Modelling environmentally assisted cracking in pipeline steels

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Abstract

An investigation has been conducted on the environmentally assisted cracking (EAC) of ferritic-pearlitic pipeline steels in contact with simulated groundwater. The loading and environmental conditions were similar to those for buried natural gas pipelines in service. An anaerobic, dilute near-neutral pH solution was used in conjunction with the open-circuit potential for this system. The intent of this work was to determine and model the growth rate of environmentally assisted cracks in the form of transgranular stress corrosion cracks (TGSCC) that have been observed following field investigations. Combinations of low frequency cycling and high stress ratio R (=minimum load/maximum load), can produce transgranular fracture and a quantitative relationship between these two parameters has been developed for the conditions under which TGSCC takes place. The recorded crack growth rates were similar to those in the field and a superposition model was applied to the experimental data, giving good agreement between the observed and predicted single crack growth rates. Applying the superposition model to operating natural gas pipeline data indicated that more realistic predictions of crack growth would result by considering the interaction of multiple cracks, as observed in the field colonies.
Keywords: crack growth, near-neutral pH solution, pipeline steel, superposition model, transgranular stress corrosion cracking.

1 Introduction

Pipeline steels with a ferritic-pearlitic microstructure are highly susceptible to environmentally assisted cracking (EAC) known as a transgranular stress corrosion cracking (TGSCC) in dilute near-neutral (pH ~ 6.5) solutions [1]. This

WIT Transactions on Engineering Sciences, Vol 54,
www.witpress.com, ISSN 1743-3533 (on-line)
doi:10.2495/ECOR070241

form of EAC which appears to be insensitive to temperature has been observed under the disbonded region of the pipeline coating where cathodic protection is not effective. Hydrogen assisted cracking due to the cathodic reaction at the crack tip and subsequent entry into the steel has been identified as the active mechanism [1,2]. TGSCC is termed “near neutral SCC” since it is uniquely different from intergranular SCC that is observed in concentrated carbonate/bicarbonate electrolytes of high pH (~10) at slightly elevated temperatures [3]. However, it is likely that a general four stage model proposed by Parkins [4], originally for the high pH case, is applicable to near-neutral SCC. It is expected that the first stage involves the breakdown of the pipe coating. This is followed by the initiation, growth and coalescence of microcracks forming a colony of very small individual macro-cracks. During the third stage, these grow and coalesce. If sufficient cracks coalesce to form a dominant, long shallow crack, relatively rapid crack growth will lead to failure. In most cases, however, cracks become dormant throughout the life-time of the pipeline [4].

The purpose of this work is to study the morphology and growth of single EAC cracks and apply a superposition model [5] to describe the later stages of crack growth using laboratory testing techniques that duplicate pipeline operating conditions. This model forms the basis for predicting the remaining life when the natural gas pipeline stress histories are analyzed.

2 Experimental procedure

Tests were carried out by Zhang et al [5] on a section of low alloy pipeline steel (API X60) 510 mm in diameter with a wall thickness of 6.35 mm. The section had been removed from service by Trans Canada Pipelines Ltd. in 1988 when some TGSCC colonies were discovered after 16 years of operation. The chemical composition of this steel was 0.22% C, 1.36% Mn, 0.34% Si, 0.018% S, 0.009% P, 0.025% Ni, 0.08% Cr, 0.01%Mo, 0.04% Cu, 0.22% Nb with traces of V, Ti, B and Al. The microstructure consisted of fine ferrite-pearlite with an average ferrite grain size of ~ 14μm. The specified minimum yield strength (SMYS) was 414 MPa, and the measured yield stress varied between 421 MPa and 470 MPa.

After conducting dye-penetrant tests to verify that TGSCC was absent, rings 10.4 mm wide were cut from the hoop orientation of the pipe and then sectioned into four 360 mm long samples which would be the base for edge crack specimens. Longitudinal welds were excluded. Inner and outer surfaces of each specimen were degreased with trichlorethane and then cleaned using a water-based alkaline solution to avoid contaminating the test electrolyte.

Using a V-shaped cutter, three notches 1.5 mm deep and 0.35 mm wide were machined in the top surface of each edge crack specimen. In this manner, more data from each test specimen could be obtained. These notches were cut normal to the specimen axis and positioned 50 mm apart after it was determined by finite-element analysis that the notches would respond independently to the applied load.

Thomas et al [6] prepared wider (40 mm) surface cracked specimens with surface notches 3 mm long and 1.5 mm deep. For these surface crack samples, as well as the edge crack samples, three or four-point bending test rigs were used to grow a fatigue crack from each starter notch to a final depth of about 3 mm, measured using the potential drop technique. Care was taken to ensure that the maximum crack tip loading was lower than that used in subsequent EAC tests.

After fatigue precracking, the specimens were carefully hand-polished to a 0.06-μm alumina finish, and the precracks were opened slightly using a small calibrated loading rig to clearly identify each crack tip location. When open, K_{max} for each crack was lower than that used during the fatigue precracking stage. A pair of microhardness indentations was made adjacent to the tip of each precrack to serve as reference points for further measurements. This was carried out on both sides and lengths of the edge and surface cracked specimens respectively. The load was then removed. Photomicrographs of the crack tips were taken using an optical microscope, giving a permanent record of the relative positions of the microhardness indentations and crack tips in order to determine any possible future environmental crack growth. The notch and fatigue precrack depths were measured using an image analyzing system, as outlined by Thomas et al [6].

Cantilever bend loading on both the edge and surface cracked specimens was used for the EAC tests. Crack tip loading was characterized using the linear elastic stress intensity factor, K. The maximum values imposed on the edge and surface crack specimens were 38 MPa√m and 31 MPa√m respectively.

Simulated ground water solution identified by TransCanada Pipelines Ltd. (TCPL) as NS4 was used as the electrolyte. Its composition was KCI-0.122 g/L, $NaHCO_3$ - 0.483g/L, anhydrous $CaCl_2$-0.093g/L and $MgSO_4.7H_20$-0.131g/L. All the environmental tests were carried out in this electrolyte at a temperature of 25°C in an oxygen-free environment. To provide the anaerobic environment, a large polymethyl methacrylate (PMMA) box, which housed the steel specimen in a separate NS4 electrolyte chamber, was purged continuously with nitrogen. A controlled mixture of 5% carbon dioxide (CO_2) and nitrogen (N_2) was bubbled through the solution to maintain the pH at 6.5 to 7.0, which was monitored using a combination pH-saturated calomel reference electrode (SCE). It also was used to measure the corrosion potential (CP) and platinum potential (Pt). Small changes in pH were controlled by decreasing or increasing the flow of the CO_2/N_2 gas mixture. For long-term tests (~1 year), the pH was also measured periodically with litmus paper. The open-circuit potential for all the tests varied from ~0.75 V_{SCE} to -0.70 V_{SCE} and the Pt potential varied between -0.85 V_{SCE} and -0.35 V_{SCE} indicating that an anaerobic atmosphere was maintained throughout the test.

Cyclic loading was used in all the EAC tests with the stress ratios (R=minimum/maximum load) being controlled between 0 and 0.95. Loads were applied by a lever system and measured using a load cell. Examination of natural gas main pipeline data [7] revealed that most pressure fluctuations were in the range of R = 0.7 to 0.99. For pipeline inspection, pressure testing or other rare occasions, the stress ratio would drop to zero before returning to operating conditions. The present tests were carried out at frequencies of 5.8×10^{-2}Hz (5000 cycles per day) to 5.8×10^{-6} Hz (1 cycle every 2 days). Tests were carried out for periods lasting from 6 to 378 days.

Upon completion of each environmental test, the specimens were removed from the test rig and examined under the microscope. The final crack size was compared to the initial fatigue crack depth or length to compute crack growth. Following these observations, the specimens were immersed in liquid nitrogen for at least 10 min. and the cracks broken open under impact. The crack faces were cleaned ultrasonically for about 1 min in a solution containing 8.8 g 2-butyne-1.4-diol., 30 mL hydrochloric acid (HCl), and 100 mL distilled water. The cleaned surfaces were then examined in detail using the SEM to determine the fracture morphology and measure the extent of TGSCC.

3 Results and discussion

3.1 Fracture morphology

In general, transgranular fracture of the ferrite grains was observed following exposure in the NS4 electrolyte. As the exposure time increased, all cracks experienced secondary corrosion causing widening. The opposing crack flanks developed a mismatch, and the tip tended to become blunt and round. The degree to which these effects took place depended upon the test time and loading conditions. Based on measured crack widths at the microhardness indentation level, half crack depth and three-quarter crack depth, the average secondary corrosion rate was about 8.0 $(\pm 1.0) \times 10^{-10}$ mm/s, whereas the primary crack tip growth rate of about 2 $(\pm 1.0) \times 10^{-8}$ mm/s was much faster for K_{max} values in the range of 30 to 38 MPa$\sqrt{m}$.

Fracture surfaces consisting of transgranular facets mixed with microvoids (termed quasi-clearage) were observed on those specimens cycled at low frequencies and high R ratios. This fracture morphology was representative of TGSCC as opposed to corrosion fatigue which displayed ill-defined striations on specimens cycled at high frequencies and low R ratios. The influence of frequency (Hz) and R ratio can be summarized by the following equation:

$$R = 0.233 \log f + 1.19 \tag{1}$$

When the left hand side of eqn. (1) exceeds the right, TGSCC takes place. For example, TGSCC was observed on specimens cycled at the lower frequencies of 4.6×10^{-4} Hz (40 cycles/day) and 4.6×10^{-3} Hz (400 cycles/day) with R ratios of 0.5 and 0.82, respectively. However, TGSCC was also observed after cycling at a faster frequency of 5.8×10^{-2} Hz (5,000 cycles/day), albeit at the higher R ratios of 0.90 and 0.95. For those specimens cycled at higher frequencies, particularly with a low R ratio of 0.5, the fracture surface features were flat and striated, typical of corrosion fatigue.

Many horizontal grooves were observed on the fracture surface. These were the original locations of MnS inclusions. It was anticipated that dissolution in the

NS4 solution produced a more acidic local environment, resulting in the formation of brittle striations in the immediate vicinity. The corrosion product, iron sulphide (FeS), is soluble in the local crack tip environment and would supply hydrogen sulphide (H_2S) to enhance crack growth [9]. Using higher temperatures, Kuniya et al [10], studied the effects of MnS inclusion dissolution on SCC in carbon steels in pure water. Flat transgranular regions associated with SCC were found next to MnS inclusions, indicating hydrogen assisted cracking (HAC) [11]. This morphology was similar to the surface features observed next to partly dissolved MnS particles in the present tests.

3.2 Superposition model

A superposition model has been applied to describe the observed the present EAC growth behaviour [5]. The cyclic (mechanical) component is added to the environmental (time dependent) component. This linear superposition model [5] is given by:

$$\left(\frac{da}{dN}\right)_T = \left(\frac{da}{dN}\right)_{cyclic} + \left(\frac{da}{dt}\right)_{SCC} x \, \frac{1}{f} \tag{2}$$

where $(da/dN)_T$ is the total EAC growth rate (mm/cycle), $(da/dN)_{cyclic}$ is the cyclic crack growth rate in air (mm/cycle), $(da/dt)_{SCC}$ is the time dependent stress corrosion crack growth rate (mm/s) and f is the frequency (Hz). The cyclic component is given by:

$$(da/dN)_{cyclic} = C\Delta K^n \tag{3}$$

For an R-ratio of 0.5, the value of each constant in eqn.(3) is C=2.92 x 10^{-10} and n = 3.97 [12]. Using this data and applying a correction for R ratio according to the ASME Boiler and Pressure Vessel Code, Section XI [13] the crack growth rates in air at R ratios of 0.82 and 0.9 were predicted according to:

$$\left(\frac{da}{dN}\right)_{cyclic} = (2.03\times 10^{-11} + 5.4\times 10^{-10} R)\Delta K^{3.97} \tag{4}$$

Within experimental error, both edge and surface cracked specimens produced similar EAC results for the same testing conditions. For a given ΔK, the growth rate increased as the frequency decreased and, as expected, the crack growth rate per cycle decreased with ΔK for the same frequency.

The specimens cycled at the high R ratios of 0.82 and 0.9 and the low frequencies of 4.6x10^{-4} Hz (40 cycles/day) and 4.6x10^{-3} Hz (400 cycles/day) recorded crack growth rates higher than in air for the corresponding conditions. However, for those cycled at a frequency of 5.8x10^{-2} Hz (5,000 cycles/day) and an R ratio of 0.5, the crack growth rates in the NS4 solution fell below the air data. This suggested that a delay occurred in initiating an EAC crack from the fatigue precrack or that bifurcation occurred during early growth period resulting in lower growth rates.

In general, the superposition model described the experimental data extremely well. For higher ΔKs, the data converged to the cyclic component. At lower ΔKs, the data tended to a constant crack growth rate, independent of ΔK, and corresponded to the SCC growth rate divided by the frequency, given in eqn.(2). The SCC time dependent component was 2.94×10^{-9} mm/s.

EAC growth rate predictions for other combinations of stress ratios and frequencies can be made using the superposition model for this type of steel exposed to the dilute near-neutral pH solution. If only one cycle R=0 were imposed every four days (2.89×10^{-6} Hz), the predicted crack growth rate would be 1.37×10^{-3} mm/cycle. For comparison, when two surface cracked specimens were tested at the same frequency of 2.89×10^{-6} Hz and R ratio of 0 for 40 days in the NS4 solution, the crack growth rates averaged 8.0×10^{-4} mm/cycle in the first specimen and 1.63×10^{-3} mm/cycle in the second, giving an overall average of 1.22×10^{-3} mm/cycle, thereby showing good agreement between the observed and predicted crack growth rates.

3.3 Remaining life prediction

In order to apply the superposition model to predict the remaining life of a pipeline containing a known crack, threshold values of 5 MPa√m were assumed for both the cyclic (ΔK) and SCC (K_{max}) parts. This is reasonable since Marsh and Gerberich [14] showed that the threshold stress intensity factor range for a 400 MPa yield strength steel cycled at R=0 in hydrogen was 4 MPa√m. This environment is significant since hydrogen assisted cracking (HAC) is regarded as the operative SCC mechanism in near-neutral solutions [11]. As stated earlier, it is anticipated that atomic hydrogen, resulting from the cathodic reaction, diffuses into the steel and accumulates at regions of high stress triaxiality, lowering the cohesive strength ahead of a crack tip. Crack advance then occurs by tearing the weakened region, producing a quasi-cleavage fracture surface, as observed by the authors [5, 15].

Together with the superposition model, the threshold value can be applied to describe the growth behaviour of representative single cracks. Plumtree and Lambert [16] reported an average surface crack length and depth of 0.37 mm and 1.54 mm respectively, in a typical SCC colony on a 10 mm thick, 500 MPa (SMYS) natural gas pipeline. The deepest crack observed was 0.86 mm and the longest length was 3 mm. The nominal applied stress was 360 MPa, which corresponded to 72% SMYS. Using an R-ratio of 0.5, this resulted in initial stress intensity factor ranges of 4.3 MPa√m at the surface and 5.6 MPa√m at the deepest point. The maximum stress intensity factors were twice these values. With this information, a fracture mechanics model based on the superposition concept was developed for single crack growth in the pipeline [17]. Simulations were carried out until the crack reached 80% (8mm) wall thickness, which was regarded as failure. For a frequency of 4.6×10^{-4}Hz (40cycles/day), R ratio of 0.5 and SCC component of 2.94×10^{-9} mm/s, the average crack would be expected to grow to 80% thickness in 32.2 years. Using the same approach, the longest crack with a depth of 0.86 mm and length of 3.0 mm, would have a life of 26.2 years. However, it must be pointed out that most pressure fluctuations (99.7% on main transmission lines, 99.9% on lateral lines) were observed [7] to be within the range of R=0.7 to 0.99, as opposed to R=0.5, used in this example.

Bainbridge et al [18] analysed thirteen actual gas pipeline pressure histories. The data was processed using the rainflow counting technique to determine the stress ranges. This allowed EAC growth rates to be estimated by applying the superposition model. Simulations were performed for single semi-elliptical surface cracks in a 10 mm thick pipeline steel. Although the pipes for which the pressure histories were available had a variety of wall thicknesses, a standard thickness was used to provide the best basis for comparison of the effect of pressure history. By simulation, the crack was grown from an assumed initial depth of either 0.5 mm or 5 mm. The latter was used to assess how fatigue would affect the later stages of crack growth. In all cases, the final crack was again 8 mm deep. The crack aspect ratio (crack depth divided by the surface half-length) was 0.1 throughout the simulations, consistent with field observations. This constant value allowed pressure history effects to be isolated.

The expected life due to time dependent growth only, based on the constant crack growth rate over the remaining ligament (7.5 or 3 mm, depending on the initial crack depth) was considered, The time required to grow a crack from 0.5 mm to 8 mm deep would be 80.9 years, corresponding to a time dependent growth rate of 0.093 mm/year or $2.94\text{x}10^{-9}$ mm/sec, derived from the present experimental program. This is in agreement with the growth rates in the field which ranged from $3\text{x}10^{-9}$ mm/s to $2\text{x}10^{-8}$ mm/s. When the various pressure histories were considered, the total life was reduced from 80.9 yrs to a range of 68.7 to 80.8 yrs for the smaller initial crack size. For the larger initial 5 mm crack size, the life would be reduced from 32.4 years to within 21.3 to 32.3 years.

These are most interesting results, but it has to be stated that TGSCC has been found mainly in the crack colonies. A more practical approach would be to determine the growth in these colonies by considering the extent of interaction between neighbouring cracks. Plumtree and Lambert [16] considered a simple crack interaction model, based on examination of a limited series of solutions for pairs of surface cracks. In this case, crack coalescence was considered based on the simple proximity model. The results gave reasonable predictions of the growth behaviour of a crack colony. Coalescence dominated crack shielding. The predicted life of about 25 years was less than the worst single crack case, above.

4 Conclusions

1. Environmentally assisted cracking (EAC) in the form of transgranular stress corrosion cracking (TGSCC) has been observed in a ferritic-pearlitic steel used for natural gas pipelines (API X60) immersed in a dilute near-neutral pH solution at open-circuit- potential.

2. Quasi-clearage was observed on the fracture surface under the combined conditions of low cyclic frequencies and high R ratios, whereas corrosion fatigue was identified at low R ratios and high frequencies. A quantitative relationship between cyclic frequency and R is given that describes the conditions under which the two fracture mechanisms are likely to develop.
3. Application of a superposition model to express growth behaviour caused by different frequencies and loading conditions gave good agreement between observed and predicted rates.
4. Using limited operating data to analyze single surface crack growth behaviour formed a good base for predicting the remaining life of ferritic-pearlitic pipeline steels. However, determining the interactive crack growth within crack clusters would be more appropriate.

Acknowledgements

The authors acknowledge the financial assistance of TransCanada Pipelines Ltd and the Natural Sciences and Engineering Research Council of Canada. The technical assistance of S. J. Burany, M. Thomas, B. Williams and X.-Y. Zhang, University of Waterloo, is greatly appreciated. The authors thank Marlene Dolson and Jian Zou for typing the manuscript.

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