COMPATIBILITY AND SUITABILITY OF EXISTING STEEL PIPELINES FOR TRANSPORT OF HYDROGEN-NATURAL GAS BLENDS

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ABSTRACT

Hydrogen is being considered as a pathway to decarbonize large energy systems and for utility-scale energy storage. As these applications grow, transportation infrastructure that can accommodate large quantities of hydrogen will be needed. Many millions of tons of hydrogen are already consumed annually, some of which is transported in dedicated hydrogen pipelines. The materials and operation of these hydrogen pipeline systems, however, are managed with more constraints than a conventional natural gas pipeline. Transitional strategies for deep decarbonization of energy systems include blending hydrogen into existing natural gas systems, where the materials and operations may not have the same controls. This study explores the hydrogen compatibility of existing pipeline steels and the suitability of these steels in hydrogen pipeline systems. Representative fracture and fatigue properties of pipeline-grade steels in gaseous hydrogen are summarized from the literature. These properties are then considered in idealized design life calculations to inform materials performance for a typical gas pipeline.

1.0 INTRODUCTION

Hydrogen is a convenient way to store electrical energy when excess energy is available or it cannot be easily transported. The advantages of hydrogen are multiplied when existing infrastructure can be put to use for storing and distribution of the hydrogen. Natural gas pipelines are one example of where opportunity exists in this regard. However, hydrogen is known to embrittle pipeline steels [1], leading to safety concerns.

Hydrogen embrittlement is somewhat of a misnomer, as many structural metals remain very ductile when exposed to gaseous hydrogen [1]. While most structural metals do show reduced ductility, reduced fracture resistance and accelerated fatigue crack growth rates in hydrogen environments, low-strength steels exposed to gaseous hydrogen generally remain more ductile than aluminum alloys in air. Indeed, thousands of kilometers of hydrogen pipeline (of low-strength steels) are used to distribute hydrogen for the oil and gas industry. Hydrogen pipelines are managed with more constraints and operated differently than a conventional natural gas pipeline; therefore, blending gaseous hydrogen into natural gas infrastructure must be carefully considered.

Recently, the American Society of Mechanical Engineers (ASME) has adopted a code specifically for hydrogen piping and pipelines: ASME Pressure Piping Code B31.12. Additionally, ASME has adopted new language in the Boiler and Pressure Vessel Code (Section VIII, Division 3, Article KD-10) for qualifying pressure vessels for hydrogen service. These rules can be adopted for pipelines as well, as part of a fitness-for-service management program.

This work is motivated by the desire to demonstrate a fracture mechanics approach to fitness-for-service for pipelines distributing blended hydrogen and natural gases. This effort does not seek a comprehensive fitness-for-service analysis, rather we seek to analyze the fatigue growth of small defects based on literature data generated in relevant gaseous hydrogen environments.

2.0 FATIGUE CRACK GROWTH ANALYSIS PROCEDURES

The service life of a cylindrical shell structure (such as pressure vessel or pipeline) can be evaluated by assuming an initial defect and propagating a crack from this defect based on measured relationships between the driving force and the fatigue crack growth rate. For the purposes of this study, we assume an initial defect with an elliptical shape that grows as a crack represented by $a/2c$ and shown in Figure 1 for the specific case of $a/2c = 1/3$. We also assume that these cracks propagate under the influence of the hoop stress, therefore the elliptical cracks are aligned along the axis of the pipe. The driving force is greater for longer cracks, in other words for lower values of $a/2c$. For the purposes of this analysis, the relationships from Anderson [2] for the driving force for crack extension (ΔK) are used.

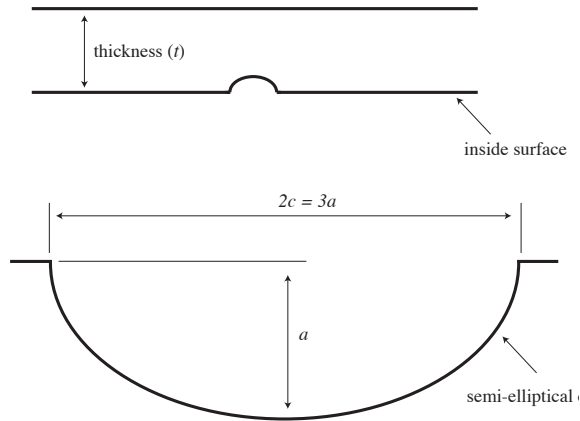

Figure 1. Schematic of semi-elliptical crack in the wall of a cylindrical shell. A semi-circular crack is characterized by $2c = 2a$.

Anderson gives the driving force for a part-through internal defect of finite length as:

$$\Delta K = \left(p_{\max} - p_{\min}\right)\left(\frac{r}{t}\sqrt{\frac{\pi a}{Q}}\right)F \tag{1}$$

where p_{max} and p_{min} are the maximum and minimum pressure during cycling, r is the average of the inside and outside radius of the pipeline wall, t is the wall thickness of the pipeline, Q is a geometric constant equal to 2.4640 for a semi-circular crack, and F is a functional form that describes the size of the crack as

$$F = 1.12 + 0.053\xi + 0.0055\xi^2 + \left(1 + 0.02\xi + 0.0191\xi^2\right)\frac{\left(20 - \frac{r}{t}\right)^2}{1400} \tag{2}$$

with the normalized crack length (ξ) equal to

$$\xi = \frac{2c}{t}. \tag{3}$$

These relationships are only valid for $a/t < 0.8$, therefore failure is assumed when the depth of the crack reaches 80% of the wall thickness ($a = 0.8t$). The crack depth (a) as a function of cycle number (N) is determined by numerical integration according to

$$a_{i+1} = a_i + \left.\frac{da}{dN}\right)_i \Delta N \tag{4}$$

where

$$\left.\frac{da}{dN}\right)_i = C\left(\Delta K_i\right)^m \tag{5}$$

C and *m* are constants.

To account for measurements where the applied load ratio (R) in fatigue crack growth testing is different from the pressure cycles subjected to the pipeline ($R^* = p_{min}/p_{max}$), the fatigue crack growth relationship (equation 5) can be modified according to the recommendations from ASME BPVC, following

$$C^* = C\frac{\left(1+C_3 R^*\right)}{\left(1+C_3 R\right)}$$

(6)

where C_3 is 3.53 and C^* corresponds to the pressure cycle in the pipeline.

3.0 PIPELINE OPERATION AND MATERIALS DATA

For the purposes of demonstrating the analysis, we consider a pipeline of X70 API 5L grade steel with an outer diameter (OD) of 762 mm and wall thickness (*t*) of 15.9 mm. This pipeline is assumed to operate at a maximum pressure of 7 MPa, and experiences two pressure cycles per day to a minimum pressure of 4 MPa. This cycle is idealized as a sine wave with a frequency of 730 cycles per year and a load ratio (R) of 0.57.

Fracture and fatigue data for several pipeline steels are reported in Refs. [3-5] for tests conducted in gaseous hydrogen at pressure of 5.5 and 21 MPa. The fracture and fatigue testing was conducted following ASTM E1820 and E647 respectively. Tests were conducted for load ratios of 0.1 and 0.5 with a frequency of 1 Hz. The data in Figure 2 show that the fatigue crack growth rates are relatively insensitive to the alloy when tested in gaseous hydrogen at pressure of 21 MPa for load ratio of 0.1. Similar data is plotted in Figure 3 for two hydrogen pressures (5 and 21 MPa) for load ratio of 0.5. These data suggest that the effect of pressure is modest for the ΔK range associated with this data. Power-law fits to the data from Ref. [3] are given in Table 1 for the load ratio of 0.5; this fit is intended to bound the upper limit in fatigue crack growth rates for these data. The values of C are corrected to $R^* = 0.57$ (C^*) from equation 6 and given in Table 1. These power law relationships from Table 1 are plotted in Figure 4 for $\Delta K > 6$ MPa m$^{1/2}$ along with the experimentally determined data at pressure of 21 MPa from Refs. [3,5].

Table 1. Fatigue crack growth constants for API X70 pipeline steel measured in gaseous hydrogen. Measurements were made with $R = 0.5$ and frequency of 1 Hz; fatigue crack growth rates at $R^* = 0.57$ are determined using equation 6.

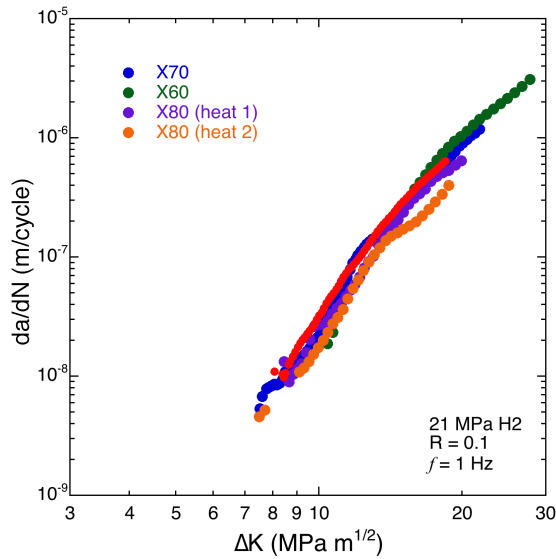| ΔK (MPa m$^{1/2}$)	R	C (m/cycle)	m	Ref.
$\Delta K < 6$	0.50	2.4 x 10^{-12}	3.5	Fit to [3]
	0.57	2.6 x 10^{-12}	3.5	Eqn 6
$6 \leq \Delta K < 11$	0.50	3.6 x 10^{-16}	8.5	Fit to [3]
	0.57	3.9 x 10^{-14}	8.5	Eqn 6
$\Delta K \geq 11$	0.50	4.6 x 10^{-11}	3.6	Fit to [3]
	0.57	5.0 x 10^{-11}	3.6	Eqn 6

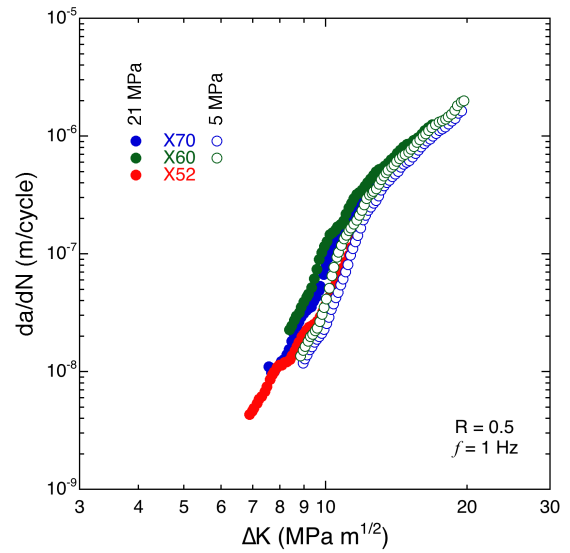Figure 2. Fatigue crack growth rates for several pipeline steels for load ratio of 0.1 [3,4]

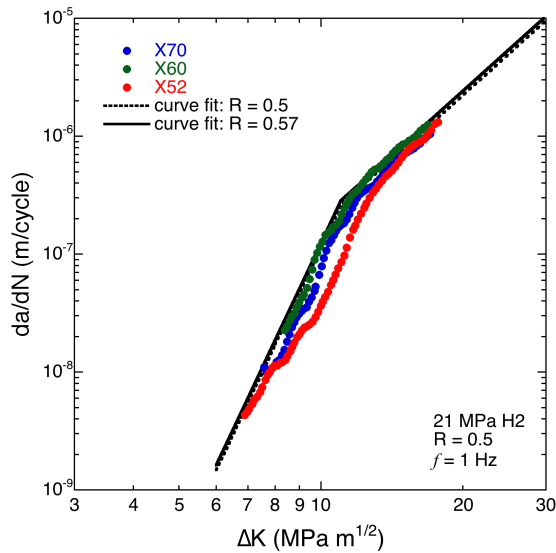Figure 3. Fatigue crack growth rates at two hydrogen pressures for load ratio of 0.5 [3,5]

Figure 4. Curve fit and determination of fatigue crack growth rates for pipeline steels with $R^* = 0.57$ (using equation 6); data from Figure 3.

4. ANALYSIS RESULTS AND DISCUSSION

For the purposes of this study, large initial defects are considered with depths that are between 30 and 50% of the wall thickness. Two propagating crack geometries are considered: a semi-elliptical crack following the guidance in the ASME Boiler and Pressure Vessel Code with $a/2c = 1/3$, and the semi-circular geometry ($a/2c = 1/2$). The evolution of several cracks is shown in Figure 5 and in all cases the cracks require tens of thousands of cycles for substantial growth. For the cracks growing with a semi-elliptical shape and initial depth of 30% of the wall, the initial defect shows little change over 50,000 cycles, which represents almost 70 years of pressure cycling at 2 cycles per day. The deeper initial defect (40%) requires over 30,000 cycles (>40 years) to reach a depth of 80% for the wall thickness.

This calculation is conservative in several aspects, including the semi-elliptical crack propagating with an aspect ratio of $a/2c = 1/3$, as the natural aspect ratio of a thumbnail crack will be $a/2c = 1/2$ [6,7]. In previous work on hydrogen pressure vessels, defects are shown to initiate semi-circular cracks when exposed to hydrogen pressure cycles. This semi-circular configuration is inherently stable because the driving force is uniform along the front of the crack. For an elliptically-shaped crack, the driving force

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is maximum in the middle (i.e., at the deepest point of the crack front) and a minimum at the ends (i.e., at the inside surface), thus promoting the semi-circular shape as the crack grows. If we consider the semi-circular crack, an initial defect of 50% of the wall thickness will grow to a crack depth (a/t) of < 0.7 over 70 years, while the smaller defect representing 40% of the wall grows nominally to $a/t < 0.45$.

The initial driving force for crack extension of a 40% deep semi-elliptical defect for the pipeline conditions described here is approximately $\Delta K = 9$ MPa m$^{1/2}$. At this value of the stress intensity factor range, the fatigue crack growth is accelerated by gaseous hydrogen, although fatigue crack growth rate is relatively small, about 5×10^{-8} m/cycle. Once the crack has reached $a/t = 0.80$, the fatigue crack growth rate is an order of magnitude faster. For such a crack ($a/t = 0.8$), the maximum applied stress intensity factor (K_{max}) is about 32 MPa m$^{1/2}$, which is modest compared to the reported fracture resistance of X70 steel in gaseous hydrogen: >80 MPa m$^{1/2}$ [3]. Subcritical crack extension can be considered further, by evaluating K_{max} for a thru-wall crack of length twice the thickness, which is about 62 MPa m$^{1/2}$, also lower than the fracture resistance reported in high-pressure gaseous hydrogen [3]. Unlike the fatigue crack growth behavior (Figure 2), fracture resistance is sensitive to pressure, therefore, the fracture resistance of X70 (and other pipeline steels) in hydrogen-natural gas mixtures with relatively low hydrogen partial pressure can be anticipated to be greater than measurements reported in high pressure hydrogen (such as [3-5]). In short, subcritical crack growth in the X70 steel should not occur in typical pipe dimensions, if a crack propagates through the wall as a thumbnail crack in gaseous hydrogen.
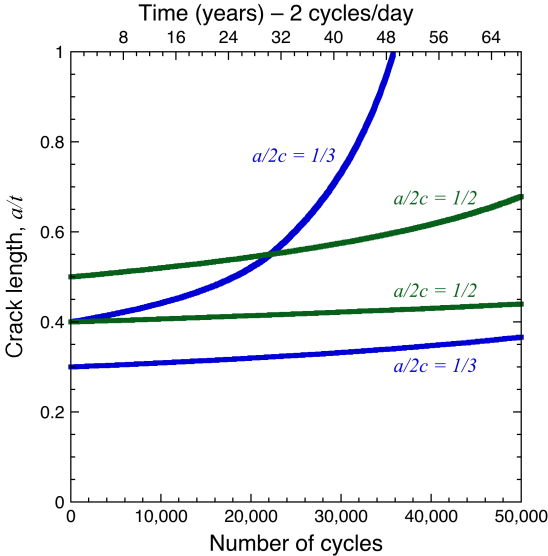

Figure 5. Crack extension considering propagating semi-elliptical defects ($a/2c = 1/3$) with intial depth of 30 and 40% of the wall thickness, and propagating semi-circular defects ($a/2c = 1/2$) with intial depth of 40 and 50% wall thickness.

It is important to recognize that the pipeline described in this document represents a relatively conservative design. The maximum wall stress in this pipe is less than 30% of the tensile strength of a typical X70 steel [3]. Transportable gas cylinders that are used for distributing hydrogen, in comparison, typically limit the maximum hoop stress to not more than 40% of the tensile strength [6,7]. Additionally, low-strength quench and tempered Cr-Mo steels show very similar fatigue crack growth in gaseous hydrogen as the pipeline steels (see also [8] in these proceedings) and are used extensively to transport small quantities of gaseous hydrogen [6,7] as well as to store large quantities of hydrogen at pressure approaching 100 MPa for stationary storage applications [9,10]. In general, low-strength steels (yield strength less than 700 MPa) are commonly employed in hydrogen service as pressure vessels and pipelines, and these steels commonly feature similar fracture and fatigue behavior in gaseous hydrogen.

The analysis described here assumes data measured in gaseous hydrogen at pressure of 21 MPa, compared to the operation pressure of 7 MPa for the pipeline. While the fatigue crack growth rate (for the same mechanical conditions) may be slightly lower at the lower pressure, the available data do not show a large effect of pressure on pipeline steels [3,11]. Therefore, to first order, mixing hydrogen at a

low partial pressure (such as 0.1 MPa or 1 MPa) into existing natural gas pipelines is the same as converting the pipeline for use with 100% hydrogen. In other words, there is no clear lower threshold of hydrogen quantity in mixed gas streams, below which the "embrittling" effects of hydrogen are mitigated – at least for the available data. The driving force for crack extension under fatigue should be dominated by the pressure cycle and the fatigue crack growth response (such as shown in Figure 4) for any partial pressure of hydrogen.

While the effects of hydrogen quantity may not strongly affect fatigue crack growth in mixed gases, there are gas species that can mitigate hydrogen-assisted fatigue if present in sufficient quantity. Oxygen, for example, has been shown to delay the effects of hydrogen to higher driving forces [12], as oxygen competes with hydrogen for surface adsorption sites. Therefore, oxygen and other strongly adsorbing gases (such as carbon monoxide) can mitigate the effects of hydrogen when they are present in natural gas-hydrogen mixtures, at least at lower driving forces. The competition between gaseous species for the surface adsorption sites depends sensitively on the rate at which new crack surface is generated and transport of the species to the newly created metal surfaces. However, establishing similitude between the local environment in a fatigue test conducted in hydrogen with specific quantity of oxygen and the local environment around a crack in a natural gas-hydrogen pipeline remains a challenge. Additionally, clean sources of methane may not contain oxygen or carbon monoxide in sufficient quantity to effectively passivate a defect or crack. However, if the effects of hydrogen are controlled by gaseous diffusion of hydrogen to the crack tip, the effects of hydrogen may be mitigated to some extent, even in the presence of inert gases.

The data and analysis presented here is based on base metal properties. In general, weld microstructures are often assumed to be a concern. Tensile residual stresses and welding defects can certainly have a negative effect on the growth of defects in pipelines; however, the available literature data of pipeline base metals, weld fusion zones and heat-affected zones in standard pipeline configurations show very similar fatigue crack growth rates in gaseous hydrogen [13-16]. Of course, welding practice that produces dissimilar composition or untempered (high-strength) martensite may generate microstructures that are more sensitive to hydrogen.

5.0 SUMMARY

This report evaluates hydrogen-assisted fatigue crack extension of a thumbnail crack in X70 pipeline steel. For a conservatively operated pipeline where the maximum wall stress is around 30% of the tensile strength of the steel, tens of thousands of cycles are required to extend a large pre-existing defect with an initial depth of 40% through the wall thickness. Since a pipeline is unlikely to see many deep pressure cycles on the time scale of a day, it can theoretically take decades to extend the crack in fatigue. Once a thumbnail crack extends through the entire pipe wall, the driving force for crack extension is still lower than the threshold for subcritical crack growth in gaseous hydrogen.

Additionally, reviewing the data in the literature, the following conclusions can be established:

- Low concentration of hydrogen in natural gas or other gaseous will not significantly change fatigue crack growth compared to 100% hydrogen

- Strongly adsorbing species in hydrogen or hydrogen gas mixtures, such as oxygen and carbon monoxide, may delay fatigue crack growth acceleration under certain circumstances, although the conditions for which hydrogen effects are mitigated are generally difficult to predict

- Welds, in general, are no more susceptible than the base material

While fatigue life calculations are very sensitive to the conditions of the growing crack, for shallow, infrequent pressure cycles and a well behaved (but growing) defect, the predicted lifetime of pipeline for a hydrogen-natural gas blend and for 100% hydrogen is about the same and many decades.

6.0 ACKNOWLEDGMENTS

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