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SANDIA NATIONAL LABORATORIES
HYDROGEN PRODUCTION AND DELIVERY PROGRAM

QUARTERLY PROGRESS REPORT FOR APRIL 1, 2012–SEPTEMBER 30, 2012

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FY 2012 MILESTONES/DELIVERABLES

Task	Planned	Status
Task 2: Enabling Hydrogen Embrittlement Modeling of Structural Steels		
Subtask 2.1: Measurement of Fracture Properties of Structural Steels in High-Pressure H_2		
Measure the fatigue crack growth (da/dN *vs* ΔK) relationship at constant H_2 gas pressure in X65 pipeline girth weld supplied by industry partner	6/12	50% complete
Subtask 2.2: Effect of Gas Impurities on Fracture Properties in H_2		
Quantify the relationship between H_2 pressure and the threshold level of oxygen impurity concentration required to mitigate hydrogen-accelerated fatigue crack growth of X52 steel.	9/12 This milestone is deferred at the lower funding target.	
Subtask 2.3: 2012 International Hydrogen Conference		
Organize and convene the 2012 International Hydrogen Conference at Jackson Lake Lodge, Grand Teton National Park, WY	9/12	Complete

TASK 2: ENABLING HYDROGEN EMBRITTLEMENT MODELING OF STRUCTURAL STEELS

Principle investigator: Brian Somerday

OBJECTIVE

The principal objective of this project is to provide an experimental component to the development of prognosis models for steel hydrogen gas pipelines. These models include both mechanism-based simulations of hydrogen embrittlement as well as structural integrity analyses to predict safety margins for pipelines. The aim of the experimental effort is to establish physical models of hydrogen embrittlement in steels and to generate material properties that serve as model inputs. The focus of the latter is on fracture mechanics properties such as crack propagation thresholds and fatigue crack growth relationships.

BACKGROUND

Carbon-manganese steels are candidates for the structural materials in hydrogen gas pipelines; however, it is well known that these steels are susceptible to hydrogen embrittlement. While hydrogen embrittlement compromises the structural integrity of steel components, decades of research and industrial experience have allowed many salient variables that affect hydrogen embrittlement of steels to be identified. As a result, established paths exist to manage hydrogen embrittlement in steels and to quantify safety margins for steel hydrogen containment structures. For example, fatigue crack growth aided by hydrogen embrittlement is a potential failure mode for steel hydrogen containment structures subjected to pressure cycling. Applying appropriate structural integrity models coupled with measuring relevant material properties in hydrogen gas allows quantification of safety margins against fatigue crack growth in hydrogen containment structures.

PROJECT STATUS

The fatigue crack growth rate (da/dN) vs stress-intensity factor range (ΔK) relationship is a necessary material-property input into damage-tolerant life prediction models applied to steel hydrogen pipelines. One such life prediction methodology for steel hydrogen pipelines was recently published in the ASME B31.12 code. The measurements of crack propagation thresholds and fatigue crack growth relationships in this task support the objective of establishing the reliability/integrity of steel hydrogen pipelines.

The X65 line pipe steel was selected for this task because of its recognized technological relevance for hydrogen pipelines. Generally, lower-strength steels such as X52 and X65 are selected for hydrogen pipelines since these steels are less susceptible to hydrogen embrittlement. A section of X65 steel pipe containing a girth weld was provided by an industry partner (Figure 1). The emphasis in FY2012 Q4 was to measure the da/dN vs ΔK relationship for the weld fusion zone and heat-affected zone in 3000 psi (21 MPa) hydrogen gas. An optical-microscope image revealing the weld fusion zone and heat-affected zone is shown in Figure 2.

The hydrogen-affected fatigue crack growth relationship (da/dN vs ΔK) for the structural steel is the basic element in pipeline life-prediction models. The ASME B31.12 code requires measurement of the fatigue crack growth relationship for pipeline steels at the hydrogen gas operating pressure. Since the maximum pressure specified for hydrogen gas pipelines in the ASME B31.12 code is 3000 psi (21 MPa), this upper-bound pressure was selected for the testing. As specified in ASME B31.12, the da/dN vs ΔK relationship was measured following ASTM Standard E647. Compact-tension crack-growth specimens were extracted from both the fusion zone and heat-affected zone such that the loading and crack propagation directions were in the longitudinal and circumferential orientations, respectively, relative to the pipe. In this way, the crack plane was fully contained in either the fusion zone or heat-affected zone for the entire range of crack growth during the tests. The load-cycle frequency selected for the testing was 1 Hz, consistent with previous testing on X52 line pipe steel in high-pressure hydrogen gas.

Figure 1. X65 steel girth weld supplied by industry partner.

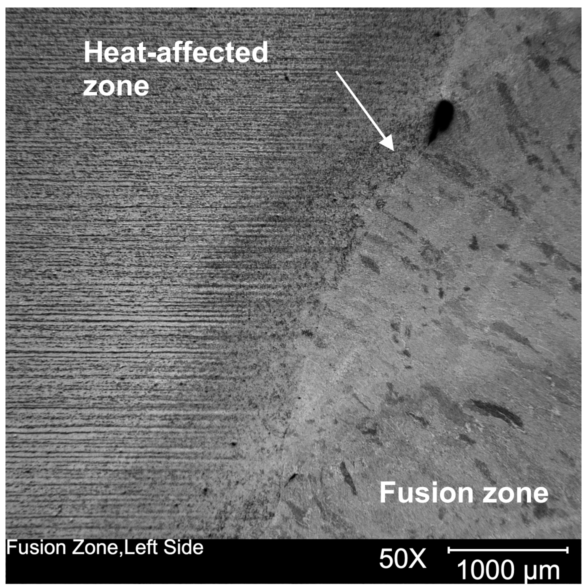

Figure 2. Optical-microscope image showing fusion zone and heat-affected zone of X65 weld.

The measurement of da/dN vs ΔK for the fusion zone was completed, and the result is shown in Figure 3. Included in Figure 3 are measurements for X52 base metal in 3000 psi (21 MPa) hydrogen gas and X52 base metal in air that were previously reported in this project. Figure 3 shows that the da/dN vs ΔK relationship for the weld exhibits several typical characteristics for pipeline steels in hydrogen gas, i.e., transition points in the da/dN vs ΔK relationship and accelerated crack growth rates above those in air. Notably, the onset of accelerated cracking for the X65 weld is at higher ΔK levels compared to the X52 base metal. However, as ΔK increases, the relationships converge so that the crack growth rates are similar. This behavior is somewhat unexpected, since welds are thought to be more susceptible to hydrogen-assisted crack growth.

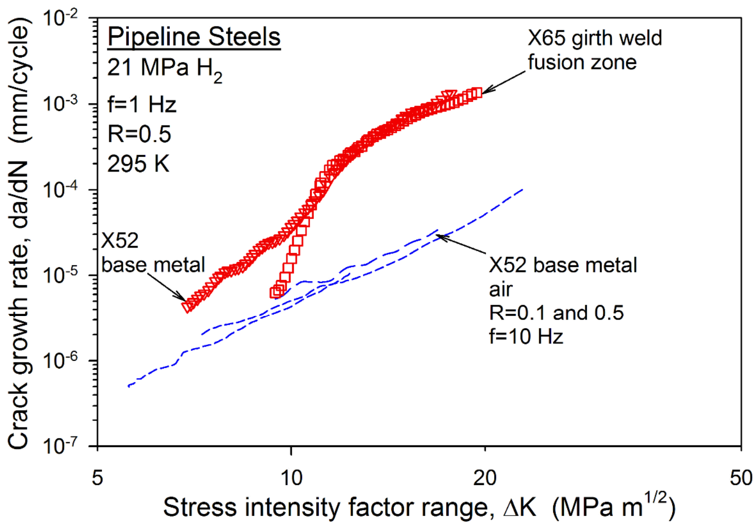

Figure 3. Fatigue crack growth relationship (da/dN vs ΔK) for X65 weld fusion zone in 3000 psi (21 MPa) hydrogen gas. The result is compared to measurements for X52 base metal in hydrogen gas and X52 base metal in air.

Testing on the heat-affected zone is in progress. The schedule was delayed by maintenance issues with the laboratory equipment and also difficulties with testing the weld specimens. Regarding the latter issue, initial attempts to test the fusion zone revealed that crack growth rates were exceedingly low and there was significant noise in the crack-length measurement. Although this issue required an extended time to resolve, it was ultimately determined that both the low crack growth rates and crack-length noise resulted from "crack closure," i.e., premature contact of the crack faces during cyclic loading. The crack closure effect was circumvented by increasing the load ratio (ratio of minimum load to maximum load, R) to 0.5. After making this adjustment, the test was executed without any difficulties, leading to the result shown in Figure 3. These modified test procedures (i.e., higher R ratio) are being applied to the test on the heat-affected zone as well. The reason for the pronounced crack closure for the welds was not determined, but one possibility is high levels of residual stress in the welds.

PLANS FOR NEXT QUARTER AND KEY ISSUES

The primary objective for FY2013 Q1 is to complete fatigue crack growth testing on the X65 girth weld heat-affected zone in hydrogen gas.

PUBLICATIONS / PRESENTATIONS

None in FY2012 Q4

REFERENCES

1. C. San Marchi and B.P. Somerday, *Technical Reference on Hydrogen Compatibility of Materials*, SAND2008-1163, Sandia National Laboratories, Livermore, CA, 2008.