STP-PT-064

EVALUATION OF FRACTURE PROPERTIES TEST METHODS FOR HYDROGEN SERVICE

ASME STANDARDS TECHNOLOGY, LLC

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Prepared by:

M. T. Miglin, PhD.
Stress Engineering Services, Inc.

ASME STANDARDS TECHNOLOGY, LLC

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ASME Standards Technology, LLC
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FOREWORD

This report evaluates testing methods on the measurement of fracture properties for design of ASME Boiler and Pressure Vessel Code, Section VIII, Division 3 (ASME BPVC VIII-3) pressure vessels for hydrogen service.

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ABSTRACT

Recommendations for appropriate testing procedures for measurement of the threshold stress intensity for fracture initiation in hydrogen, K_{TH}, and for the threshold stress intensity range for fatigue crack initiation in hydrogen, ΔK_{TH}, are provided. This includes specifics on the type of loading, loading rate, specimen size, etc, for K_{TH} tests. Guidance for the appropriate fatigue test parameters (test frequency, R-ratio, etc) are provided. Development of standards for determination of K_{TH} and ΔK_{TH} in hydrogen is encouraged. Recommendations for an appropriate ΔK_{TH} value that represents expected vessel behavior are made.

To obtain conservative estimates of K_{TH} in hydrogen, it is necessary to actively load a fracture mechanics specimen in hydrogen. Testing with concurrent straining and hydrogen exposure, i.e. rising load testing, is recommended for measuring K_{TH} for steels in hydrogen. Guidelines in ASTM E1820 should be followed to determine specimen size. The loading rate that produces the lowest measured K_{TH} will vary among steels, but will be on the order of 0.1MPa√m/min (0.09 ksi√in/min).

For fatigue testing, the test frequency and the R-ratio should adequately reflect the actual loading conditions expected in vessels during service, but also be realistic for laboratory test conditions. Fatigue crack growth rates in hydrogen are affected by loading frequency. The frequency selected for fatigue crack growth rate testing in hydrogen must balance the conflicting issues of test duration and data reliability. A frequency near 0.1 Hz appears to be a reasonable value for testing quenched and tempered steels in hydrogen.

Increasing R-ratio results in increased fatigue crack growth rates when plotted versus ΔK. Data from various sources are in agreement that testing at higher R-ratios produces faster crack growth rates than testing at low R-ratios. An R-ratio of at least 0.8 is needed to produce conservative crack growth data. This is also true in the threshold region.

Crack growth rates in the treshold region are higher in hydrogen than in moist air. It is likely that tests in hydrogen produce faster crack growth rates and lower ΔK_{TH} values because they do not allow oxidation at the crack tip, which produces a crack closure effect, reducing the effective ΔK at the crack tip. A threshold value ΔK_{TH} = 2 MPa√m (2.2 Ksi√in) is suggested for inclusion in the ASME BPVC VIII-3 for hydrogen vessel design.

1 INTRODUCTION

Vessels designed for hydrogen service for ASME BPVC VIII-3 require threshold stress intensity factor and fatigue crack growth rate data. The purpose of this report is to survey the existing literature and provide guidance on the adequacy of the testing procedures provided in the above Code to measure these properties.

2 SCOPE

A literature survey was performed to locate published articles on measurement of the following properties of pressure vessel steels in hydrogen:

(a) Threshold stress intensity factor, K_{TH}. This is defined as the stress intensity factor below which a crack will not propagate when subjected to hydrogen gas at the design pressure.

(b) Fatigue crack growth rate, $da/dN=C(\Delta K)^m$. The values of the constants C and m are measured in hydrogen gas at the design pressure.

Recommendations for specific details of appropriate testing procedures for the measurement of K_{TH} are provided. This includes specifics on the type of loading, loading rate, specimen size, etc. Guidance for the appropriate fatigue test parameters (test frequency, R-ratio, etc) are also provided. Variables such as temperature, pressure and humidity are not addressed; other forms of hydrogen damage are not included.

The feasibility of a safety factor approach for the adjustment of the da/dN data from experiments to correspond to actual design parameters could not be specified because of the lack of full-scale test data. Recommendations for an appropriate ΔK_{TH} value that represents expected vessel behavior are made.

2.1 Measurement of K_{TH}

Current testing procedures (paragraph KD-1045 ASME BPVC VIII, Div. 3) allow the determination of K_{TH} by either constant displacement or constant load testing of fatigue precracked specimens. A review of these procedures and of the rising load test procedure is presented below. The available literature has been searched for the following information:

(a) Static constant load or displacement vs. rising load test data

(b) Effect of exposure time on static tests

(c) Effect of strain or loading rate on rising load test

(d) Effect of specimen size on both test methods

(e) Application of static and rising load test data to actual pressure components in the presence of a crack.

A critical evaluation has been made of the existing test procedures specified in ASTM and ISO standards for measurement of K_{TH} in hydrogen. The existing K_{TH} test data for pressure vessel and piping steels in hydrogen has been compiled and compared. The literature was searched for full-scale test data to compare with properties obtained using the above-defined test procedures. No full-scale test data were found.

2.2 Measurement of da/dN

The available literature has been searched for information on the effects of test frequency, shape of the load-time cycle, and R-ratio on threshold fatigue crack growth rate, as follows:

(a) The appropriate test frequency and R-ratio to be used in da/dN measurements are suggested. The test frequency and the R-ratio should adequately reflect the actual loading conditions expected in vessels during service, but are also be realistic for laboratory test conditions. No data was found for shape of the load-time cycle.

(b) The effect of R-ratio on da/dN has been evaluated.

(c) A value of ΔK_{TH} for Q&T steels has been identified for inclusion in the ASME BPVC VIII-3 for hydrogen vessel design.

2.3 Recommendations

Recommendations for specific details of appropriate testing procedures for the measurement of K_{TH} are provided. This includes specifics on the type of loading, loading rate, specimen size, etc. Guidance for the appropriate fatigue test parameters (test frequency, R-ratio, etc) are provided. The feasibility of a safety factor approach for the adjustment of the da/dN data from experiments to correspond to actual design parameters could not be specified because of the lack of full-scale test data. Recommendations for an appropriate ΔK_{TH} value that represents expected vessel behavior are made.

3 MEASUREMENT OF K_{TH}

ASME BPVC Section VIII, Division 3 allows for threshold fracture toughness testing using the constant load or constant displacement techniques. Testing details are outlined in ASTM E1681-03, "Standard Test Method for Determining Threshold Stress Intensity Factor for Environment-Assisted Cracking of Metallic Materials." This test method utilizes fracture mechanics specimens as described in ASTM E1820-09, "Standard Test Method for Measurement of Fracture Toughness", with modifications to allow them to be self-loading. An additional test method, termed the "rising load test", also utilizes standard fracture mechanics specimens, but with a constant applied strain rate. The rising load testing details can be found in Reference [1]. Technical issues surrounding threshold testing in hydrogen are discussed in detail in References [2] and [3]. All of the above test methods involve testing in a gaseous hydrogen environment. This type of testing is complex, hazardous and expensive. However, accurate results cannot be obtained by precharging specimens and testing in laboratory air, as the hydrogen diffuses out of the specimens too quickly, as shown in Figure 1.

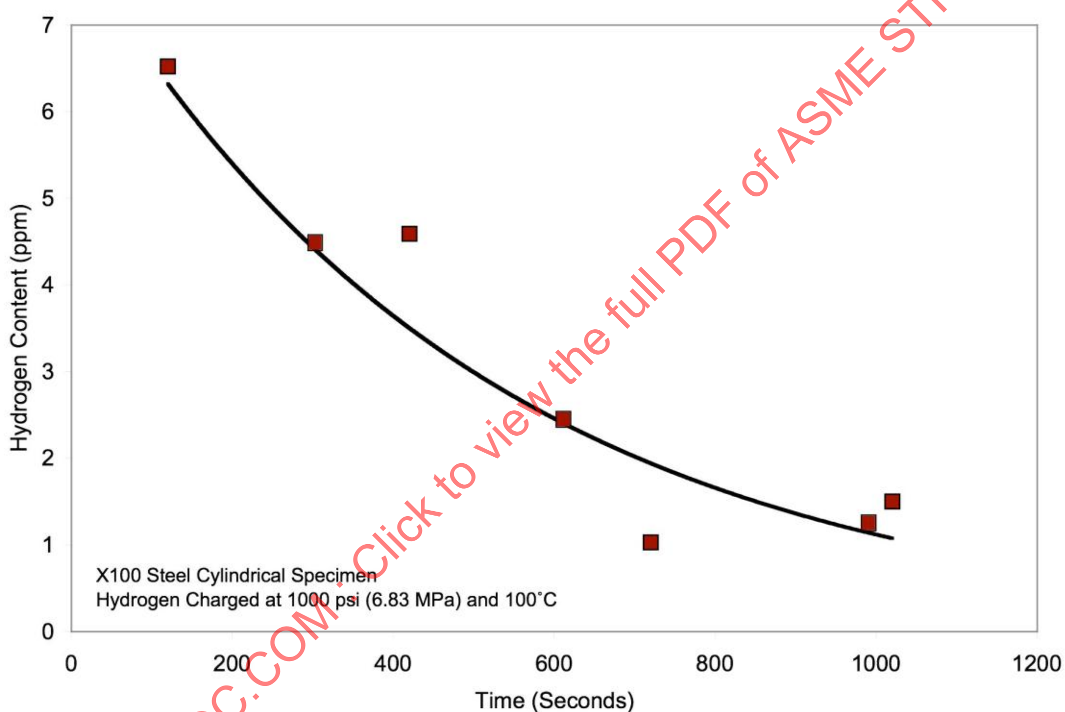

Figure 1 - Hydrogen Diffusion from an X100 Steel Cylindrical Specimen in Laboratory Air [4]

3.1 Constant Displacement Test Method

ASTM E1681-03 describes the constant displacement test methods in detail. For the constant displacement test, K decreases as the crack grows, down to a threshold commonly designated as K_{TH}. (ASTM E1681-03 uses the term K_{IEAC}, defined as the stress intensity threshold for environmentally assisted cracking.) The constant displacement test specimen is typically a bolt-loaded compact specimen, as shown in Figure 2. As described in ASTM E1681-03, the specimen is fatigued to produce a sharp crack at the tip of the machined notch prior to loading. The validity of the K_{TH} value determined by this test method depends on meeting the size requirements to ensure plane strain conditions, as stated in ASTM E1820. The stress intensity level at which the fatigue precracking of the specimen is conducted is limited to the requirements of ASTM E1681.

The displacement is applied with a bolt tightened against a flattened pin and measured with an electronic crack-mouth-opening-displacement (CMOD) gage, as described in ASTM E1820. The specimen is placed in the test environment and the crack length is monitored remotely, in some cases by a direct current potential drop (DCPD) technique, described in ASTM E1820, until crack growth stops. This technique requires electrical isolation of the bolt from the specimen using ceramic inserts. Additional testing details are provided in ASTM E1681-03.

Figure 2 - Bolt-Loaded Compact Specimen

Figure 3 presents data for CrMo steel obtained by US Steel Corporation using the constant displacement test method along with data for cylinder material tested by TI Chesterfield Cylinders Ltd. (Multiply the fracture toughness values by 0.032 to convert to MPa√m. Tensile strength units are equivalent to MPa.) The two sets of test results are in good agreement.

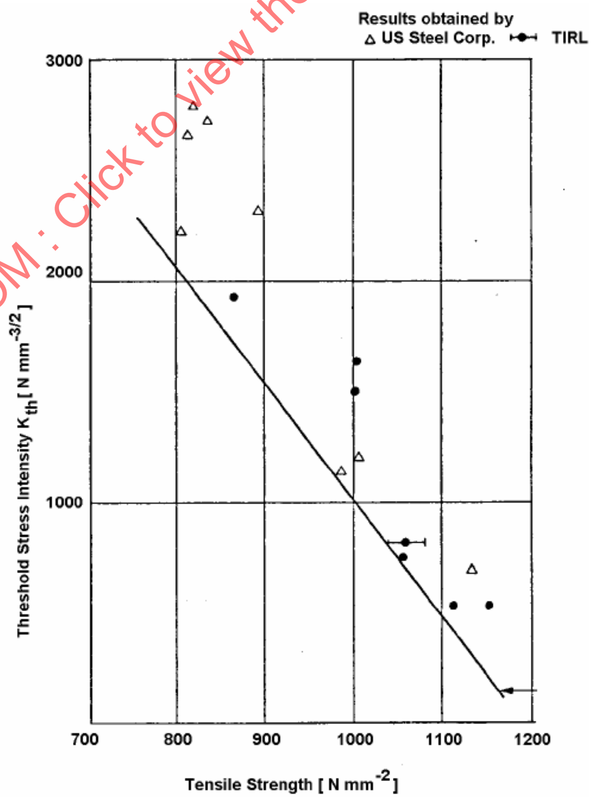

Figure 3 - K_{TH} for CrMo Steel Measured in Gaseous Hydrogen at 200 bar [5]

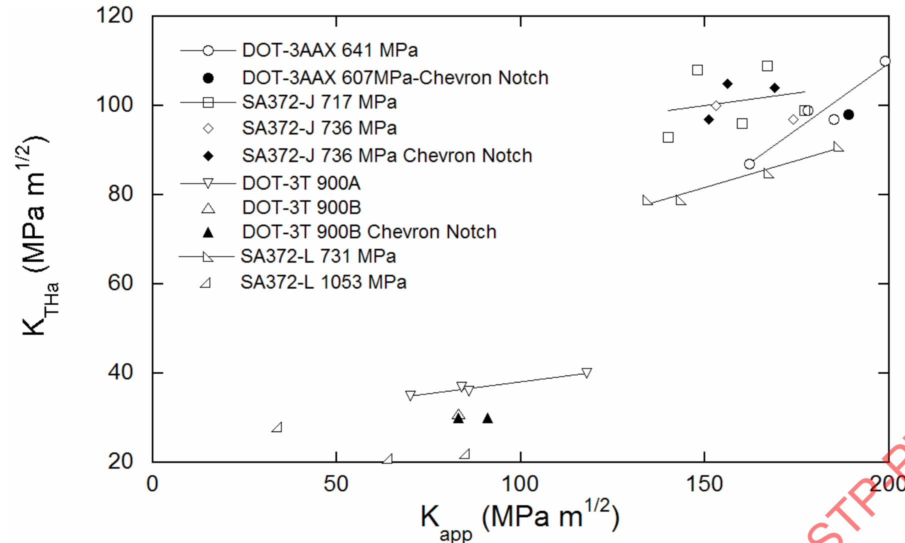

Figure 4 - Measured Threshold Stress Intensity Values versus Applied Stress Intensity

With the constant displacement method, there is a relationship between the initial applied stress intensity, K_{app}, and the measured threshold stress intensity at crack arrest, K_{THa}. Figure 4 presents measured threshold stress intensity values versus applied stress intensity where a trend between K_{THa} and K_{app} apparently exists such that K_{THa} tends to increase as K_{app} is increased [3]. This trend is magnified among the lower strength steels. Variations in K_{app} led to differences in K_{THa} that were as great as 25%. The difference could not be accounted for by systematic variations in the distance of the arrested crack tip from the back face of the specimen. This relationship exists because the crack-tip deformation history affects the measurement of the crack arrest threshold, K_{THa}, making it dependent on specimen geometry and therefore unsuitable as a measure of K_{TH}.

Figure 5 shows the decrease in KR, the crack growth resistance, with crack extension. Theoretically, when K_{app} equals K_R, the crack will arrest and this point could be defined as K_{THa}. However, as shown in Figure 5, KR is strongly dependent on δa for small delta a, and thus is specimen geometry dependent. Therefore K_{THa} is also dependent on geometry for low values of δa, especially for lower strength steels.

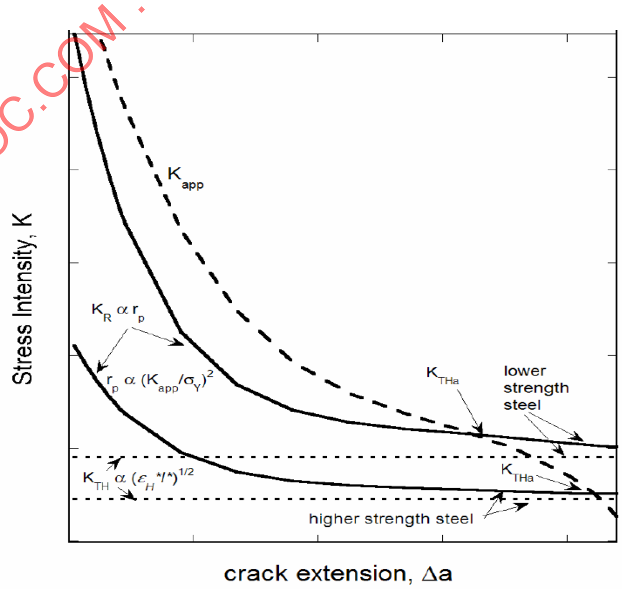

Figure 5 - K_{app}, K_R, and the True Fracture Threshold (K_{TH}) as a Function of Crack Extension [1]

A geometry independent threshold is desirable, and this can only be obtained at large δa values, especially for low strength steels. For a compact specimen, if δa becomes too large, the crack tip plastic zone encounters the free surface at the back of the specimen, and a different geometry dependency is encountered.

3.2 Rising Load Test Method

The rising load test method is described in detail in Reference [1]. The compact specimen geometry is typically used for rising load fracture toughness measurements, following the procedures of ASTM E1820. The specimen is contained in a pressure vessel mounted in a servohydraulic or screw-driven mechanical testing frame, such that the load rod penetrates the vessel head to engage the specimen. A constant displacement rate is applied to the specimen, and the crack length is monitored using DCPD, as for the constant displacement test method.

As shown in Figure 6, K_{TH} values measured using the rising load method depend on the applied loading rate. High loading rates produce higher K_{TH} values, especially for specimens tested at lower hydrogen pressures [3]. Rising load data produced in 1976 by Clark and Landes [6] is shown in Figure 6 in comparison with data of Nibur, et al [3]. Clark and Landes showed that the rising load results decreased with decreasing loading rate down to a lower bound that was equivalent to the static results. Rising load results for AerMet 100 high steel (Figure 7) show that K_{TH} decreases with decreasing loading rate until the fracture mode becomes completely brittle. No static data are presented.

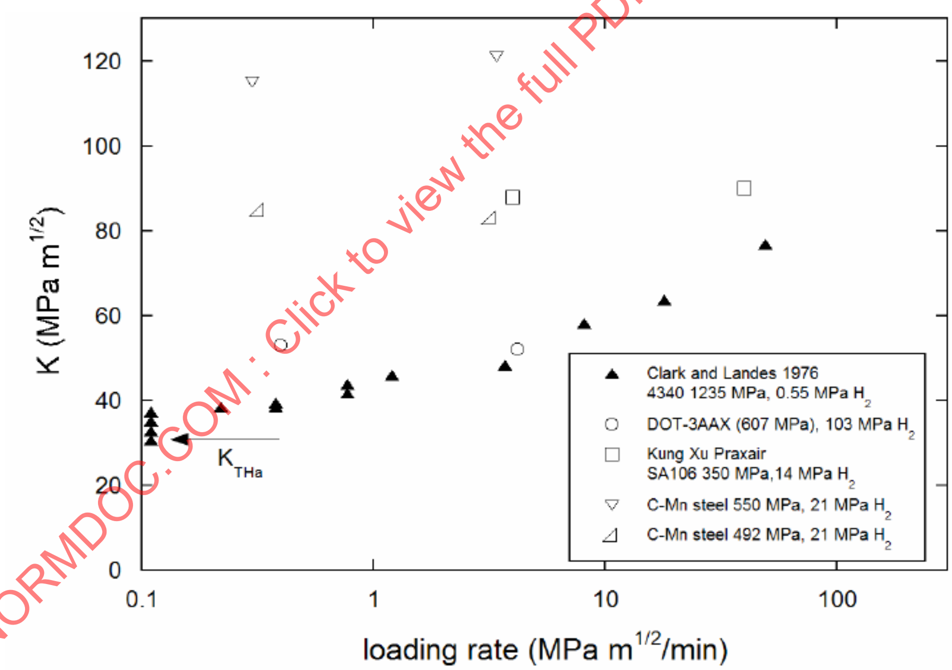

Figure 6 - K versus Loading Rate

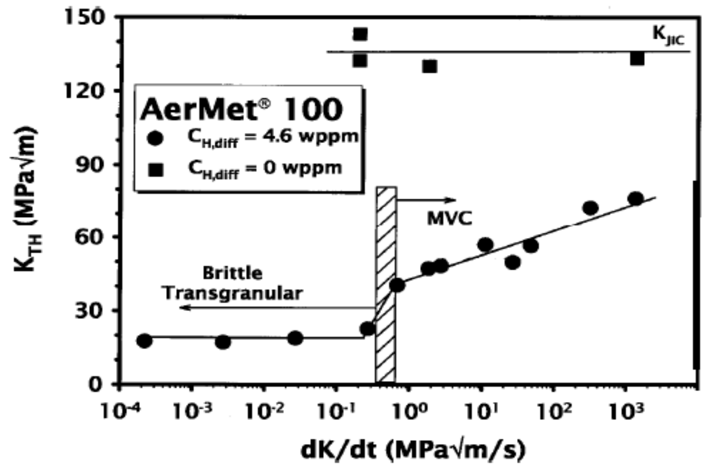

Figure 7 - Rising Load Results for AerMet 100 High Strength Steel with/without Hydrogen [7]

Rising load data for 5%NiCrMoV steel tempered to two hardness levels and tested in hydrogen are presented in Table 1. Contrary to expectations, the softer steels have lower K_{TH} values, most likely because they were tested at a lower loading rate.

Table 1 - Rising load results for 5% NiCrMoV steel with three tempering temperatures tested in 1500 psi hydrogen [8]

Temperature, ℃	Hardness, Rc	C.H. Speed in/min	K_{Max}, MPa $m^{1/2}$	I.G.
0.002	69.2	0.002	76.0	<5%
200	35.5	0.0002	35.6	~35%
400	35.1	0.0002	44.7	~30%

Clark and Landes showed that K_{TH} values from constant displacement tests form the lower bound for rising load data. However, other studies have shown that rising load fracture threshold measurements yield lower values than constant displacement tests, at least for low alloy steels that fail by strain-controlled fracture mechanisms, i.e. fracture occurs when a critical value of strain is reached [9]. Figure 8(a) shows a collection of K_{TH} results for alloy and C-Mn steels in hydrogen-bearing environments, most of which are from constant displacement tests (except for those designated KIH or Rising CMOD, which are rising load test results), as a function of yield strength. For 2-1/4Cr 1Mo steel, rising load results are shown in Figure 8(b), and they are as little as one-fourth of the static results.

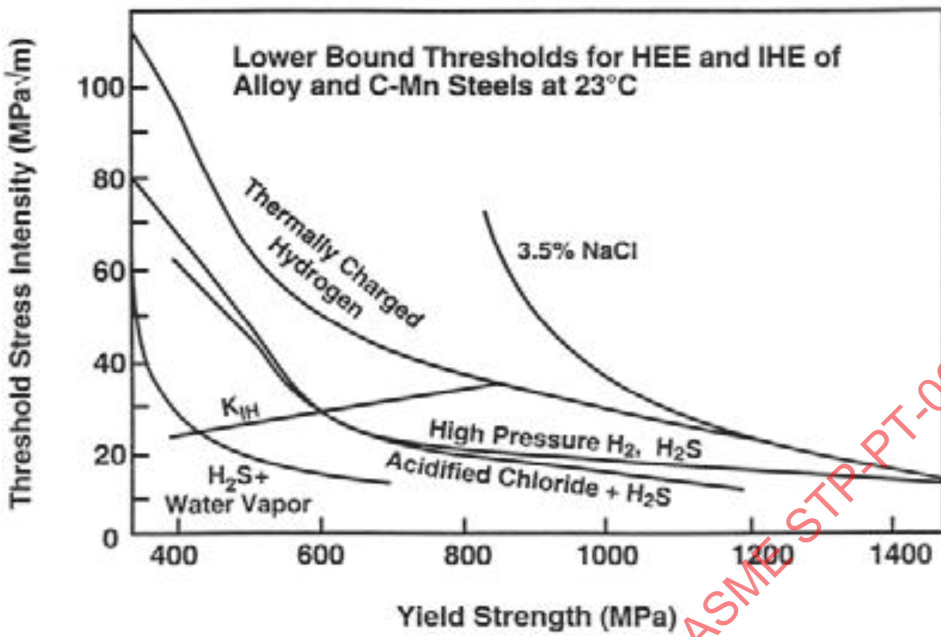

Figure 8(a) - KTH Results for Various Steels Precharged with Hydrogen and Tested in Moist Laboratory Air

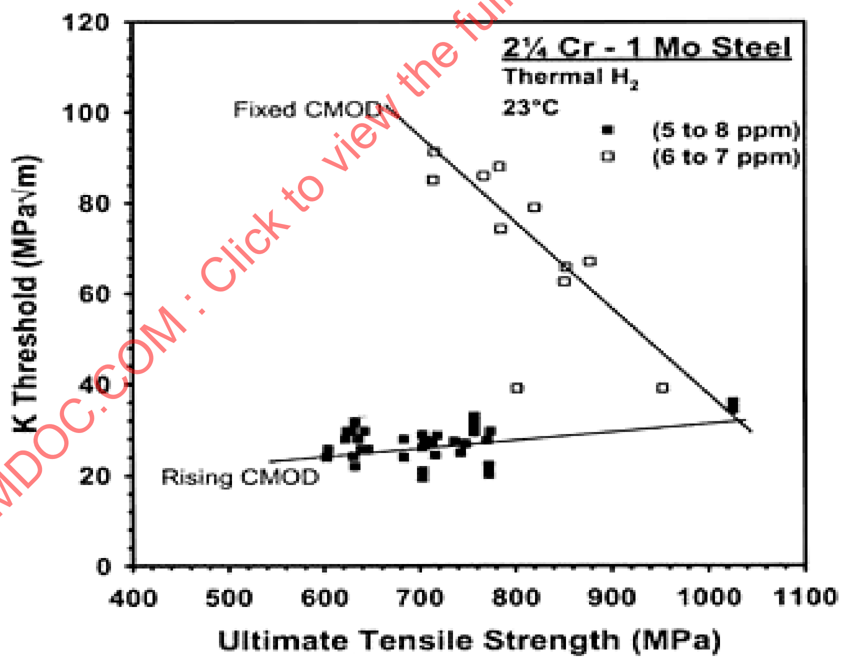

Figure 8(b) - Comparison of Rising Load and Constant Displacement (Fixed CMOD) Results as a Function of Tensile Strength [10]

It is clear from Figure 8 that rising load testing produces lower threshold values in hydrogen than constant displacement testing. This is especially true for lower strength steels.

Figure 9 shows that even for high strength steels, applying a constant displacement rate can reduce K_{TH} values. Figure 10 presents rising load and constant displacement data over a broad range of strength levels. It is apparent from Figure 10 that applying a rising load significantly depresses the measured K_{TH}. Across this broad strength range, the lowest values of K_{TH} in hydrogen are produced by tests with concurrent straining and hydrogen exposure (K_{JH} values).

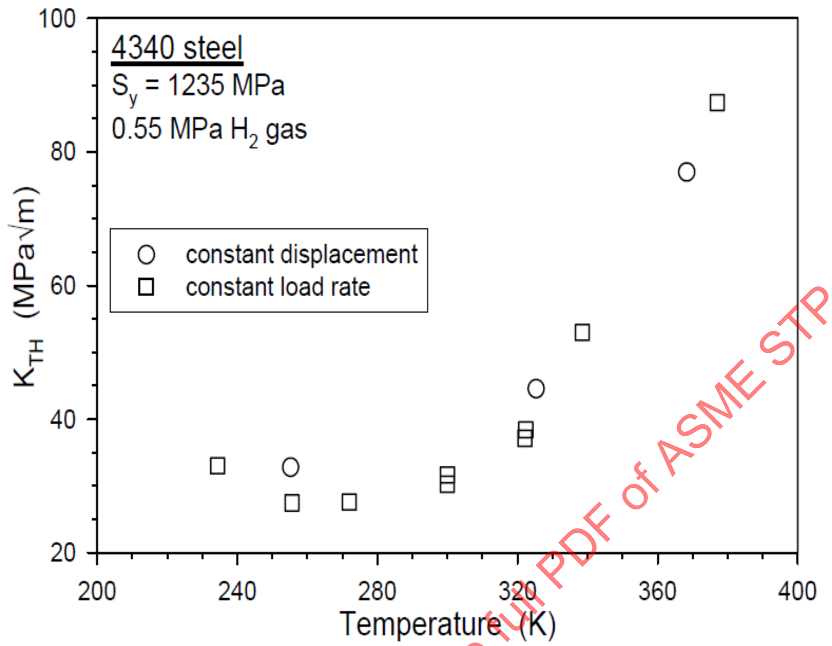

Figure 9 - Constant Load Rate and Constant Displacement Tests of 4340 with 179 ksi Yield in 80 psi Hydrogen Gas [11]

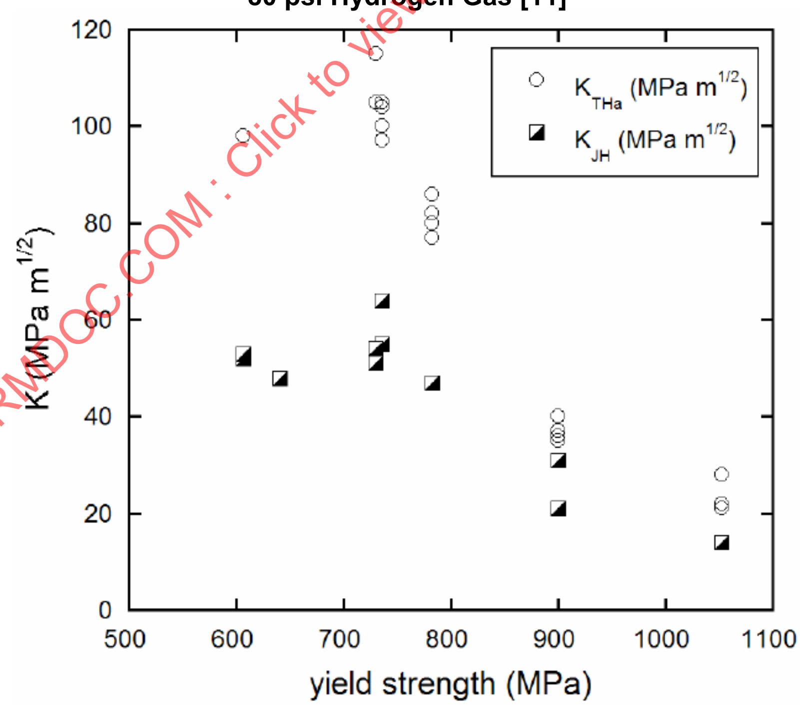

Figure 10 - Constant Load Rate K_{JH} vs. Constant Displacement K_{THa} Results for Several Steels DOT-3T (900 MPa A), DOT-3AAX (607 MPa), SA 372 Grade J (641, 730, 736 and 783 MPa), and SA372 Grade L (1053 MPa) [3]

3.3 Summary

ASME BPVC Section VIII, Division 3 allows for threshold fracture toughness testing using the constant load or constant displacement techniques. Testing details are outlined in ASTM E1681-03, “Standard Test Method for Determining Threshold Stress Intensity Factor for Environment-Assisted Cracking of Metallic Materials.” This test method utilizes fracture mechanics specimens as described in ASTM E1820-09, “Standard Test Method for Measurement of Fracture Toughness”, with modifications to allow them to be self-loading. An additional test method, termed the “rising load test”, also utilizes standard fracture mechanics specimens, but with a constant applied strain rate. [1]

Rising load fracture threshold measurements yield lower K_{TH} values than constant displacement tests, for steels that fail by strain-controlled fracture mechanisms. For 2-1/4Cr 1Mo steel, K_{TH} values from rising load tests are as little as one-fourth of the static K_{TH} values. For lower strength steels, the difference between rising load and static K_{TH} values is greater than for higher strength steels. Testing with concurrent straining and hydrogen exposure, i.e. rising load testing, is recommended for measuring K_{TH} for steels in hydrogen. Guidelines in ASTM E1820 should be followed to determine specimen size. The loading rate that produces the lowest measured K_{IH} will vary from one steel to the next, but will be on the order of 0.1 MPa√m/min (0.09 ksi√in/min). Using a loading rate that is too high will produce non-conservative results.

4 MEASUREMENT OF da/dN

The available literature has been searched for information on the effects of test frequency, shape of the load-time cycle, and R-ratio on threshold fatigue crack growth rate, as follows:

1. The appropriate test frequency and R-ratio to be used in da/dN measurements are suggested. The test frequency and the R-ratio should adequately reflect the actual loading conditions expected in vessels during service, but should also be realistic for laboratory test conditions. No data was found for shape of the load-time cycle.
2. The effect of R ratio on da/dN has been evaluated.
3. A value of ΔK_{th} for quenched and tempered (Q&T) steels has been identified for inclusion in ASME BPVC VIII-3 for hydrogen vessel design.

Recommendations for appropriate testing procedures for the measurement of ΔK_{TH} are provided. This includes specifics on the loading rate, specimen size, etc. Guidance for the appropriate fatigue test parameters (test frequency, R-ratio, etc) are provided. The feasibility of a safety factor approach for the adjustment of the da/dN data from experiments to correspond to actual design parameters could not be specified because of the lack of published full-scale test data [5]. Recommendations for an appropriate ΔK_{TH} value that represents expected vessel behavior are made.

The effects of hydrogen on the fatigue crack growth curve are shown schematically in Figure 11. Hydrogen affects the threshold behavior and the behavior at high ΔK. At the onset of accelerated fatigue crack growth, the fracture mode can be intergranular and then transition to a transgranular mode. The crack growth rate is increased above the air values. At intermediate ΔK levels, hydrogen and air data overlap. At low ΔK, cracking is transgranular with and without hydrogen; however, the presence of hydrogen increases the crack growth rate. Hydrogen reduces the ΔK_{TH}, and raising the R-ratio decreases ΔK_{TH} further.

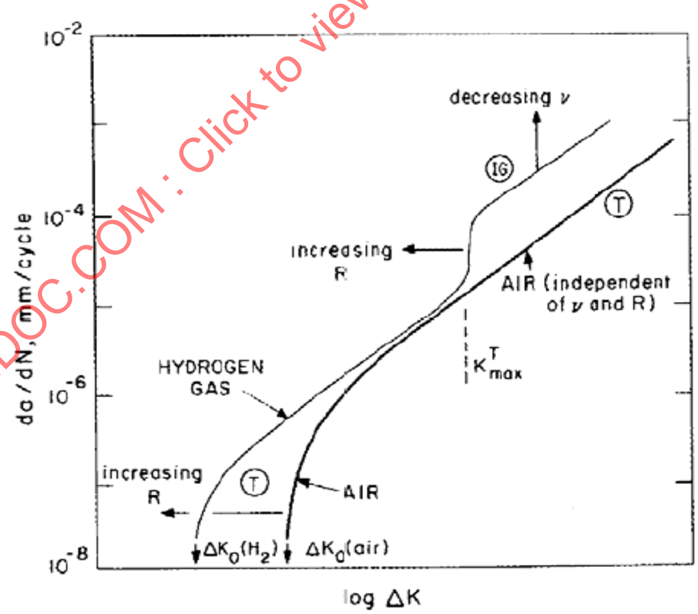

Figure 11 - Crack Growth Rate as a Function of ΔK Showing Effects of Hydrogen and R-Ratio on the Shape of the Fatigue Crack Growth Rate Curve

Note: IG = intergranular, T = transgranular, K^T_{max} = threshold value, below which hydrogen has no effect on crack growth rates until the lower threshold region is reached [12].

The effect of hydrogen on the Ni-Cr-Mo steels HY80 and HY130 is shown in Figure 12. Hydrogen accelerates the fatigue crack growth rates for both steels over the air levels. Hydrogen has a greater effect on the lower strength steel.

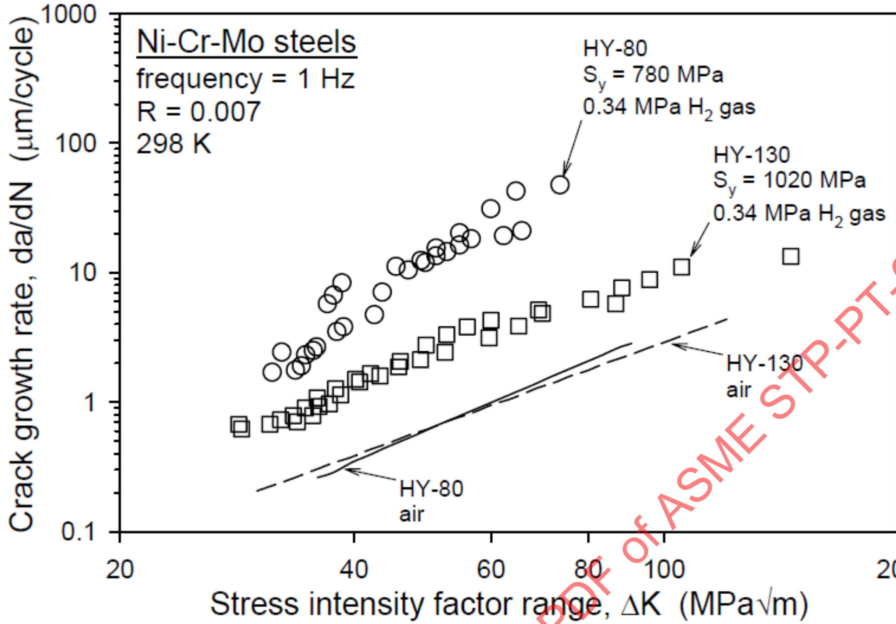

Figure 12 - Fatigue Crack Growth Rate of HY-80 and HY-130 in Air and Hydrogen [11]

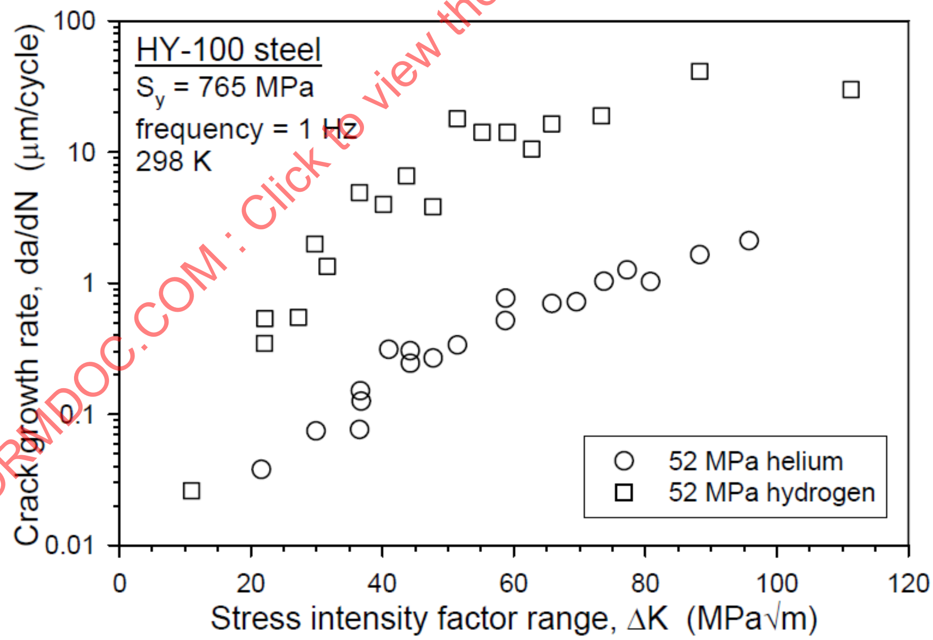

Figure 13 - Fatigue Crack Growth Rate of HY100 Steel in Hydrogen and Helium [11]

Above the threshold region, the effects of hydrogen on fatigue crack growth are not simply due to the absence of oxygen. Hydrogen also increases fatigue crack growth rates relative to inert environments, ΔK levels above threshold. Figure 13 shows higher fatigue crack growth rates (at ΔK levels of 20 MPa√m and above) for HY100 in hydrogen than in helium.

4.1 Effects of Frequency

Cyclic frequency affects fatigue crack growth rates in hydrogen, but the magnitude of the effect depends upon the R-ratio and the steel. Figure 14 shows fatigue crack growth rates for DOT 4130X cylinder steel in hydrogen at two frequencies and R-ratios. Increasing the frequency from 0.1 to 1.0 Hz affects the crack growth rates at R=0.5 but not at R=0.1 [13].

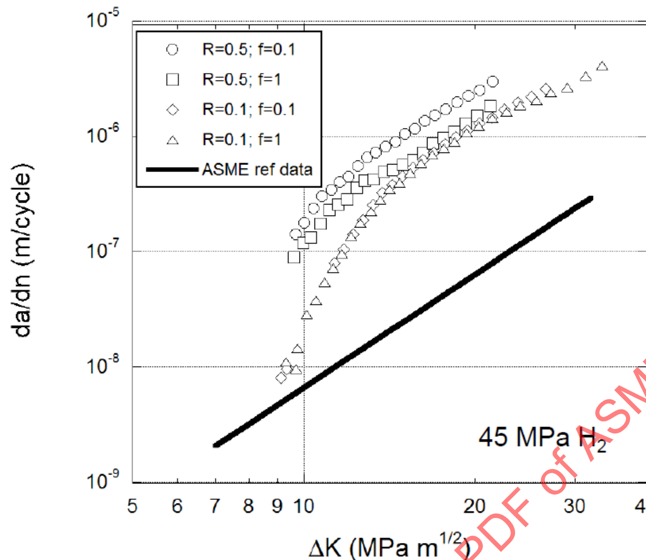

Figure 14 - Fatigue Crack Growth Rates for 4130X in Hydrogen at Two Frequencies and R-Ratios

As shown in Figure 15, the effects of frequency on fatigue crack growth rate are prominent at high ΔK values. Decreasing frequency from 25 Hz to 0.01 Hz increases the fatigue crack growth rate by more than an order of magnitude.

A.H. Priest, British Steel, EHC-(1)42-012-81UK(H), 1983

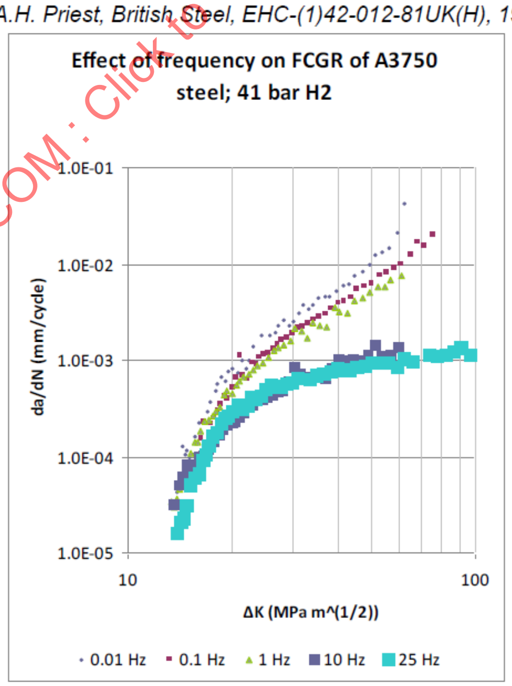

Figure 15 - Fatigue Crack Growth Rates for A3750 in Hydrogen at Frequencies Ranging from 0.01 to 25 Hz [14]

The effects of low frequencies are shown in Figure 16 for SA-105 C-Mn steel in 100 MPa H_2. Crack growth rate is observed to increase with decreasing frequency from 1 Hz down to 0.00083 Hz, and the effect does not appear to saturate or reverse over that frequency range.

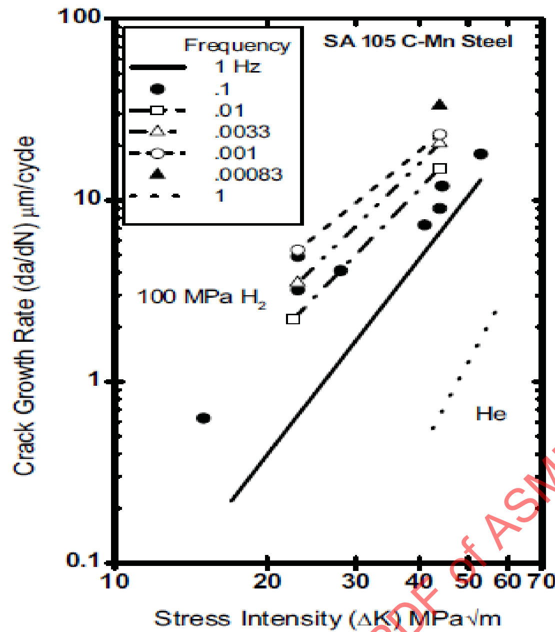

Figure 16 - Fatigue Crack Growth Rate of SA105 C-Mn Steel in Hydrogen and Helium over a Range of Frequencies from 0.00083 to 1 Hz [10]

In contrast, Figure 17 shows fatigue crack growth rates for X52 pipeline steel that remain stable as frequency is decreased from 0.1 Hz to 0.001 Hz for ΔK=17.5 MPa√m. However, these tests were performed at lower ΔK levels than those in Figure 16. The frequency effect on crack growth rate is a function of the magnitude of da/dN.

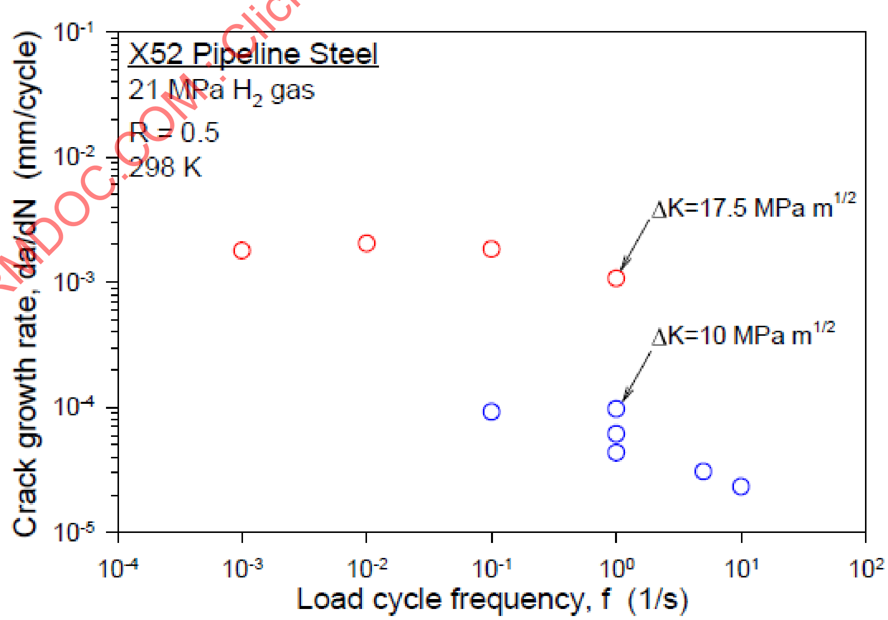

Figure 17 - Fatigue Crack Growth Rates as a Function of Frequency for X52 Pipeline Steel Tested at R=0.5 in Hydrogen Gas [13]

In Figure 18, fatigue crack growth data in hydrogen are plotted with respect to inverse frequency, such that the abscissa is in seconds. All testing was done at ΔK=23 MPa√m [10]. At this ΔK level, in gaseous hydrogen, taking five seconds or more to reach K_{max} produces the fastest crack growth rates. This corresponds to a frequency of 0.1 Hz.

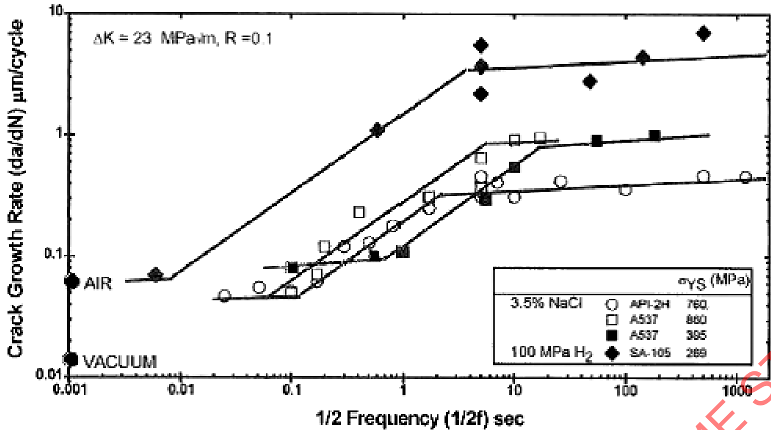

Figure 18 - Effect of Frequency on Crack Growth Rates for C-Mn Steels Charged with Hydrogen in Aqueous Solution and in Gaseous Hydrogen

The frequency selected for fatigue crack growth rate testing in hydrogen must balance the conflicting issues of test duration and data reliability. The effect of frequency on crack growth rates diminishes at low da/dN levels, so near the threshold, higher frequencies can be used. From the data above, a frequency in the vicinity of 0.1 Hz appears to be a reasonable value.

4.2 Effects of R-Ratio

The applied load ratio R=Kmin/Kmax affects fatigue crack growth rates in the threshold region. Increasing the R-ratio increases the crack growth rates and thereby pushes the threshold to lower ΔK levels. The data in Figure 19 illustrate this effect for 4340 low alloy steel in dry hydrogen.

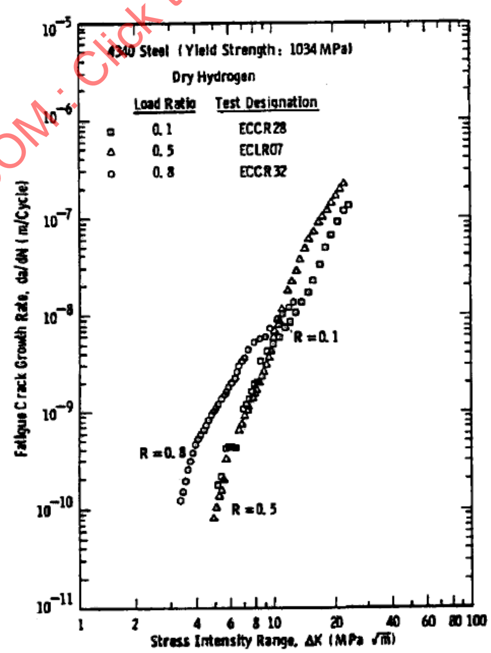

Figure 19 - Near-Threshold Fatigue Crack Growth Rate Curves for 4340 Steel in Dry Hydrogen at Various R-Ratios [15]

Figure 20 shows near threshold results in dry hydrogen plotted for several NiCrMoV steels. The data are plotted as ΔK_{TH} (termed ΔK_0) as a function of R-ratio. From this figure it is apparent that increasing R-ratio reduces ΔK_{TH}, and the effect appears to be linear and larger for lower strength steels. Based on these results, testing at an R-ratio of 0.8 appears to be conservative. It is apparent from Figure 19 and Figure 20 that ΔK_{TH} for high-strength steels (yield strength above 1000 MPa) in hydrogen is quite low at 2-3 MPa√m.

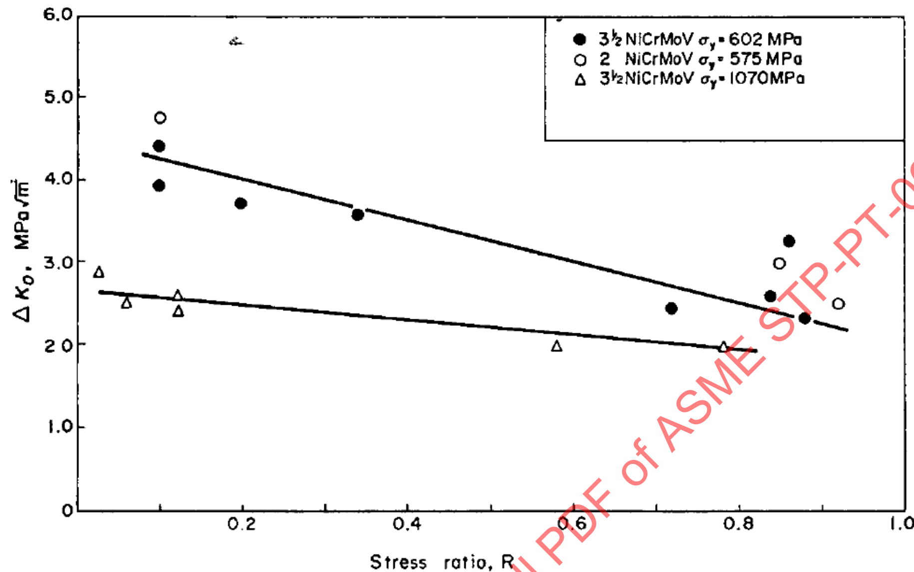

Figure 20 - Effect of R-Ratio on ΔK_{TH} for NiCrMoV Steels Tested in Dry Hydrogen [16]

Figure 21 presents fatigue crack growth data for 4130X specimens with yield strength equal to 607 MPa tested in hydrogen at two frequencies and R-ratios. The air data represents the crack growth relationship provided in ASME VIII-3 Article KD-4 [17]. At high ΔK, fatigue crack growth rates in hydrogen are more than an order of magnitude greater than rates in air.

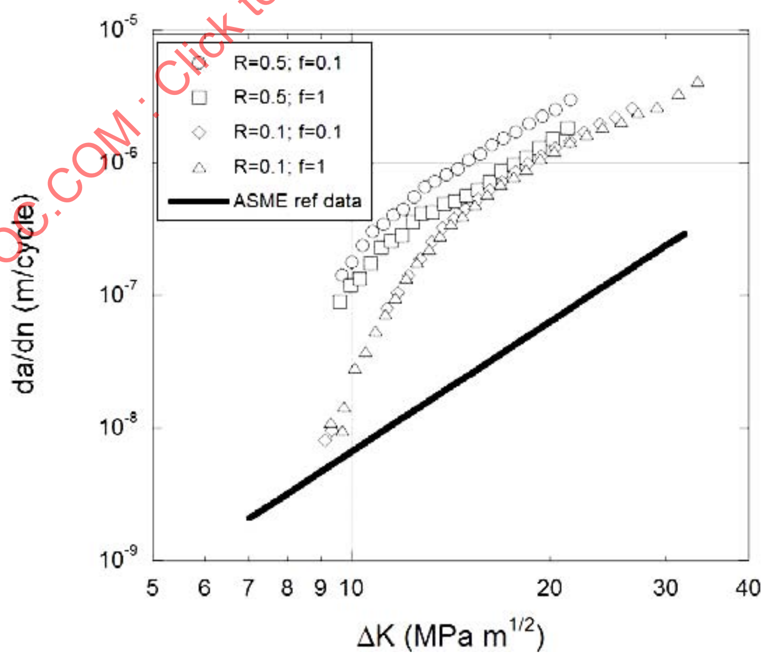

Figure 21 - Fatigue Crack Growth Rates for Four 4130X Specimens (Open Symbols) in 45 MPa Hydrogen and Expected Fatigue Crack Growth Data in Air (Solid Line)

The most aggressive combination of test conditions is the lower frequency (0.1 Hz) combined with the higher R-ratio (0.5). Individual sections of each curve can be fitted to power-law relationship such as equation (1)

$$da/dN = C \Delta K^m \quad (1)$$

in which the coefficient, C, and the exponent, m, are constants. The values of the constants for several ΔK ranges are given in Table 2.

Table 2 - Fatigue coefficients derived from fitting the data in Figure 20 to the power-law relationship given as Equation 1 [17]

R	frequency (Hz)	ΔK range (MPa $m^{1/2}$)	C	m
0.5	0.1	<12.5	8.06 E-13	5.33
		>12.5	2.89 E-10	3.01
0.5	1	<12.5	4.69 E-13	5.4
		>12.5	1.85 E-10	2.99
0.1	0.1	11-14	2.47 E-15	7.13
		14-20	2.61 E-11	3.61
		>20	5.77 E-10	2.56
0.1	1	10-13	1.05E-16	8.41
		14-20	3.87E-11	3.44
		>20	1.45E-09	2.24

Figure 22 presents fatigue crack growth rates for X80 pipeline steel in hydrogen at two R-ratios. It is apparent from Figure 22 that increasing the R-ratio from 0.1 to 0.5 increases the fatigue crack growth rates. At low ΔK levels, the hydrogen data approach the air data.

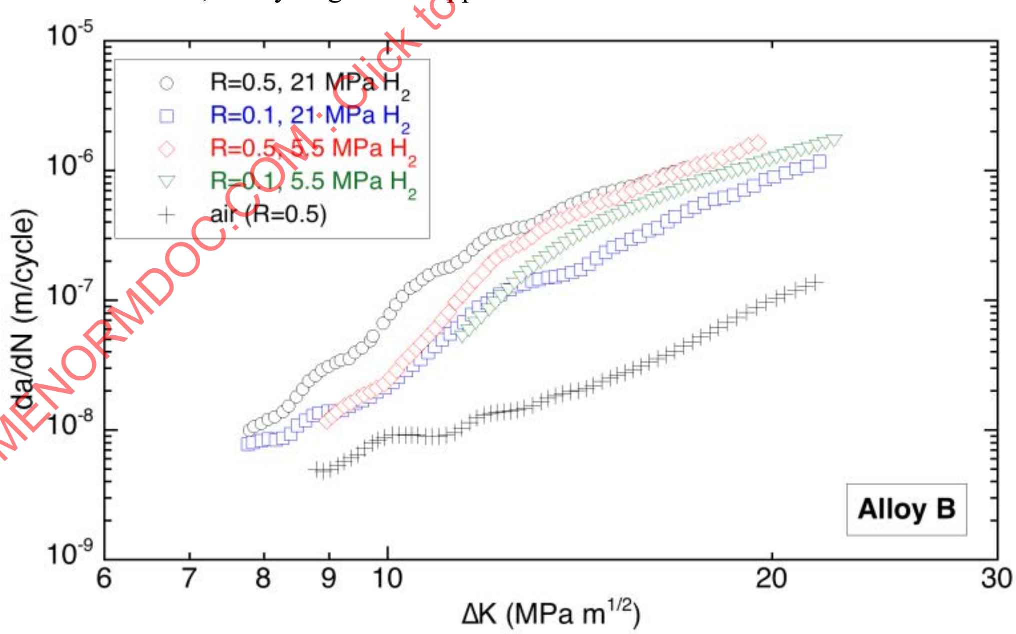

Figure 22 - Crack Growth Rate as a Function of Applied ΔK for X80 Pipeline Steel Tested in Dry Hydrogen [1]

Figure 23 shows the data from Figure 22 replotted as crack growth rate per cycle versus K_{max}. It is apparent from Figure 23 that, if the K_{max} can be maintained at a low enough level in a real structure, that crack growth rates in hydrogen will be close to those in air. When plotted versus K_{max}, crack growth rate decreases with increasing R-ratio.

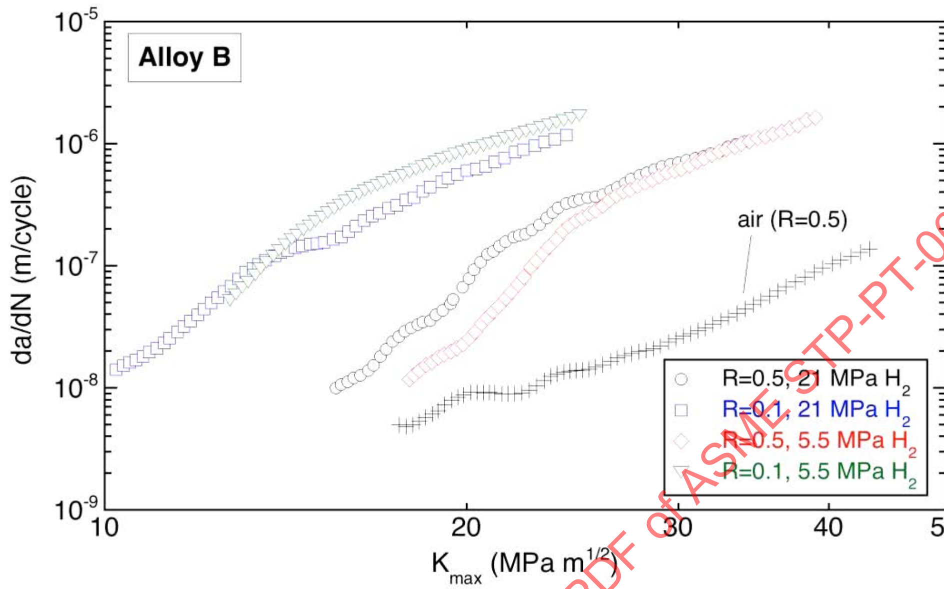

Figure 23 - Data from Figure 21 Replotted as Crack Growth Rate versus K_{max} [1]

The same effect of K_{max} on crack growth rates is observed for X60 (see Figure 24 and Figure 25). In Figure 25, the data in 21 MPa H_2 tested at R=0.5 approach and meet the air curve at K_{max}~18 MPa√m. Suresh and Ritchie [12] proposed a stress intensity factor threshold (K^T_{max} as shown in Figure 11) below which hydrogen does not affect fatigue crack growth rates. This is entirely conceivable, given that crack growth rates in hydrogen approach those in air as K_{max} decreases. However, as shown in section 4.3 below, this generalization does not apply in the threshold region.

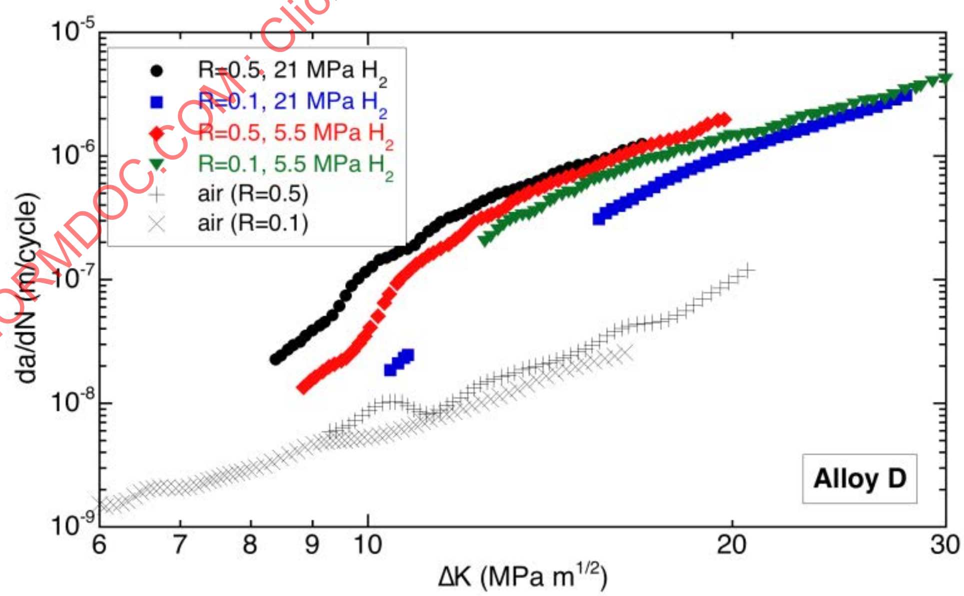

Figure 24 - Crack Growth Rate as a Function of Applied ΔK for X60 Pipeline Steel Tested in Dry Hydrogen [1]

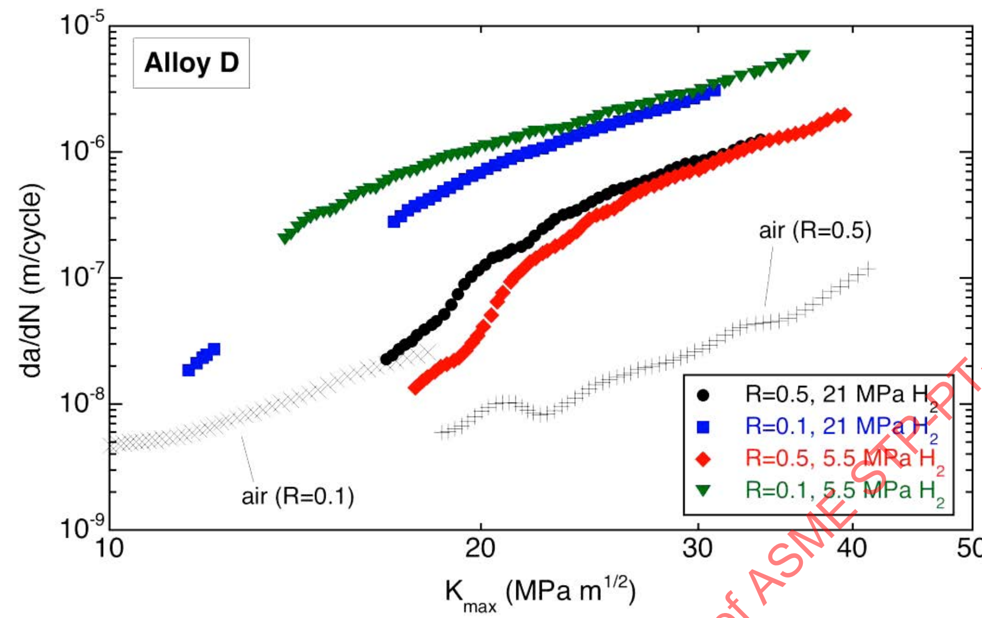

Figure 25 - Data from Figure 21 Replotted as Crack Growth Rate versus K_{max} [1]

In summary, increasing R-ratio results in increased fatigue crack growth rates when plotted versus ΔK. According to Figure 20, testing at high R-ratio produces a lower ΔK_{TH}, suggesting that threshold tests should be conducted at an R-ratio of 0.8 or higher. The data in Figure 19, 21, 22 and 24 all show that testing at higher R-ratios is more aggressive than testing at low R-ratios. From Figure 19 and Figure 20, it appears that an R-ratio of 0.8 or larger is needed to produce conservative crack growth data.

4.3 Threshold Effects

Testing at low ΔK levels is complicated by the effects of crack closure. Specimens tested in moist air have oxide films on the crack faces, which may be thickened by fretting oxidation. These films wedge the crack open, reducing effective ΔK levels at the crack tip. This does not happen in dry hydrogen, so near-threshold crack growth rates in dry hydrogen are higher than those in air. The same is true for dry argon, although it is inert. Near-threshold fatigue crack growth rates in dry argon are comparable to those measured in hydrogen, and higher than those measured in air. Correspondingly, ΔK_{TH} values measured in dry hydrogen and dry argon are similar, and both are lower than ΔK_{TH} measured in air [18]. Threshold behavior is influenced by R-ratio. Figure 26 shows that, as R-ratio is increased, ΔK_{TH} approaches 4 MPa√m (4.4 Ksi√in).

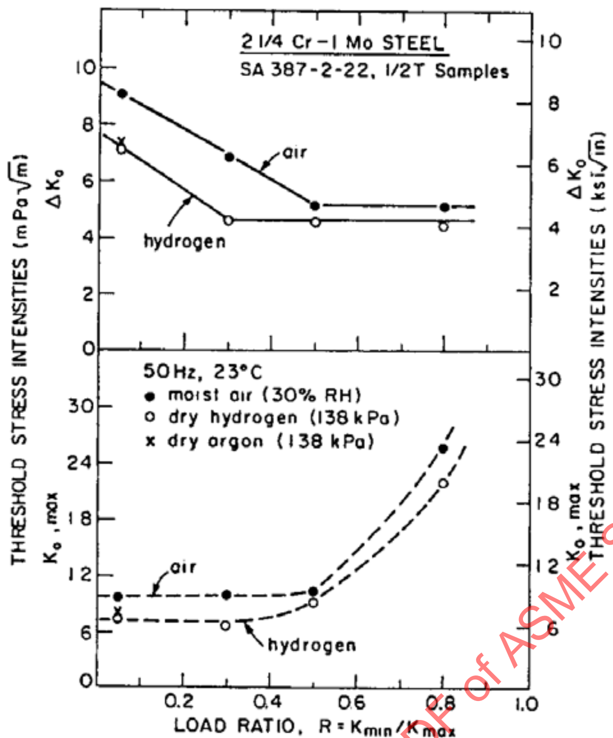

Figure 26 - Variation of Alternating and Maximum Stress Intensities at Threshold, ΔK_0 and $K_{0,max}$, Respectively, with Load Ratio R for SA387-2-22 Tested in Moist Air and Dry Hydrogen at 50 Hz [18]

Threshold values for fatigue crack growth in hydrogen are discussed in Reference [17]. Figure 27 and Figure 28 present threshold data for 2.25 Cr 1Mo steel and X70 pipeline steel. These data support a threshold value between 3 and 4 MPa√m (3.3 to 4.4 Ksi√in) at R=0.75. The data in Figure 20 support an even lower threshold of 2.0 MPa√m (2.2 Ksi√in). In agreement with Ritchie, et al [18], the threshold decreases as R-ratio is increased.

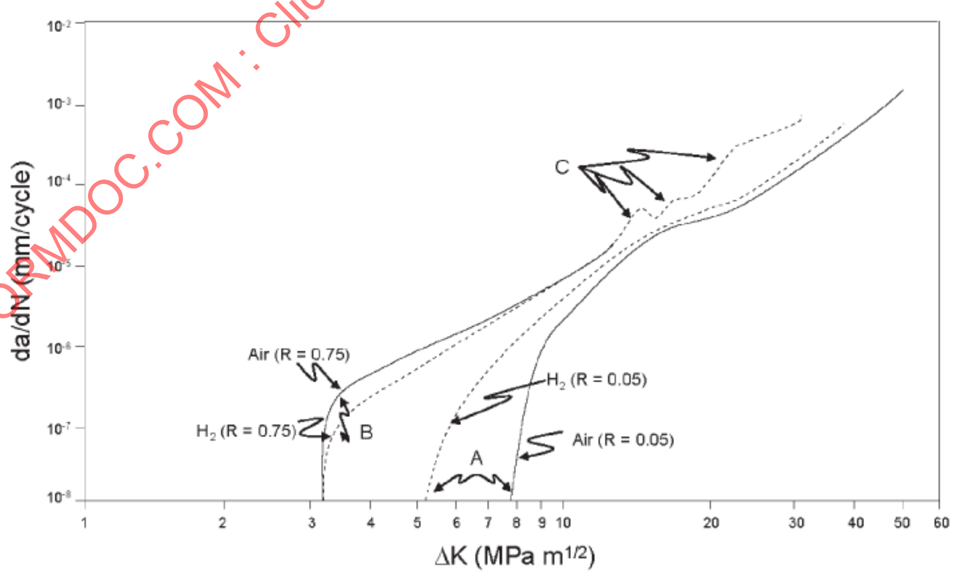

Figure 27 - Fatigue Crack Growth in 2-1/4 Cr 1 Mo Steel Tested in Moist Air and Dry Hydrogen at Atmospheric Pressure [19]