III.2 Fatigue Performance of High-Strength Pipeline Steels and Their Welds in Hydrogen Gas Service

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Overall Objectives

- Enable significant cost savings through implementation of high strength steels as compared to lower strength pipes.
  - Demonstrate that 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) 2016 Objectives

- Complete triplicate HA-FCG measurements for each material region (base metal, weld fusion zone, and heat-affected zone [HAZ]) in current practice arc weld at hydrogen pressure, load cycle frequency (1 Hz), & load ratio (R = 0.5). (SNL)
- Complete HA-FCG tests at constant ΔK to identify most susceptible locations in the fusion zone and HAZ of current-practice arc weld. (SNL)
- Develop controlled microstructures using Gleeble™. (Oak Ridge National Laboratory [ORNL])
- Fabricate a high strength steel girth weld using an alternative consumable. (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, Permitting

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. While, allowable stresses are significantly more restricted for high strength steel pipe compared to low strength, recent testing performed at both SNL and National Institute of Standards and Technology (NIST) [2-4] have shown similar fatigue performance of steel pipelines over a large range of SMYS. The conservative allowable stress restrictions 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 2016 Accomplishments

- Paper accepted to *Materials Performance and Characterization*. The paper documents fatigue behavior of lower strength welded steel pipelines tested in a previous project.
- Performed triplicate fatigue crack growth rate tests on X100 base metal at 21 MPa and a single test at 5.5 MPa, at load ratio of R = 0.5, and loading frequency of 1 Hz.

- Developed a detailed procedure to generate controlled-microstructure gradients in the laboratory using Gleeble™ on low alloy carbon steel specimens.

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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 inhibit cost savings that could be realized if higher strength steel pipelines were permitted with reduced material performance factors. When material performance factors are not accounted for, increasing the strength of steel reduces the requisite wall thickness in a pipeline for a given operating pressure; higher strength steels could therefore reduce material and installation costs if their material performance factors were reduced [5].

This project focuses on developing a pathway to enable the use of high-strength steel in pipelines. 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 the ASME B31.12 code [1], and requires testing of the base metal, weld, and heat-affected zones of the pipe. A gap in the current understanding of steel pipelines is the fatigue performance of high strength steel welds; it is unknown whether welds will have the same behavior as base metal exhibited in the SMYS range of interest. An additional void in the research to date is the existence of physics-based relationships that correlate fatigue crack growth rates and microstructure. Physics-based relationships would greatly enhance the reliability of structural integrity models, and drastically reduce the burden of testing required to qualify materials for hydrogen use. The relationships between the microstructures of high-strength steels and welds, and hydrogen-assisted fatigue crack growth rates are evaluated in this study.

APPROACH

The objectives for this project are to (1) characterize the fatigue performance of girth welds of high-strength steel pipe 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

One objective in FY 2016 was to measure the hydrogen-assisted fatigue crack growth behavior of a high-strength pipeline girth weld. To accomplish this task, an X100 gas metal arc girth welded pipe, designated X100A, was supplied by NIST to Sandia in the first quarter of FY 2016. Figure 1

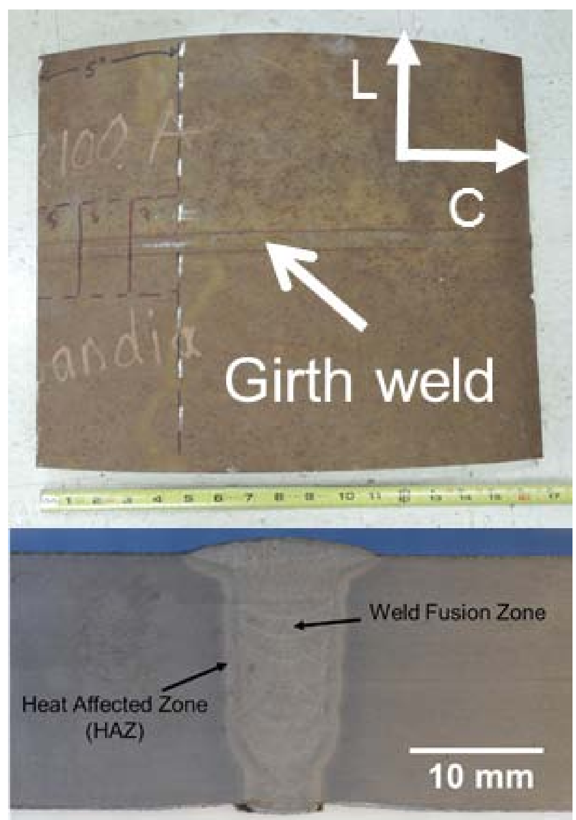

FIGURE 1. Section of X100 steel pipe containing girth weld. Macrograph of the girth weld showing the weld fusion zone and heat-affected zone

shows the supplied pipe section. A cross-section of the weld was polished and etched to reveal the microstructure of the weld as shown in Figure 1. The weld fusion zone and heat-affected zones are clearly identifiable in the macro-image of the weld. This welded pipe represents a fusion weld fabricated according to current practices. The base metal pipe has a nominal thickness of 19 mm and longitudinal yield strength of 731 MPa. Compact tension and eccentrically loaded single edge notched specimens were extracted from the base metal and weld fusion zone according to ASTM E647-11 [6] in the C-L and L-R orientations, respectively. The C-L terminology implies that the load is applied in the circumferential (C) direction and the crack growth is in the longitudinal (L) direction. Similarly the L-R orientation indicates load applied in longitudinal (L) direction and crack growth in radial (R) direction.

Fatigue crack growth rate versus stress-intensity factor range relationships were measured of the base metal at 21 MPa, load ratio of R = 0.5, and frequency of 1 Hz as shown in Figure 2. A single test was also completed at 5.5 MPa, although triplicates are planned. For comparison, a test was performed in air at a frequency of 10 Hz. All tests in hydrogen exhibited HA-FCG. The triplicate tests at 21 MPa showed good repeatability throughout the da/dN vs. ΔK curves. The test at 5.5 MPa exhibited HA-FCG; however, the onset of HA-FCG was shifted to the right (e.g., higher ΔK). Overall the fatigue crack growth rates appear to be lower in 5.5 MPa compared to in 21 MPa. This pressure dependence of HA-FCG is consistent with previous results reported by NIST [2,7]. Overall the HA-FCG behavior at 21 MPa in the X100A base metal was similar to other lower strength pipes tested in high pressure hydrogen [2-4]. Testing is planned for the weld fusion zone and heat affected zone using the eccentrically loaded single edge notched specimens in 21 MPa hydrogen gas.

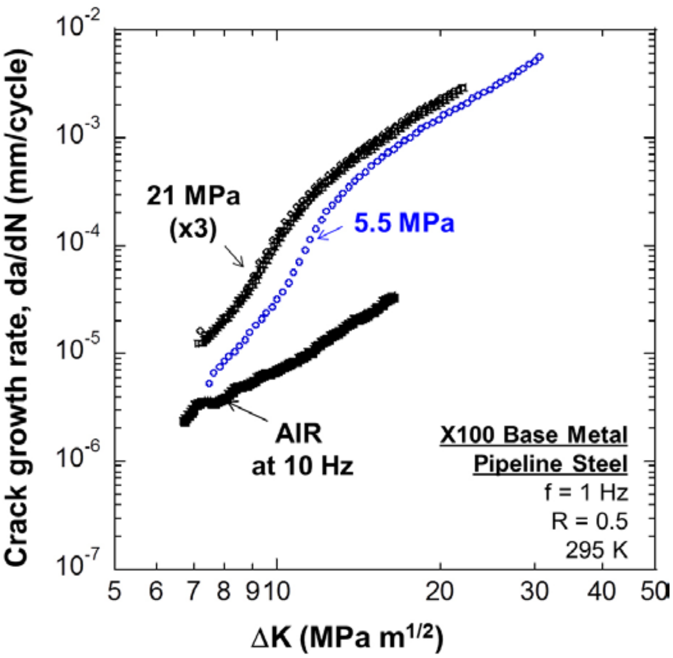

FIGURE 2. Fatigue crack growth curves (da/dN vs. ΔK) for X100A base metal tested at 5.5 MPa and 21 MPa hydrogen gas at R = 0.5 and frequency of 1 Hz

One of the complexities associated with welds and heat affected zones is the possibility of varied microstructure and strength across the weld due to the non-uniform thermal history generated by the welding process. As a result, certain microstructural regions of the weld might be more susceptible to HA-FCG than others. Constant stress intensity factor range tests are planned to assess the possibility that fatigue crack growth rates may be higher for particular locations in the HAZ and weld fusion zone. Constant-ΔK tests serve as a means to survey the microstructure and identify the most susceptible regions of the weld or HAZ. In this test, a crack will propagate through the weld and HAZ at a constant applied ΔK while measurements of crack growth rate are recorded. Microstructural regions identified as having higher crack growth rates will be the focus of subsequent tests to measure the full da/dN vs. ΔK behavior. Initial testing proved to be a challenge as crack extension was impeded or was non-uniform. The cause is likely due to residual stress. Measurements of residual stress are planned to help determine a path forward for constant ΔK testing.

NIST developed a phenomenological model that can predict HA-FCG in pipeline steels as a function of hydrogen pressure and mechanical loading parameters [7]. The model in its published form must be calibrated for each material of interest and does not take into account microstructure [7]. One reason for this shortcoming of the model is a gap in fundamental understanding of the relationship between microstructure constituents and HA-FCG. Development of a physics-based model to describe HA-FCG as a function of microstructure is one of the goals of this project. Current efforts of the model are focused on laying the groundwork for the physics-based implementation of microstructure specific phenomena such as hydrogen transport, plasticity, decohesion laws, and orientation specific mechanical properties at the grain level. The model is in its infant stages but has been shown to accurately predict some experimental results in the literature.

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. Low-carbon steel samples were subjected to non-uniform heating by placing the sample in between two internally cooled copper jaws. Samples were fixed with thermocouples and the sample was heated followed by rapid cooling with the predominant heat transfer in the longitudinal direction. The goal was to generate a microstructure gradient that encompasses microstructures typical of high-

strength steels, welds, and heat affected zones. Compact tension specimens can then be extracted from the Gleeble^{TM} samples and constant ΔK tests can be performed in high pressure hydrogen gas to determine the relationship between microstructure and HA-FCG. Due to heat transfer characteristics of the specimen, the microstructure gradient is expected to exist only in the direction of crack propagation of the specimen. The optimized specimen geometry is shown in Figure 3 along with the peak temperature distribution in the direction of crack propagation as experimentally measured on the surface.

CONCLUSIONS AND FUTURE DIRECTIONS

- Repeatable fatigue crack growth curves were measured for X100A base metal in 21 MPa gas and 5.5 MPa. Results were comparable with lower strength pipeline data, tested previously, exhibiting some pressure dependence.
- (Future) Perform fatigue crack growth testing on X100 weld and heat affected zoned at 21 MPa and compare behavior to lower strength steel welds.
- Developed procedure to generate laboratory-controlled microstructures using Gleeble^{TM}.
- (Future) Fatigue test specimens will be extracted from Gleeble^{TM} samples with imposed microstructure gradients to measure relationship between microstructure and HA-FCG.

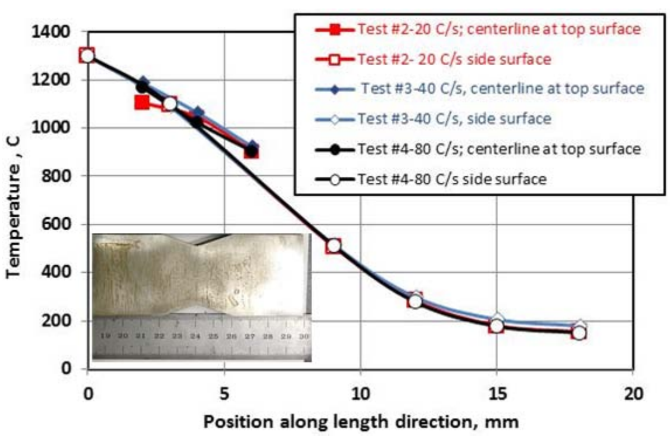

FIGURE 3. Optimized specimen geometry for producing graded microstructure using Gleeble^{TM}, and the temperature profile measured on the specimen as function of distance from center

FY 2016 PUBLICATIONS/PRESENTATIONS

1. J. Ronevich, "Fatigue Performance of High-Strength Pipeline Steels and Their Welds in Hydrogen Gas Service," SAND2016-3003 PE, Hydrogen Delivery Tech Team meeting, Livermore, CA, April 5, 2016.

2. J.A. Ronevich, B.P. Somerday, "Assessing Gaseous Hydrogen Assisted Fatigue Crack Growth Susceptibility of Pipeline Steel Weld Fusion Zones and Heat Affected Zones," Materials Performance and Characterization, *accepted April 2016.*

3. J. Ronevich, B. Somerday, "Accelerated Fatigue Crack Growth in Pipeline Steels and Their Welds in High Pressure Hydrogen Gas," NACE Corrosion conference, Vancouver, Canada, March 9, 2016.

4. J. Ronevich, B. Somerday, "Assessing Steel Pipeline and Weld Susceptibility to Hydrogen Embrittlement," Fuel Cell Technologies Office webinar, January 12, 2016.

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