SAND2022-16360C

Effects of Gaseous Hydrogen on Fatigue Lives of Natural Gas Pipeline Material

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Sandia National Laboratories, Livermore, CA, USA

AMPP's Annual Conference,
Denver CO
March 19-23, 2023

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Abstract

The effects of hydrogen on embrittlement of natural gas infrastructure is receiving considerable attention as concepts for injecting hydrogen into natural gas transmission and distribution systems gain momentum as a preliminary step toward decarbonization of the energy sector. In this study, we investigate the effect of gaseous hydrogen environment on the fatigue life of commercial black pipe steel used in natural gas distribution networks. Stress-fatigue life curves were developed using circumferential notched tensile specimens ($K_t \sim 4$, $R = 0.1$) in both air and in gaseous hydrogen at a pressure of 210 bar. In general, stress versus fatigue life data generated in gaseous hydrogen exhibit decreased fatigue life. However, hydrogen-assisted fatigue depends on the driving force: at low values of applied (nominal) stresses, the stress-life curves in air and in hydrogen tend to converge, whereas at higher applied stresses, fatigue life in hydrogen decreased by a factor of three. Additionally, gaseous hydrogen had a minimal effect on the number of cycles to crack initiation, while a significant effect was observed on the crack propagation life. For identical number of cycles after crack initiation, the increment in crack size was observed to be significantly larger for the test conducted in hydrogen.

Keywords: Hydrogen embrittlement, Distribution pipeline, Fatigue, Black pipe

1. Introduction

Hydrogen is a convenient medium to store energy and can reduce the need for carbon-based fuels. [1]. One of the applications that is being considered is to inject gaseous hydrogen into natural gas and distribute the blend via natural gas distribution network. However, studies have shown that the mechanical properties of metallic materials including pipeline steels tend to degrade in the presence of even a small amount of gaseous hydrogen [2, 3].

The presence of gaseous hydrogen (GH2) has also been observed to have a detrimental effect, typically at higher values of applied stresses, on the fatigue life of various steels. Matsunaga et al. [4] studied the effect of GH2 on the fatigue lives of two different types of steels, JIS-SCM435, a Cr-Mo steel and JIS-SM490B, a carbon steel. In both of the steels, the reduction in the fatigue lives in the presence of 1150 bar GH2 was observed primarily at the higher values of applied stresses, while the fatigue lives were not affected at the lower values of applied stresses. In addition, Ogawa et al. [5] showed that crack initiation behavior, crack growth rate, and fracture toughness of JIS-SM490B steel were similar to those observed in air at a lower gas pressure of 7 bar, while they significantly degrade in the presence of 1150 bar GH2.

Studies investigating the effect of gaseous hydrogen on the fatigue life behavior of various steels in absence of a crack, especially for pipeline steels, are limited in the literature. The extent of the detrimental effect of hydrogen on the structural integrity of material depends on the applied loading conditions and hydrogen pressure, which ultimately affects the fatigue life, crack growth rate and fracture resistance of the material. Most studies have shown that GH2 has a minimal effect on fatigue lives and crack growth rates at low stresses and small stress intensity factors, respectively [6-8]. Therefore, a thorough understanding of how hydrogen affects the fatigue behavior of pipeline materials is needed to develop technical basis for safe hydrogen injection into existing natural gas infrastructure.

2. Materials and Experimental Methods

Black pipe is commonly used in a variety of relatively low-pressure applications, including distribution systems for natural gas. For the purpose of this study, black pipe was acquired from a commercial hardware supplier, specifically ASTM A53 grade A, type F, Nominal Pipe Size (NPS) 6, Schedule 40. The nominal dimensions of this pipe are 168 mm outside diameter and 7 mm wall thickness. Black pipe is a low-strength carbon steel with a ferrite-pearlite microstructure, whose tensile strength and yield strength was calculated to be 495 MPa and 390 MPa, respectively. The requirements of black pipe, including composition and standard pipe dimensions are given in [9].

Circumferentially notched tension (CNT) specimens extracted in the longitudinal orientation were used to evaluate fatigue life behavior in air and in GH2. The CNT specimens had a net section nominal diameter of 4 mm with an elastic stress concentration factor (K_t) of approximately 4. The specimen geometry is shown in Fig. 1.

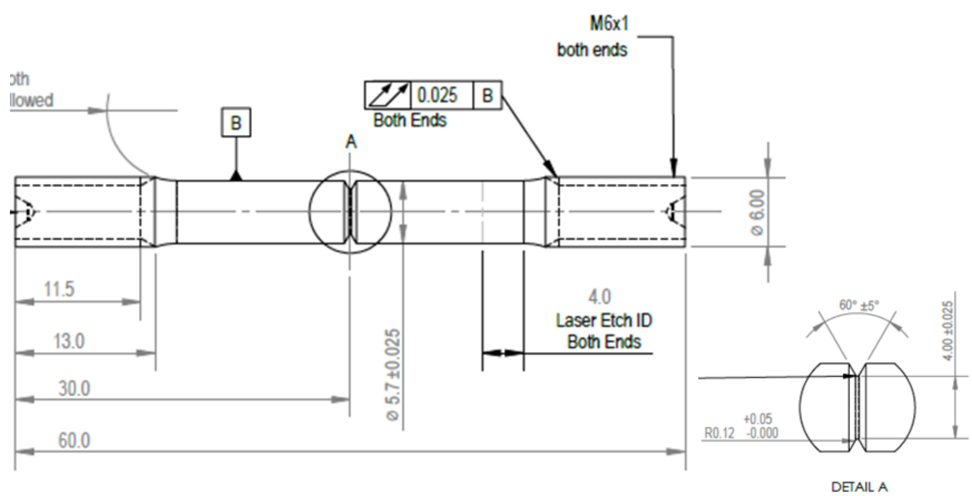

Figure 1. Specimen geometry for circumferentially notched tensile (CNT) specimens. All dimensions are in mm.

Fatigue life tests were conducted either in air or in pure (99.9999%) GH2 at pressure of 210 bar. To execute gaseous hydrogen tests, a custom-designed pressure vessel rated up to 1380 bar is incorporated into a standard hydraulic test frame with internal load and displacement transducers, as well as signal feed-throughs for direct current potential difference (DCPD) measurements. A detailed description of testing methodologies and capabilities is documented in [10]. The test chamber was first purged with nitrogen three times followed by an additional three purges with pure GH2 to eliminate the potential effects of impurities, such as oxygen and moisture. Gas analysis conducted at the end of one test revealed an oxygen concentration of 0.58 ppm and water content of 18 ppm, both by volume.

The fatigue tests were conducted in constant load amplitude in the tension-tension configuration with a load ratio of 0.1 and frequency of 1 Hz. For the purposes of this testing, the stress is characterized by the maximum applied net section stress (maximum applied load divided by the cross sectional area at the notch root). The loading conditions were selected to be nominally equivalent to 50, 60, 65, and 70% of the measured tensile strength (495 MPa).

Under fatigue loading condition, the total life of a specimen can be divided into crack initiation and propagation. The onset of crack initiation can be estimated using the DCPD method outlined in Ref. [11] and was used in the current study to better understand the effect of GH2 on the crack initiation behavior of black pipe material. An example of the DCPD data in terms of arbitrary unit (a.u), obtained from a test conducted in air at σ_{max} = 300 MPa is shown in Fig. 2. The number of cycles to crack initiation, N_i is taken as the point where the curve deviates from a linear trend and the difference between the total number of cycles to failure and cycles to crack initiation was taken as the crack propagation life.

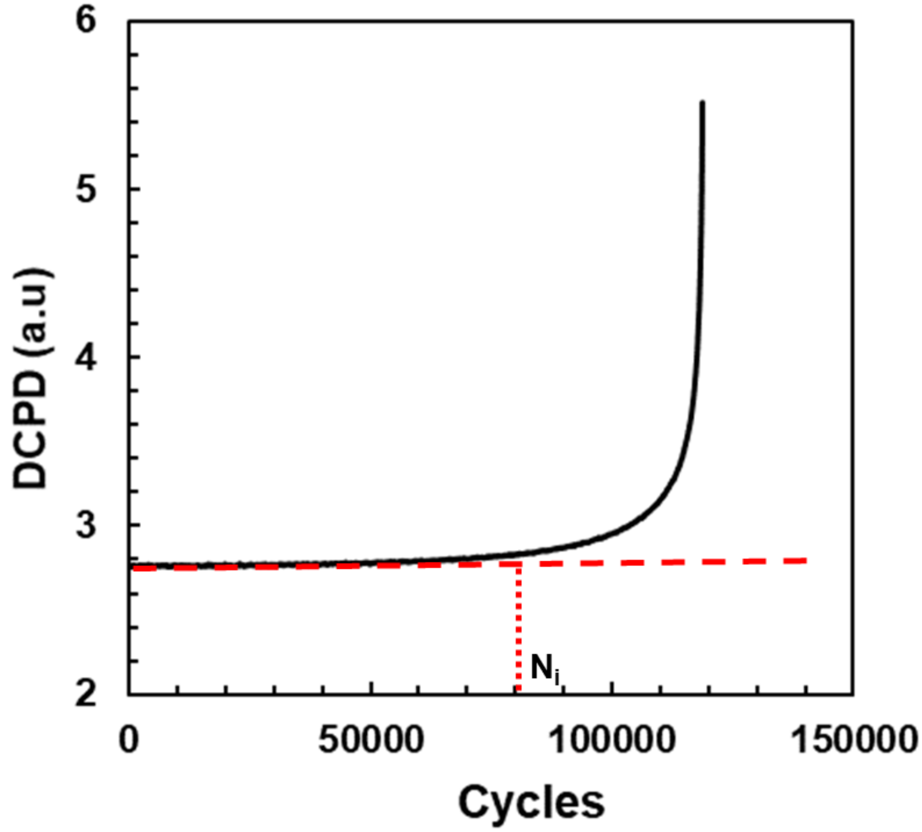

Figure 2. Direct current potential difference (DCPD) data versus number of cycles obtained from test conducted at σ_{max} = 300 MPa in air and illustrating the onset of crack initiation, which is represented by N_i.

3. Experimental Results

3.1. Fatigue life

Figure 3 shows the maximum net section stress, $\sigma_{max,}$ versus cycles to failure, N_f, obtained for the black pipe material in air and in GH2 at pressure of 210 bar. The curves in this plot represent power-law fits to the data in air and in GH2, respectively. The detrimental effect of GH2 depends on the applied maximum net section stress . At low stress (≤250 MPa), the fatigue life in the two environments appears to converge. At higher stresses, the stress-life curves diverge, demonstrating greater effects of hydrogen at higher values of maximum net section stress.

One of the aspects that governs hydrogen embrittlement in materials is the driving force, which dictates crack initiation and propagation behavior. Many studies have shown that with a lower driving force, such as low stress intensity factors or applied stresses, the detrimental effect of GH2 on both fatigue crack growth rate and fatigue lives is minimal [6-8]. Hence, with careful design consideration, black pipe material may be used in low pressure GH2 distribution systems.

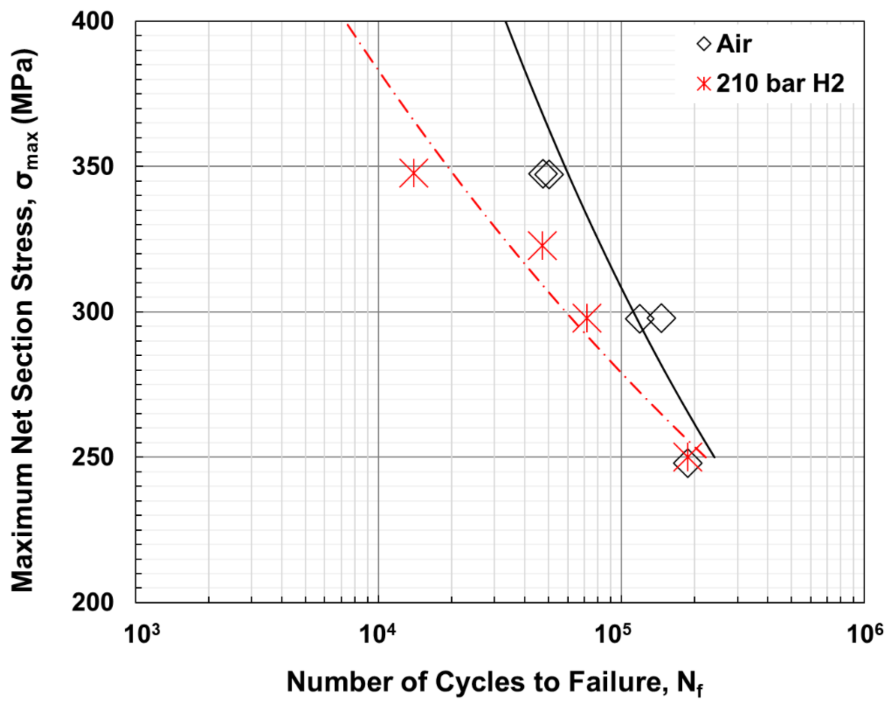

Figure 3. Stress life (S-N) data and curve for black pipe material in air and in GH2 at pressure of 210 bar tested at R = 0.1 and a frequency of 1 Hz.

3.2. Crack initiation

Figure 4 shows the estimated number of cycles for crack initiation versus maximum net section stress for tests conducted in air and in GH2. Crack initiation occurred after similar numbers of cycles in both environments at low stress (≤ 300 MPa). Interestingly, at the lowest applied stress, hydrogen appears to have delayed crack initiation. At the lowest applied stress, plasticity near the notch root is lower and crack initiation appears to require more fatigue cycles in GH2. This suggests that when stresses are sufficiently low, air environments are more conducive to crack initiation than GH2, due to presence of moisture and oxygen in air. Of course, the data are limited in this stress regime and the small differences in initiation life at maximum net section stress of ~250 MPa may reflect uncertainty in the measurement. Nonetheless, the presence of GH2 may have a negligible effect on the crack initiation behavior of black pipe material at low stresses.

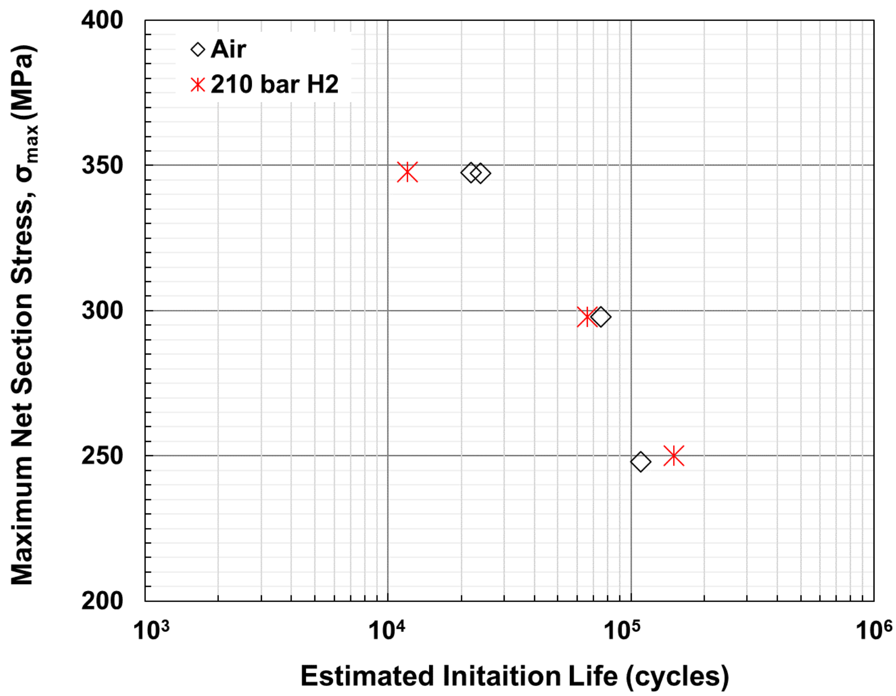

Figure 4: Maximum net section stress versus estimated initiation life for black pipe material in air and in 210 bar GH2.

At maximum net section stress of about 70% of the measured tensile strength (~350 MPa), hydrogen appears to have initiated cracking earlier in the cycle history than in air. The local stress near the notch root is certainly much higher than the net section stress and for this particular loading condition exceeds the yield strength of the material, resulting in large plastic deformation. Therefore, the synergistic effect of plasticity and hydrogen environment may lead to an earlier crack initiation for tests conducted in GH2. Even for the lower net section stress, the local stress should exceed the yield strength, which also suggests that substantial plasticity is necessary for hydrogen-induced crack initiation in black pipe material.

One of the tests was interrupted at 115,227 cycles once the DCPD reading had deviated upwards in a recognizable amount to ensure that the upward deviation of DCPD data resembles the onset of crack initiation. The specimen was heat tinted to mark the crack front at 115,227 cycles, which is shown in Fig. 5. It is clear from the fracture surface that after 115,227 cycles, the crack had propagated a notable amount. For this particular test, based on the DCPD data and following the procedure shown in Fig. 2, the crack was estimated to initiate at ~75,000 cycles.

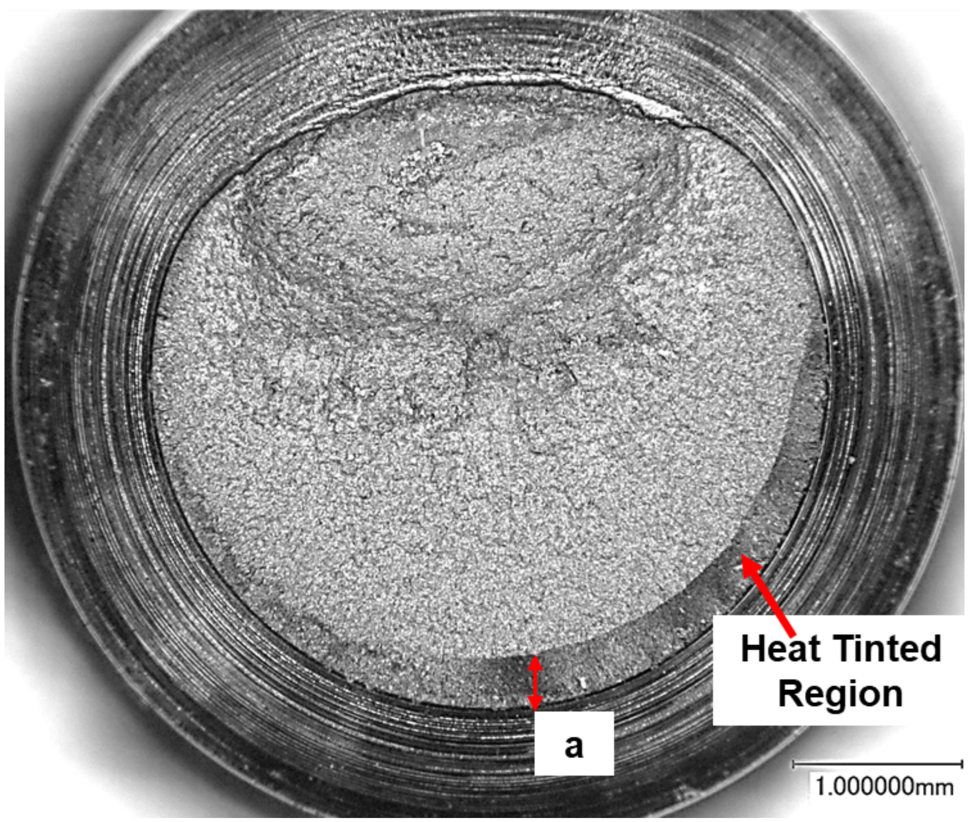

Figure 5: Fracture surface of a CNT specimen subjected to an interrupted test at σ_{max} = 300 MPa in air and heat tinted to mark the crack front at 115,227 cycles. Specimen failed at 145,515 cycles.

3.3. Crack propagation

In the case of black pipe material, at lower maximum net section stresses (~250 MPa), fatigue cycles required to initiate a crack is not significantly affected by the presence of GH2 (Fig. 4). Whereas, at 300 and 350 MPa net section stresses, the detrimental effect of GH2 on the total fatigue life was significant (Fig. 3). The total fatigue life can be differentiated into crack initiation and crack growth steps, as shown in Fig. 6. In GH2, the propagation portion of the fatigue life is much smaller (<20%), implying faster fatigue crack growth rates in GH2 than in air. In air, the propagation portion of fatigue was close to 50% of the total life. Conventional fatigue crack growth rate testing indeed corroborate that cracks propagate faster (by a factor of 10 or more) in GH2 than in air [12-14].

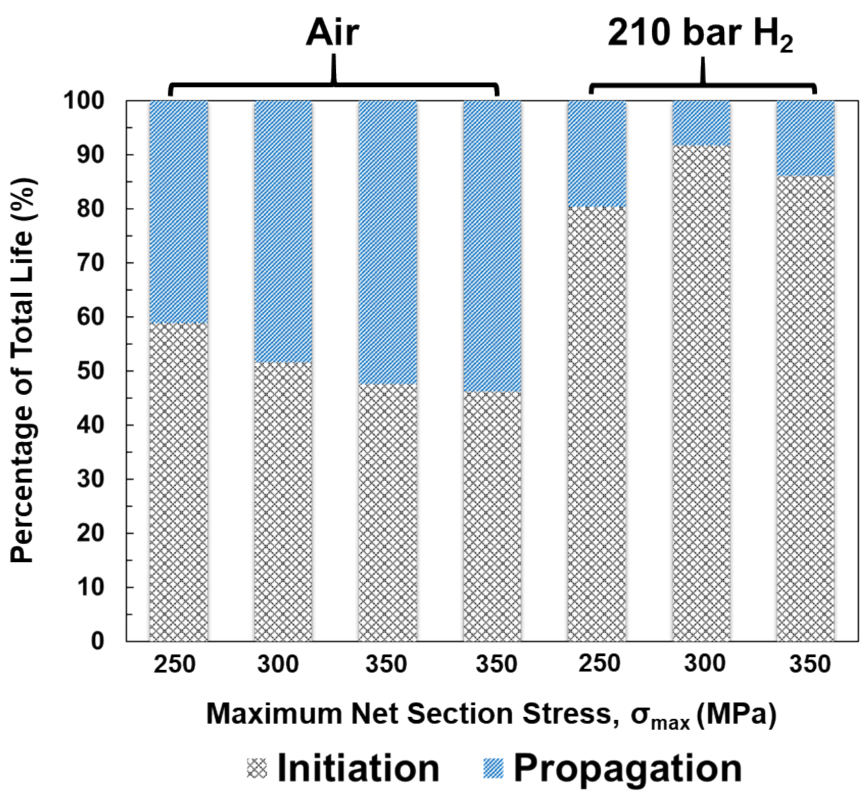

Figure 6: Bar chart showing ratio of crack initiation and crack propagation to total fatigue life at different maximum net section stress for black pipe material in air and in 210 bar GH2

DCPD data was further converted into crack length using the Johnson's equation given as [11]:

$$\frac{a}{W} = \frac{2}{\pi} cos^{-1}\left[\frac{\cosh\left(\frac{\pi y}{2W}\right)}{cosh\left\{\frac{V}{V_o} cosh^{-1}\left[\frac{cosh\left(\frac{\pi y}{2W}\right)}{cos\left(\frac{\pi a_o}{2W}\right)}\right]\right\}}\right] \quad (1)$$

where, a is the instantaneous crack length, W is taken as the net-section nominal diameter, y is half the distance between the DCPD leads, a_o is the initial crack length, V is the instantaneous voltage reading, and V_o is the voltage reading corresponding to N_i (i.e. estimated fatigue cycle for crack initiation). Crack length calculated using Eqn. 1. was also corrected based on the final crack length determined using image analysis of the fracture surface. Detailed procedures for calculating and correcting the crack length based on the Johnson's equation is provided in ASTM E1820 [11]. The crack length estimated using Eqn. 1 was also validated using optical microscopy from an interrupted CNT test shown in Fig. 5. The value of 'a' was determined to be 0.307 mm using image analysis and 0.328 mm using Eqn. 1.

Crack length determined using Eqn. 1 is plotted against the crack propagation life in Fig. 7 for specimens subjected to σ_{max} = 300 MPa in air and in 210 bar GH2. Crack propagation life is calculated by subtracting crack initiation life from the total fatigue life. In the case of tests conducted in air, the crack tends to grow in smaller increments between 10 and 10,000 cycles and a rapid growth of crack is evident only after ~ 40,000 cycles after initiation of the crack. On the other hand, for the test conducted in 210 bar hydrogen, the crack tends to grow in larger increments just after 100 cycles of crack initiation. Hence, Fig.7 also indicates that the crack in black pipe material grows faster in GH2 environment once the crack initiates.

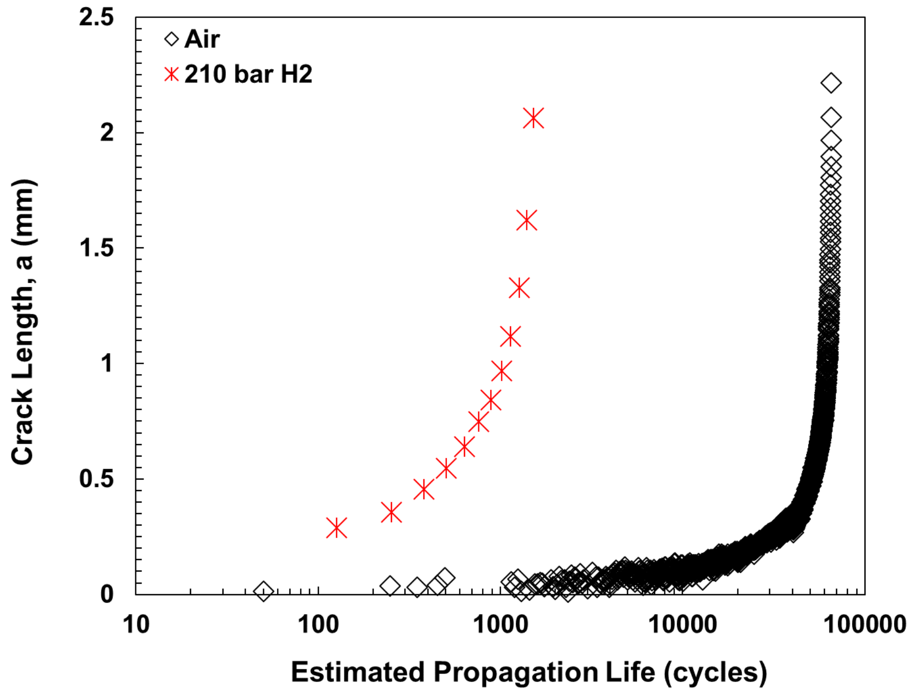

Figure 7: Crack length versus crack propagation life for black pipe specimens subjected to σ_{max} = 300 MPa in air and in 210 bar GH2.

4. Conclusions

In the current study, the effect of gaseous hydrogen on total fatigue life, cycles to crack initiation, and crack propagation of ASTM A53 Grade A black pipe material was investigated. Furthermore, using DCPD data, crack growth behavior of black pipe material was also evaluated in the presence of gaseous hydrogen at the pressure of 210 bar. The conclusions drawn are as follows:

1. Degradation in the fatigue lives of black pipe material in hydrogen environment was evident from the S-N type fatigue life analysis. Hydrogen has a more detrimental effect at higher stresses. Cycles to failure were similar in air and hydrogen at stresses of 50% of UTS. At higher stresses, the cycles to failure were reduced by as much as three times in hydrogen.
2. The effect of 210 bar gaseous hydrogen on the initiation of fatigue cracks in black pipe material is also affected by applied stress. At higher stresses, cracks in black pipe material initiated at lower number of fatigue cycles for tests conducted in hydrogen, while at lower stresses, cracks initiated slightly faster for tests in air.
3. For tests in GH2, most of the fatigue life (>80%) was spent in crack initiation step, whereas in air, approximately 50% of the life was spent in crack initiation step.
4. At identical stress and number of cycles after crack initiation, the increment in the size of the fatigue crack was larger for the test conducted in hydrogen compared to that in air, indicating a significant increase in crack growth rate in hydrogen environment.
5. Curiously, data from the current study suggests that higher crack growth rate, combined with similar fatigue life at low stress, implies more resistance to crack initiation in GH2 than in air, corroborating the observation that more cycles are required to initiate a crack in GH2 at low stress (Figure 3). This result may reflect the importance of oxygen and moisture on crack initiation at low stresses and the need for substantial plasticity (high stress) to activate hydrogen-induced crack initiation.

Acknowledgements:

Sandia National Laboratories is a multimission laboratory managed and operated by National Technology and Engineering Solutions of Sandia, LLC., a wholly owned subsidiary of Honeywell International, Inc., for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-NA-0003525. This work is supported by the U.S. Department of Energy, through the Office of Energy Efficiency and Renewable Energy's (EERE) Hydrogen and Fuel Cell Technologies Office (HFTO). This paper describes objective technical results and analysis. Any subjective views or opinions that might be expressed in the paper do not necessarily represent the views of the U.S. Department of Energy or the United States Government.

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