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CRACK GROWTH-BASED FATIGUE LIFE PREDICTION FOR AGING PIPELINE STEEL IN HYDROGEN WITH PRE-EXISTING CORROSION

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Abstract

Using existing pipeline infrastructure for hydrogen transport is under prime focus nationwide and globally. As a result, several studies were conducted under gaseous and electrochemically charged hydrogen environments. However, most existing studies focused on virgin material degradation under a hydrogen environment but did not include the effect of pre-existing damage due to aging, such as corrosion. This study focuses on a hydrogen-assisted fatigue crack growth model that can capture the growth rate behavior for various line pipe steels at various operating conditions. Pre-existing corrosion (both general material loss and pitting) effects are naturally included as surface irregularities in the form of roughness. Modified stress intensity factor solutions for surface roughness and crack growth kinetics function are integrated for fatigue life prediction. Model predictions are validated with collected experimental data from the open literature. Several future research directions are recommended based on the current findings.

1. Introduction

Most transmission pipes are made of line pipe steels ranging from X52 to X80. These existing pipes have been in service for a while and have internal and external corrosion damages due to aging. Using such infrastructure to transport hydrogen is a significant challenge as the corroded surfaces could behave as stress risers. Additionally, the gaseous hydrogen adsorbs onto the steel surface and diffuses into the lattice structure, which causes hydrogen embrittlement. Combined surface roughness and hydrogen embrittlement will significantly reduce the material integrity. Previous studies have confirmed that the fatigue crack growth rates (FCGRs) in pipeline steels increase over an order of magnitude after exposure to hydrogen. However, there is a limited understanding of how various operational parameters affect this behavior. Also, it was identified that higher strength steels do not necessarily have a higher susceptibility to hydrogen embrittlement as they were initially perceived and were found to have lower FCGRs than some of the lower strength steels. As a result, significant concerns have been raised in the community about whether existing pipeline infrastructure should be used for transporting hydrogen and how to maintain the high reliability of hydrogen transportation. This study focuses on a subcycle fatigue crack growth model to capture the effects of the hydrogen environment and the presence of surface roughness in pipeline steels.

2. Results

Fatigue crack growth behavior in the Paris regime is usually governed by two constants: C and m. In the presence of pressurized hydrogen in gas pipelines, experimental data for the Paris regime shows a bilinear trend: region-I with a steep slope followed by region-II having a reduced slope similar to that of air. This study focuses on region-II, and assuming the Paris constant C to be a function of hydrogen gas pressure (P), loading frequency (f), and stress ratio (R), an expression is proposed to estimate the constant 'C' as: $C_{hydrogen} = C_{air} \times \left[1 + \left(\{4.6 - 4.6\, exp^{-0.05P}\} \times 3^{2(1+R)} \times f^{-0.08} \times q\right)\right]$, where q is a material fitting parameter. Using this equation, the constant 'C' is estimated for different pipeline steel grades (X52, X60, X70 and X100) at various gas pressures, frequencies, and stress ratios, and compared with experimental data for validation. One of the predictions for X52 steel is shown in Fig. 1. Gas pipelines are not smooth and have their surfaces corroded; those irregularities can be considered as surface roughness. In this study, the surface roughness is modeled as a single equivalent notch with a stress concentration factor (K_t) based on Arola-Ramulu model [1] using standard roughness parameters (R_a, R_y, R_z, and ρ). This is combined with a stress intensity factor (SIF) solution for edge notch with a crack ahead of notch tip given as [2]: $K = 1.122\alpha\sigma\sqrt{\pi\left(a + d\left\{1 - exp\left[-\frac{a}{d}\left(\frac{K_t^2}{\alpha^2} - 1\right)\right]\right\}\right)}$, where '$d$' is the notch depth assumed to be the average roughness (R_a), 'α' is the finite dimension correction factor, 'a' is crack length estimated from equivalent initial flaw size (EIFS) [3]. This solution for SIF is incorporated into a previously developed subcycle fatigue crack growth framework to estimate the fatigue life under uniaxial and multiaxial random loading conditions [4] , considering the effect of surface roughness. The subcycle framework calculates the crack growth per unit time and is expressed as: $\frac{da}{dt} = \frac{A(K_{max} - K_{th})^B}{\sqrt{\delta_i} + \sqrt{\delta_{i-1}}} d\delta$, where A and B are material constants that can be obtained from Paris constants C and m as $A = \frac{C*(1-R)^B*\sqrt{2E\sigma_y}}{0.6}$ $and\ B = m - 1$. δ is the crack tip opening displacement and K_{th} is the threshold stress intensity factor. The proposed methodology for life prediction is validated against experimental data for an additively manufactured titanium alloy and stainless steel (Figs. 2(b-c)).

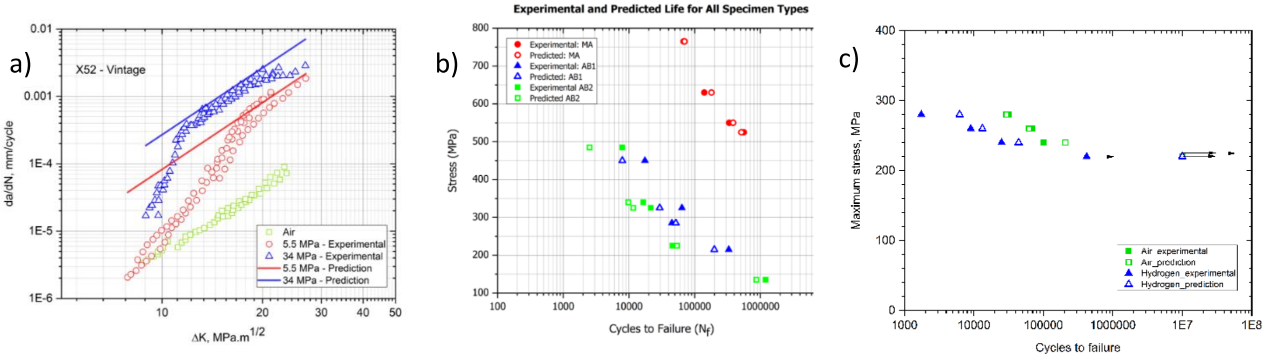

Fig.1. Preliminary model validation a) FCG under hydrogen and air; b) Life prediction for AM Titanium specimen with surface roughness; c) Life prediction for stainless steel in hydrogen and air

3. Conclusions

A methodology is proposed to predict FCG rates in a hydrogen environment for various pipeline steel grades, which can then be used to estimate the fatigue life of hydrogen transporting pipelines under different operational conditions. Additionally, a methodology is developed to account for surface roughness and its effect on fatigue performance. Finally, the proposed methodologies were validated against experimental data from the available literature.

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