, kinematic work hardening, yield surface evolution.

package, ABAQUS [9]. Inclusion in ABAQUS will ultimately expand the model's applicability to a wide range of three-dimensional geometries; it is currently only applicable to coupon specimens. In parallel, NIST has been evaluating the behavior of steel specimens in hydrogen using neutron diffraction, to elucidate hydrogen diffusion behavior and interactions with microstructural features (e.g. dislocations), as well as crack tip plasticity that develops during mechanical loading. In FY 2018, the model developed will be calibrated to additional microstructures of steel that are developed by ORNL and tested at Sandia, and efforts will be made to expand it with the ability to simulate microstructure-specific phenomena such as hydrogen transport, plasticity, de-cohesion laws, and orientation specific mechanical properties at the grain level.

CONCLUSIONS AND UPCOMING ACTIVITIES

- Decoupling residual stress effects from FCGR curves facilitated direct comparison of fatigue performance of different regions of welded pipe. Once residual stress effects were removed, the base metal and weld data exhibited similar FCGR relationships in H_2 with the HAZ exhibiting the lowest FCGR.
- Fabricated three additional welds using different filler metals to provide comprehensive study on high strength welds. Additionally, fabricated gradient microstructures using Gleeble™.
- (Future) Residual stress measurements are planned for alternative weld test coupons to ensure FCGR relationships can be compared without the complications of residual stress.
- Initial testing of gradient microstructures from Gleeble™ samples was unmanageable due to significant residual stresses. (Future) Redesigned cooling profiles of Gleeble™ heat treatment were performed to mitigate residual stress to facilitate comparisons between microstructure and HA-FCG.

FY 2017 PUBLICATIONS

1. J. Ronevich, B. Somerday, Z. Feng, "Hydrogen accelerated fatigue crack growth of friction stir welded X52 steel pipe," *Int. Journal of Hydrogen Energy*, Vol. 42, Issue 7, February 2017, pp. 4259–4268.

2. J. Ronevich, B. Somerday, "Hydrogen-accelerated fatigue crack growth in arc welded X100 pipeline steel," *in proceedings of 2016 International Hydrogen Conference,* Jackson Hole, WY.

3. Amaro, R.L., Long, B.L., Slifka, A.J., Drexler, E.S., O'Connor, D.T., "Application of a Model of Hydrogen-Assisted Fatigue Crack Growth in 4130 Steel," *Proceedings of International Hydrogen Conference 2016*, Jackson Hole, WY.

4. O'Connor, D.T., Long, B.L., Slifka, A.J., Drexler, E.S., Amaro, R.L., "Computational Modeling of Hydrogen-Assisted Fatigue Crack Growth in Pipeline Steels," *Proceedings of International Hydrogen Conference 2016*, Jackson Hole, WY.

5. J. Ronevich, B. Somerday, "Hydrogen Effects on Fatigue Crack Growth Rates in Pipeline Steel Welds PVP2016-63669," *ASME 2016 Pressure Vessels & Piping Conference,* Vancouver, Canada, July 17–21, 2016.

FY 2017 PRESENTATIONS

1. J. Ronevich et al., "Fatigue Performance of High-Strength Pipeline Steels and Their Welds in Hydrogen Gas Service," 2017 FCTO Annual Merit Review, Washington D.C., June 6, 2017.

2. J. Ronevich, "Fatigue Performance of High-Strength Pipeline Steels and Their Welds in Hydrogen Gas Service," Joint Delivery-Storage Tech Team Meeting, Detroit, MI, February 15–16, 2017.

3. J. Ronevich, C. San Marchi, B. Somerday, "Hydrogen accelerated fatigue crack growth of welded steel pipelines,"

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4. J. Ronevich, C. San Marchi, B. Somerday, "Fatigue and Fracture Performance of High Strength Pipeline Steels in High Pressure Hydrogen Gas," *ASME International Mechanical Engineering Congress & Expositions,* Phoenix, AZ, November 14–17, 2016.

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6. J. Ronevich, C. San Marchi, "Safety, R&D, and Deployment of Hydrogen Infrastructure," *International Workshop for Hydrogen Infrastructure Reliability,* Daejeon, Korea, June 27, 2016.

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4. C. San Marchi, B.P. Somerday, K.A. Nibur, D.G. Stalheim, T. Boggess, S. Jansto, "Fracture Resistance and Fatigue Crack Growth of X80 Pipeline Steel in Gaseous Hydrogen," in ASME Pressure Vessles & Piping Division, Baltimore, Maryland USA, 2011.

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6. ASTM, "E647-11 Standard Test Method for Measurement of Fatigue Crack Growth Rates," ed. West Conshohocken, PA, 2011.

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9. Amaro, R.L., Long, B.L., Slifka, A.J., Drexler, E.S., O'Connor, D.T., "Application of a Model of Hydrogen-Assisted Fatigue Crack Growth in 4130 Steel," Proceedings of International Hydrogen Conference 2016, Jackson Hole, WY.