FATIGUE CRACK GROWTH RATES OF API X70 PIPELINE STEELS IN PRESSURIZED HYDROGEN GAS COMPARED WITH AN X52 PIPELINE IN HYDROGEN SERVICE*

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ABSTRACT

The current ASME B31.12 code used to guide the design of hydrogen pipelines favors the use of API 5L X52, but is being modified to include higher strength steels, such as X70 to enable cost reductions without affecting safety. To provide a scientific basis for code modification, fatigue crack growth (FCG) tests were conducted on an X52 pipeline steel that is currently in service transporting hydrogen gas, as well as two X70 pipeline steels designed for natural gas. Compact tension specimens were tested in hydrogen gas pressurized to 5.5 MPa or 34 MPa. A comparison of these tests, conducted at a cyclic loading frequency of 1 Hz, shows that there is very little difference between the FCG rates of the base metal among the three steels at a given hydrogen pressure. All three metals exhibited some increase in FCG rate at a hydrogen pressure of 34 MPa compared with 5.5 MPa. Analysis of the data provide a rationale for allowing higher strength steels to be used for hydrogen gas transport. A recommendation was made to the ASME B31.12 Committee on Hydrogen Piping and Pipelines to allow higher-strength steels that is based on this and other data acquired at hydrogen pressures ≤ 21 MPa.

INTRODUCTION

Two federal agencies are tasked with ensuring that present and future hydrogen pipelines are safe and efficient. According to the US Department of Energy (DOE) [1], there are approximately 1500 miles of steel pipelines for the transportation of hydrogen gas in service today. That number is likely to increase, particularly if hydrogen fuel-cell cars become a popular alternative to gasoline-powered cars. Pipelines will be a necessary component to enable market penetration beyond the coastal US. The DOE has set a goal to reduce the cost of hydrogen delivery by the year 2020 from the production site to the point of use in consumer vehicles to <$2/gge (gallon of gasoline equivalent) for at least one delivery pathway [2]. This will help pave the way toward making hydrogen a competitive choice for powering cars and heating homes. Meanwhile, the mission of the Department of Transportation, Pipeline and Hazardous Materials Safety Administration (DOT/PHMSA) is to maintain the safety of pipelines transporting fuels in the US.

Both agencies are working to develop the transmission infrastructure needed to support hydrogen fuel cell vehicles. Pipelines are the most cost-effective means of transporting hydrogen gas, but to attain the DOE goal for delivery cost, the expense of laying new pipelines must be further reduced. This can be achieved with higher strength steel. Fekete *et al*. [3] have described the savings generated by the use of steel with the grade API 5L X70 instead of API X52 for hydrogen pipelines. However, these savings can only be realized if the proposed material is as safe for operations as X52.

At the present time, the code used to design hydrogen pipelines is ASME B31.12 Hydrogen Piping and Pipelines [4]. This code states that API 5L X52 (PSL 2) grade steel can be used for hydrogen pipelines without additional testing. If a stronger grade of steel is desired, fracture toughness tests in pressurized hydrogen gas must be conducted. As few facilities have the capability of testing in pressurized hydrogen gas, X52 is virtually the only grade used in the US. This grade became the default choice in the code, because it exhibits minimal loss in ductility under monotonic loading in hydrogen gas.

However, it is rare for a pipeline to fail because it has exceeded its ultimate tensile strength, where the loss of ductility becomes critical. Safety factors ensure that stresses remain well below the yield strength of the steel. Rather, steel pipelines fail because fatigue cracks initiated by damage or flaws eventually propagate through the wall thickness of the pipe. If fatigue is the failure mechanism of concern, then limiting the choice of steels to X52 may not be the most effective means of designing safely operating hydrogen pipelines. For example, Cialone and Holbrook [5] found that for X42 pipeline steel there the fatigue crack growth rate (FCGR) increased by an order of magnitude for tests conducted in pressurized hydrogen and nitrogen. Other research groups have also found the FCGR of pipeline steels to increase by an order of magnitude or more when tested in pressurized hydrogen gas, as compared with those tested in air or an inert environment [6-8]. However, more data are needed to characterize the effect of strength on fatigue lifetimes in hydrogen.

In order to provide the ASME B31.12 Committee on Hydrogen Piping and Pipelines with a body of data from which to base a modification to the code, FCGR tests have been conducted that compare X52 steel from a currently operational hydrogen pipeline that was designed to the current B31.12 code, and two X70 steels from natural gas pipelines. Compact tension (CT) specimens were cyclically loaded in air and in hydrogen gas pressurized to either 5.5 MPa, a typical pressure at which to operate a hydrogen pipeline, or 34 MPa, the highest pressure currently considered.

MATERIALS AND METHODS

The base metals from two X70 pipeline steels that were designed for natural gas transmission and the modern X52 steel that is currently used in a hydrogen pipeline that went into operation in 2011 were tested to compare their FCGRs in pressurized hydrogen gas. The tests were conducted at a cyclic loading frequency of 1 Hz. Other researchers have found that in general there is an inverse relationship between the cyclic loading frequency and the hydrogen-assisted fatigue crack growth rate (HA-FCGR) for most structural alloys, particularly for frequencies at or above 1 Hz [9-13]. A limited number of tests were conducted at 0.1 Hz in order to determine the relationship between the FCGR for these steels and the loading frequency.

The chemical compositions of the three low-carbon, micro-alloyed steels are found in Table 1. The microstructures from near the mid-line of each steel are shown in Figure 1, and from optical microscopy were determined to be polygonal and acicular ferrite. There may be other constituents that are not resolvable without employing more advanced analytical techniques. Tensile data was acquired for each steel in air and in the transverse orientation, according to ASTM E8 [14]. The mean of those data and the dimensions of the pipes from which they came are shown in Table 2. Note that the X52 has a far higher yield strength than might be expected for an X52, although it meets the specification for API 5L X52 PSL 2, which has a minimum yield strength of 359 MPa (52 ksi) and a maximum yield strength of 531 MPa (77 ksi) [15].

The fatigue tests were conducted in accordance with ASTM E647 [16] and with a constant load ratio (R=0.5). The data generated are (increasing) stress intensity range (ΔK) and fatigue crack growth rate (da/dN); the tests were conducted in load control and regulated by the load cell located within the chamber, and the crack length was calculated from compliance, as provided by a CMOD (crack mouth opening displacement) gage located at the load line of the specimen. An internal load cell was used because it can more accurately represent the forces on the specimen(s), as the frictional forces of the seals are eliminated. The signal drift of the internal load cell in hydrogen gas up to 34 MPa results in a change in load ration of less than 2 %. In order to obtain sufficient data in a span of two years, a new apparatus was employed that permits the cyclic loading of ten specimens simultaneously within a test chamber [17]. The CT specimens were machined from the C-L orientation (see Figure 1c of ASTM E399 [18]) with a width W= 44.5 mm, a chevron notch to facilitate growth of a straight precrack, and the surface roughness Ra≤0.25 μm. The precrack was grown in air at a load ratio of R=0.1. The test chamber was purged three times with 99.9999 % helium and three times with 99.9995 % hydrogen before a final fill with the hydrogen and commencing the fatigue tests. The tests continued 24 hours/day, 7 days/week until all specimens were completed. The chamber pressure was continuously monitored and automatically maintained to ±3 % of the designated pressure.

Table 1. Chemical composition in mass percent of the steels tested. The balance is Fe.

Element	C	Mn	P	S	Si	Cu
X52	0.071	1.06	0.012	0.004	0.24	0.016
X70A	0.048	1.43	0.009	0.001	0.17	0.220
X70B	0.053	1.53	0.01	0.001	0.16	0.250

	Ni	Cr	Mo	V	Nb	Ti	Al
X52	0.016	0.033	0.003	0.004	0.026	0.038	0.017
X70A	0.14	0.240	0.005	0.004	0.054	0.027	0.015
X70B	0.14	0.230	0.003	0.004	0.054	0.024	0.012

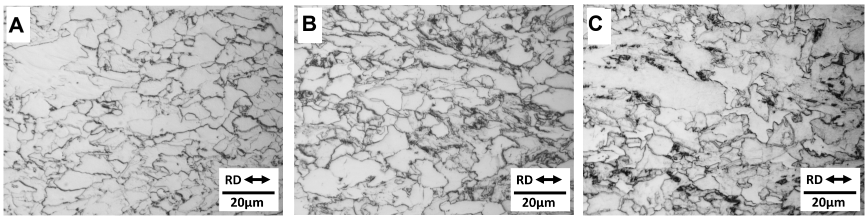

Figure 1. The microstructure from near the mid-line of the pipe through thickness for the (A) X52, (B) X70A, and (C) X70B steels.

Table 2. The tensile properties and the pipe dimensions for each of the steels reported.

Material	σ_y [MPa ± std. dev.]	σ_{UTS} [MPa ± std. dev.]	Pipe diameter [mm (in)]	Wall thickness [mm]
X52	487 ± 5	588 ± 5	508 (20)	10.6
X70A	509 ± 19	609 ± 4	914 (36)	18
X70B	553 ± 18	640 ± 9	914 (36)	22

RESULTS

The purpose of this study was to determine whether X70 can safely be used to construct pipelines for hydrogen gas transmission. Variability of the measurement on these steels in air can be found in Drexler *et al.* [17]. It is not possible to report on the variability of the measurement at any hydrogen condition because there is not sufficient data over the requisite range to allow calculations to be performed according to McKeighan et al. [19]. Uncertainty of the measurement would be expected to be much smaller than the variability, so calculating the uncertainty would not provide meaningful information.

The data at a cyclic loading frequency of 1 Hz are shown in Figure 3, and each dataset (line style) represents one to four individual specimens tested. In Figure 3A, it can be seen that for the specimens tested in hydrogen pressurized to 5.5 MPa, there is little difference between the FCGRs of steels designated as X52 and those designated as X70. The FCGRs of the steels in air (shown for comparison) are lower than those tested in hydrogen gas by as much as 20 times for the range of data tested. In pressurized hydrogen gas, subtle differences in the relative FCGR among the steels exist between low values of ΔK (<11 $MPa\cdot m^{1/2}$) and those at higher values (>15 $MPa\cdot m^{1/2}$). These differences are negligible when compared with the overall effect of hydrogen-assisted fatigue on the FCGR of pipeline steels.

At a hydrogen pressure of 34 MPa (Figure 3B), there is an even greater difference between the air and hydrogen data—as much as 50 times higher for the hydrogen data at a given value of ΔK. As seen in the figure, the three tests conducted in hydrogen gas on the X52 steel are visibly different. They were conducted simultaneously with the new apparatus, so the differences are not from variations in test conditions from one test to another. Furthermore, these specimens originated from a single piece of material that was removed from the pipe, and were from a similar clock position. Rather, this variability appears to be attributable to the way hydrogen interacts with microstructural features.

The data for both hydrogen pressures are shown on the same graph (Figure 4) to emphasize the effect of hydrogen test pressure on the FCGR of these steels.

The fatigue crack grew rapidly in the higher hydrogen pressure, resulting in little data acquisition at low ΔK. Nevertheless, it is apparent that at low values of ΔK (<15 MPa·m$^{1/2}$), the FCGRs of tests conducted at 34 MPa are higher than those conducted at 5.5 MPa. Above ΔK=20 MPa·m$^{1/2}$, however, the data coalesce.

The remaining variable, cyclic loading frequency, is illustrated in Figure 5 for tests conducted at a hydrogen gas pressure of 5.5 MPa. From this graphical representation of the data, it is difficult to determine if frequency has a consistent effect on the FCGR. To clarify the effect of frequency on FCGR, data were analyzed for all materials and hydrogen gas pressures at one value of ΔK. A value of 14 MPa·m$^{1/2}$ was chosen because it was the value for which the most data was available. Bar graphs showing the average value of d*a*/d*N* for all the data available for that condition are shown in Figure 6. This snapshot of these limited conditions reveals that the slower cyclic loading frequency leads to slight increases in the FCGR for all conditions, except for the X52 steel when tested at a hydrogen gas pressure of 5.5 MPa (black bars). The hydrogen gas pressure (gray bars represent data acquired at a hydrogen gas pressure of 34 MPa) has a far larger effect on the FCGR than does the cyclic loading rate.

DISCUSSION

It is important to quantify the differences in the hydrogen-assisted fatigue crack growth rate (HA-FCGR) in X52 and X70 steels for two reasons. The first, as stated earlier, is that pipelines are expected to provide the means by which hydrogen fuel is transmitted between where it is produced and the end user. To accomplish this at a competitive cost, pipelines will have to be constructed of higher grade steel, so that less material can be used while still providing comparable margins of safety. Less steel lowers the cost. The impetus for the second reason can be found in the tensile data provided in Table 2. The owners of the hydrogen pipeline that provided our X52 steel, wanted and thought they were getting X52-strength steel. Instead they received material with an average yield strength closer to that of an X70 than an X52. It is not unusual for foundries to provide steel that exceeds the specified minimum yield strength (SMYS), because the API specification provides so much leeway.

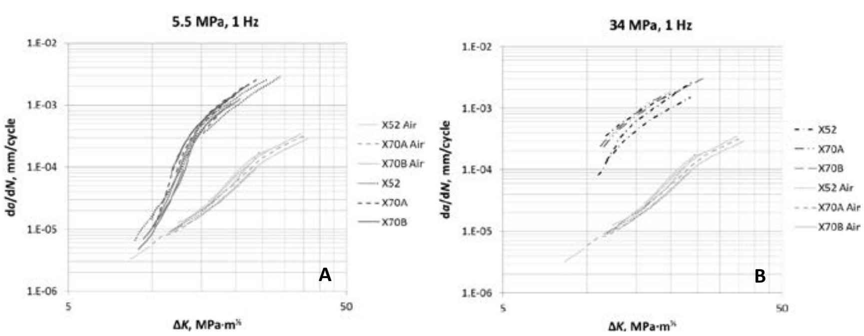

Figure 3. FCGR results from tests conducted at a cyclic loading frequency of 1 Hz and hydrogen gas pressures of (A) 5.5. MPa and (B) 34 MPa. Data collected in air are shown for comparison.

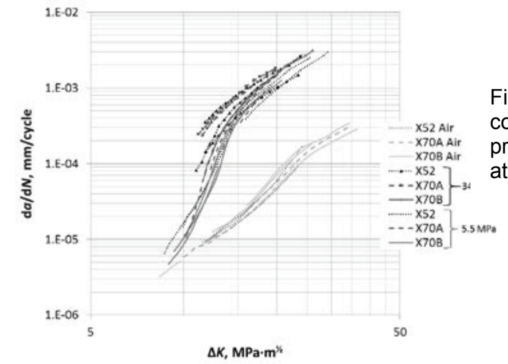

Figure 4. FCGR data comparing tests conducted in air, and at hydrogen gas pressurized to 5.5 MPa and 34 MPa at a cyclic loading frequency of 1 Hz.

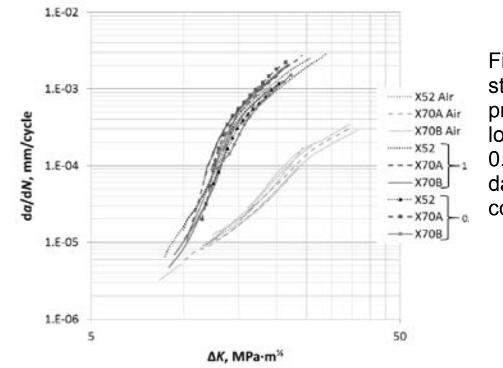

Figure 5. FCGR data for the three steels tested at a hydrogen gas pressure of 5.5 MPa and a cyclic loading frequency of 1 Hz (lines) and 0.1 Hz (lines with symbols). FCGR data acquired in air are included for comparison.

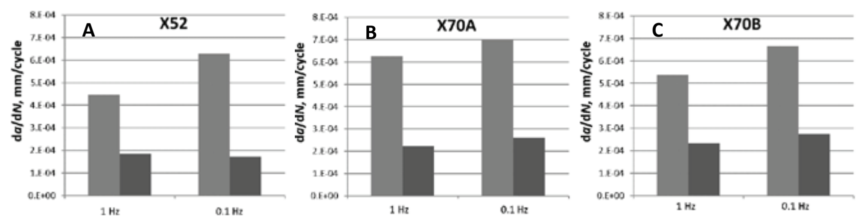

Figure 6. Bar graphs comparing the average value of the d*a*/d*N* data at ΔK = 14 MPa·m$^{1/2}$ for the available data at cyclic loading frequencies of 1 Hz and 0.1 Hz for the (A) X52 steel, (B) X70A, and (C) X70B. Gray bars represent data acquired at a hydrogen gas pressure of 34 MPa and the black at 5.5 MPa.

The FCGR data generated at NIST show that all the reported materials are strongly, but comparably, affected by the presence of high-pressure hydrogen. This is observed for both hydrogen pressures and both cyclic loading rates discussed here. The findings were reported to the ASME B31.12 Committee on Hydrogen Piping and Pipelines. They concurred that, as long as pipelines operate well below the specified minimum yield strength (SMYS)—below the stresses for bursting or fracture, fatigue is the likely failure mechanism for hydrogen pipelines. (At higher operating pressures with respect to the SMYS, fracture toughness tests are still required.) Furthermore, these fatigue tests

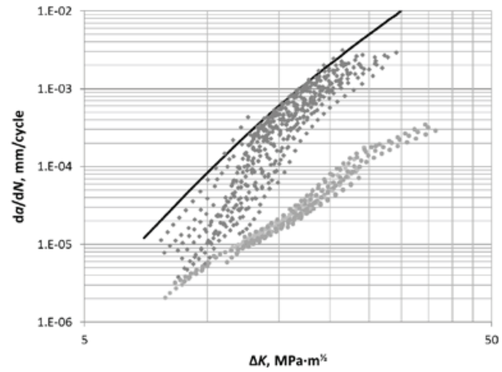

Figure 7. All of the data acquired on the fatigue crack growth rate of X52 and X70 steels in air (lt. gray circles) and in hydrogen gas (gray diamonds) pressurized to 5.5 MPa with the modeled fit of the upper bound that is now part of the ASME B31.12 code (black line).

provide the foundation upon which to modify the code. It was decided by the Committee that rather than requiring each material to be tested, an upper bound to all the available data that was acquired at hydrogen gas pressures of 21 MPa or below would be modeled [20] and that would be established as the minimum fatigue lifetime to which hydrogen pipelines will be designed. Figure 7 shows all of the NIST data acquired at hydrogen gas pressurized to 5.5 MPa throughout this test program (including an X52 pipeline steel, ca. 1964, that is not reported here) and the upper-bound fit to the data. The modification to the code has been approved by all requisite entities within ASME, and the modification will be implemented in the 2016 version of the code that is scheduled for release in February 2017.

CONCLUSIONS

Fatigue tests are a more accurate measure of how pipeline steels will perform in a pressurized hydrogen environment than tensile tests. However, sufficient FCGR data on which to base a code for designing hydrogen pipelines has not been available before now. Scores of tests were conducted at NIST on X52 steels (currently approved for use without further tests in the ASME B31.12 code) and X70 steels. Both grades of steel exhibited HA-FCGR, which accelerated crack growth up to 1 to 1.5 orders of magnitude over the FCGR in air. Since the HA-FCGRs for the two grades are comparable, X70 could be used for constructing hydrogen pipelines operating at current pressures with no loss in performance or safety when the modeled upper-bound FCGR is used. The ASME B31.12 Code on Hydrogen Piping and Pipelines has been revised and accepted to reflect this finding. Should future pipelines operate at pressures higher than 21 MPa (the maximum pressure used for the model fit for the code revision), the model will need to be modified and the code revised to reflect the higher FCGRs measured on steels tested at higher pressures, such as those reported here at 34 MPa.

Further studies on the HA-FCGR of the fusion zone and associated heat-affected zones should be conducted to elucidate whether these areas are more susceptible to degradation from hydrogen than the base metal. Even more fundamental, a general study on the interaction of hydrogen and predominant microstructural constituents in ferritic steels is needed. With that data, a fully-predictive physics-based model can be developed.

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