

Fatigue and Static Crack Growth Rate Study of X-65 Line Pipe Steel in Gas Transmission Pipeline Applications

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ABSTRACT

Hydrogen embrittlement phenomenon has been investigated in the current study by performing crack growth rate (CGR) measurements under static and fatigue loading conditions on fracture mechanics-based specimen extracted from X-65 line pipe steel. The source of hydrogen inside the line pipe could be the green/blue hydrogen blending that is being considered in an effort to reduce the carbon footprint of the oil and gas industry. Other environments could be aqueous impurities such as NaCl in presence of the transported CO₂ and hydrogen charging conditions created by a possible use of sacrificial metallic coatings. The effect of cyclic loading frequency on fatigue crack growth rate (FCGR) has been investigated in a simplified hydrogen charging environment - 3.5% NaCl solutions containing CO₂ at room temperature, with imposed CP. The applied hydrogen charging conditions were electrochemical potentials associated with mixed potential of Zn and/or Al based coatings, being considered for sacrificial metal coatings. FCGR in environment was found to be significantly higher than in-air values and was also found to increase with decrease in frequency of applied fatigue loading, suggesting susceptibility to environmentally assisted cracking.

A segmented crevice electrode setup was designed to simulate electrochemical conditions experienced by crack tip for a given bulk chemistry and cathodic polarization (CP) applied to freely exposed surface. It was found that the CP level experienced by electrodes inside the crevice was not the same as that of the freely exposed surface in solution. These experiments supplement the results of the CGR measurement tests.

Key words: X-65, Line pipe steel, Fatigue crack growth rate, Static crack growth rate, Hydrogen embrittlement, Cathodic protection

INTRODUCTION

The United States has a large investment in natural gas (NG) transmission pipelines. The need for these pipelines is only expected to increase in the future, with these pipelines potentially being used, in a blended or batched mode, for transporting CO₂ and hydrogen. There are currently about 300,000 miles of transmission pipeline¹. With this large installed base, it is in the country's interest to extend pipeline lifespan. While the exterior of a pipeline is protected by a combination of organic coatings and cathodic protection, the interior is typically bare steel.

Hydrogen embrittlement issues have long been studied in reference to exterior protection of NG pipelines. The interior of the pipeline introduces a different environment. This research was conducted to study the phenomenon of hydrogen embrittlement that can be created by environments in the interior of the pipeline. The source of hydrogen could be the green/blue hydrogen blending, that is being considered in an effort to reduce the carbon footprint of the oil and gas industry. Other environments, although less likely, could include aqueous impurities such as NaCl in presence of the transported CO₂ and hydrogen charging conditions created by a possible use of protective sacrificial metallic coatings. For sacrificial metallic coatings it is expected that primarily Zn/Al based coatings will be used for this application. While these coatings serve to protect the steel, they do lead to production and ingress of hydrogen. The presence of hydrogen in steel, irrespective of the source, can lead to increased susceptibility to cracking under high static and cyclic loads associated with steady state, startup and shut down conditions.

NG pipelines are typically made of longitudinally or spirally welded API 5L, often of the X65 grade, steel². These pipelines may have weld and corrosion defects which can serve as crack initiation sites. Hence it is important to understand the crack growth rate behavior of these steels under hydrogen charging conditions. The current study was performed on parent material from X-65 steel. Future studies can build upon this work to compare the behavior of the weld region. Typical pipeline operations involve low cycle fatigue events associated with pressure transients, followed by long term holds under constant load operating conditions. The severity of hydrogen embrittlement may vary depending on partial pressure of hydrogen in the blended hydrogen/natural gas mixtures. It is to be noted that these systems may be operated at higher pressure and the intent here is not to replicate the exact conditions but to present the effect hydrogen presence in the steel can have on fatigue and static CGR properties. In case of hydrogen charging conditions arising from possible use of coatings, electrochemical charging potential may vary as a function of life and also as a result of areas where IR drops may exist, such as cracks. In order to predict pipeline performance over the course of the lifetime, it is important to characterize the crack growth rate behavior under a range of potential charging condition that exist. Tests are required to evaluate the environmentally assisted cracking (EAC) behavior in hydrogen charging conditions and co-relate with the hydrogen concentration in the steel under these conditions. These hydrogen charging conditions have been achieved in this laboratory study using electrochemistry in the form of cathodic protection in a general chloride containing solution with a pH of 4, and not a simulation of the exact environments.

The study reported in this work was performed with the objective of understanding the impact of important environmental and loading conditions on susceptibility of the material to EAC. A fracture mechanics based single compact tension specimen was used to explore the effect of mechanical loading parameters - stress intensity factor – K , ΔK and frequency of loading in simulated environment of interest.

EXPERIMENTAL

Material

The API 5L specifications provides requirements for pipeline steels and X-65 grade is a commonly used grade. While API 5L is generally a mechanical property driven specification and there are a few chemical requirements. The specifications describe low carbon steels. Table 1 presents the chemistry of the X-65 material that was used in this investigation along with the allowed specs for API 5L – X-65 material. The test material used was in a strain-aged condition. The pipe had been strained to 1.12% strain/cycle for 4 cycles and aged at 250 °C for 1 hour. The resulting yield strength of the material was 92 ksi (635 MPa) and is higher as compared to typical X-65 grade. Pipelines are commonly subject to plastic strains during installation as well as mechanical damage due to dents. The presence of plastic strains in combination to exposure to slightly elevated temperatures over extended periods can cause strain aging in C-Mn steels. The strain-aged microstructure can be simulated by elevated temperature shorter duration exposure. The basis for selecting the temperature and duration for the treatment was DNVGL-ST-F101³. Hence, the strain aging treatment was performed to simulate a microstructural state that is expected in service, while being on a relatively conservative side.

Test Environment

The hydrogen charging environmental conditions were produced using a 3.5 wt% sodium chloride solution with a 0.4 wt% sodium acetate to provide buffering adjusted to an initial pH of 4 using hydrochloric acid. The test solution was saturated with research grade carbon dioxide at ambient pressure. The tests were performed at 25 °C. Typical cathodic protection (CP) applied during the test was -1050 mV vs a saturated calomel reference electrode (SCE), to simulate the potentials associated with the mixed potential of Zn and/or Al based metallic coatings. In some cases, the effect of more negative applied potential was also studied to determine its effect on the measured parameters.

Test Approach for Crack Growth Rate Testing

A fracture mechanics-based test methodology was used to characterize the fatigue and static crack growth rate response of the studied steel in the above environment of interest. A single specimen of compact tension (CT) design was used to characterize the fatigue crack growth rate (FCGR) and static crack growth rate (SCGR) under several loading conditions, similar to approach reported earlier by Thodla et al⁴. The test method allows transition from an FCGR test to a constant K/static crack growth rate test on the same specimen, hence enabling characterizing both of these primary modes of damage for transmission pipelines. FCGR measurements were performed over a range of frequencies at different stress intensity factor ranges (ΔK). The fatigue loading was applied using an asymmetrical triangular waveform, where the rise time, t_{rise} , from minimum K, K_{min} to maximum K, K_{max} was 9 times the fall time, t_{fall} , from K_{max} to K_{min} . A schematic of the loading regime where FCGR was characterized is shown in Figure 1. The frequency of the period is defined as $1/(t_{\text{rise}}+t_{\text{fall}})$. The frequencies were typically in the range of 0.1 Hz to 1 mHz. The same specimen was used to characterize the crack growth response of the material under static loading condition in the studied environment by introducing periodic holds of increasing length (t_{hold}) at K_{max} . Such cycles result in a trapezoidal wave form as shown schematically in Figure 2. The higher time spent in the rise portion of the loading cycle is to allow for more damage accumulation during the same total cycle period. It is reasonable to assume that environmentally assisted crack propagation would likely occur during the rise time and hold periods of the loading cycle and not during the fall period of the loading cycle. This was done to transition from an environmentally assisted fatigue crack to a statically loaded crack under constant K conditions i.e, no cycling/unloading.

The desired K conditions were maintained by load adjustment or varying K as needed. The program adjusted loads only when the K changed by more than 0.1% due to crack growth. The program did not adjust loads when crack lengths appeared to decrease based on DCPD signals. Crack growth rates for

different loading conditions were calculated based on the slope of the crack length – ‘a’ vs time plot, during a given loading time interval. The frequency reported were calculated as $1/(t_{\text{rise}} + t_{\text{hold}} + t_{\text{fall}})$.

The CT specimen had a thickness of 1" (2.54 cm) and a width of 2" (5.08 cm). It was pre-cracked to a target a/W of 0.425 using a servo-hydraulic machine at a frequency of 20 Hz at an R ratio of 0.16 with the final ΔK of less than 15 ksi- $\sqrt{\text{in}}$ (16.5 MPa- $\sqrt{\text{m}}$) based on surface crack length measurements. The sample was then provided a side-groove of 5% of thickness on each side. Environmental interaction with the crack tip can result in crack branching, out of plane cracking, especially at lower frequencies. This can result in a different local stress at the crack tip than applied. Side grooving helps keep the crack tip planar during the test and hence was applied for the CT specimens. The specimens were machined such as the crack was in the L-C orientation.

The test vessel was configured with the CT test sample in the load train. The CT sample was isolated from the test vessel to prevent galvanic corrosion issues. It was also isolated from the servo electric test frame to prevent ground loop issues in the crack length monitoring system. The isolation of the sample from the frame was achieved using a pin-loaded clevice arrangement. The pins were ceramic coated to maintain isolation from the test frame. A platinized niobium wire was used as the counter electrode while a SCE was used as the reference electrode for the electrochemical circuit. A potentiostat was used to apply the CP on the X-65 sample.

The CT sample was instrumented to measure in-situ crack length using the direct current potential drop (DCPD) method. The current/potential leads were made of platinum and enclosed in PTFE heat shrink tubing. They were spot welded to the specimen and coated with epoxy to prevent corrosion at the junction. A constant current of 4 A was applied for DCPD crack length monitoring. The resultant voltage drop across the crack mouth was measured using a high-resolution digital multimeter (DMM) and switch. Crack length was calculated from voltage drop using Johnson equation (equation A1.2 in ASTM E1457)⁵. A LabVIEW® program was used to record the data. Reference voltage signals were measured from the reference sample, which was exposed to the same environment/conditions as the test sample but with no load applied. The measured voltage from the test sample was normalized with the voltage readings from the reference sample to normalize for noise in the measurement and test systems.

The data acquisition system collected voltage signals for crack length determination and load-line displacement data. The system is designed to change loads for the measured crack length to maintain or change stress intensity factor.

The test cell was closed and flushed with ultra high purity nitrogen to remove oxygen from the test vessel. The test chemistry was prepared, as described in “Test Environment” section, in a pre-conditioning vessel (PCV) and purged with research grade carbon dioxide gas for at least 12 hours to remove dissolved oxygen from the test solution. The de-oxygenated solution was then transferred to the test vessel under carbon dioxide pressure. The X-65 CT test sample was soaked in the test solution for 4 days prior to start of loading. This was done to allow enough time for the hydrogen generated as a result of the applied cathodic protection to diffuse through the material and the test to provide representative results of the hydrogen embrittlement phenomenon for the material/environment combination.

Table 1
X-65 steel composition (compared with specifications from API 5L – X65)

	Fe	C	Mn	Si	P	S	Ti
API 5L (X-65)	Balance	< 0.22	< 1.44	--	< 0.025	< 0.015	< 0.06
X-65 used	Balance	0.09	1.07	0.27	0.012	0.001	0.002

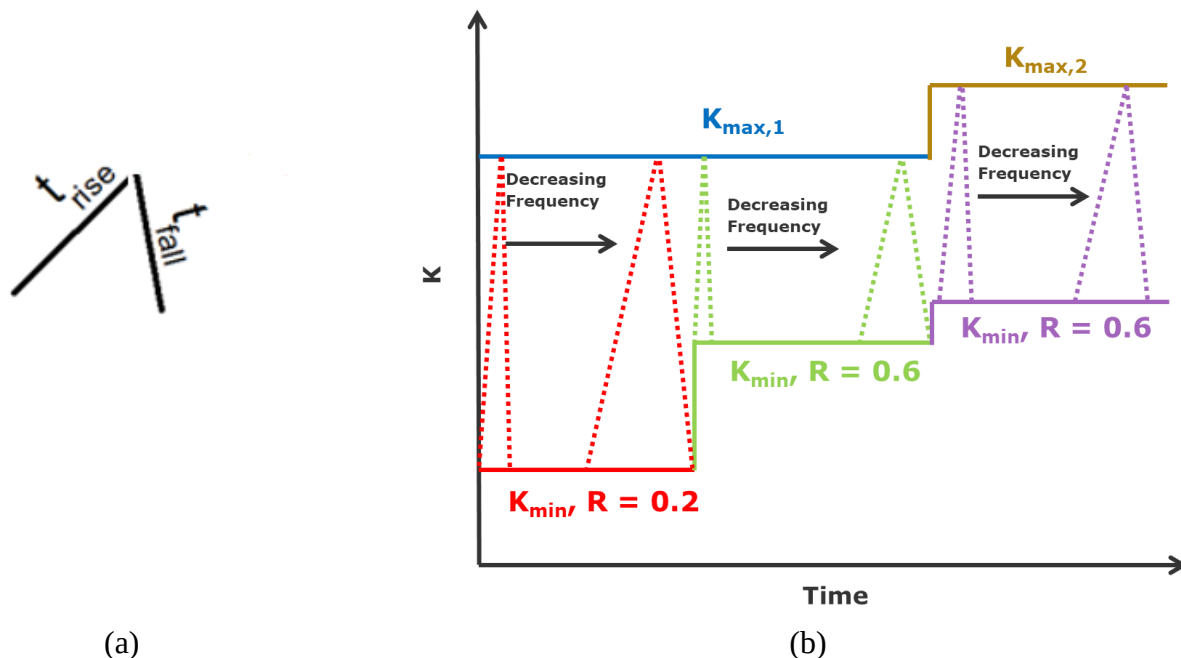


Figure 1: Schematic illustration of the approach to develop FCGR relation with frequency at different ΔK .

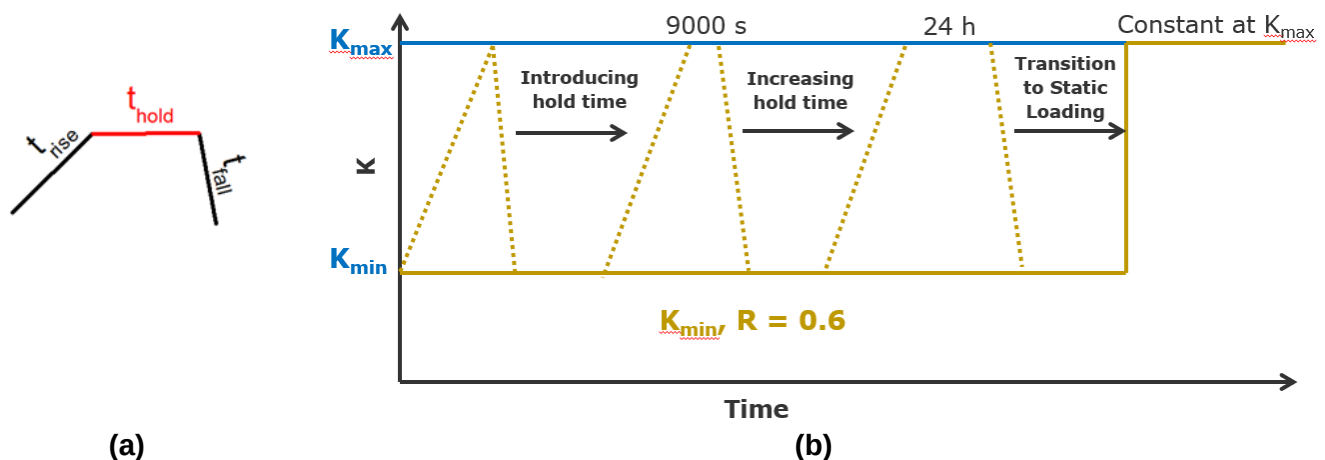


Figure 2: Schematic illustration of the approach to transition to constant K .

Segmented Crevice Electrode Experiment

A segmented crevice electrode experiment was a designed device, based on work done by Gangloff et al⁶, to simulate conditions that exist at bottom of crack tip. An attempt was made to study the pH and potential at the bottom of crack tip with the designed set up. The set up is based on a crevice scaling law which establishes electrochemical equivalence between a rescaled crack and small length scale cracks⁷. The segmented electrode assembly was created by mounting X-65 electrodes as shown in Figure 3 and electrically coupling them outside the test chamber. The crevice gap (G) was created