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Application of Paris' law for estimation of hydrogen-assisted fatigue crack growth

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ABSTRACT

Based on the general form of Paris' law a new method is proposed for estimating the rate of cracking of metals under Hydrogen-Assisted Fatigue. It is based on relating the fatigue crack growth rate of hydrogen embrittled metal to the fatigue crack growth rate of the metal without hydrogen embrittlement. One-dimensional hydrogen diffusion is assumed. Simulations using the proposed method on steel types X52, X70–80 and X80 are in agreement with published experimental tests results. The new method obviates numerical modelling of crack propagation and much reduces the computational costs.

1. Introduction

Hydrogen has a detrimental effect on metals [1,2] through reducing ductility [3,4] and thus increasing rate of fatigue cracking [5,6]. Some stainless steels are particularly susceptible to hydrogen embrittlement when mechanically formed into shape for pipelines [7]. Hydrogen can be accessible to the steel in pipelines in several different ways. For example, pipes conveying hydrogen (as a fuel) are directly prone to the possible damaging effects of hydrogen. Despite this, steel remains the first choice for pipelines [8–10] in the expanding market for hydrogen fuel [9,11]. Development in recent years of design codes for hydrogen piping and pipeline, such as ASTM B31.12 [12] is the direct result of the increasing demand for conveyance of hydrogen using steel pipelines. Another example is that hydrogen may contact the internal surface of pipes when a contaminant such as H_2S is part of the conveyed fluid, such as in sour gas pipelines [13,14]. Further, aqueous soil environments can generate hydrogen electrochemically on the pipe surface [15–18]. All these highlight the necessity of reliable methods for evaluating hydrogen influence on metallic component such as pipelines and other components when hydrogen may be involved in some way in the transmission system.

Computational models for representing Hydrogen-Assisted Fatigue Cracking (HA-FC) usually are classified in two general categories according to the effect hydrogen has on material fracture properties [10]. In the first category the failure of a hydrogen affected region is attributed to "hydrogen enhanced decohesion" (HEDE). In this approach a so-called "traction separation law" [19–22] is used to overcome, in numerical modelling, the singularity at the crack tip. The second category includes methods in which failure is attributed to "hydrogen enhanced local plasticity" (HELP). Typically in both cases numerical modelling usually employs Finite Element methods. These are known to have high computational requirements and high associated costs. The present study proposes a different approach, focussed on HA-FC. This approach does not involve finite element modelling and thus has considerably lower computational costs. The approach proposed herein is based on the use of Paris' law to estimate the rate of cracking under a HA-FC mechanism. The general form of Paris' law proposed in [23] is invoked and the crack growth rate of an embrittled metal is estimated by using the device of magnifying the growth rate that would have occurred in absence of hydrogen in the virgin metal. The overall basis for this approach is outlined in the next section. The following section outlines details of the modelling employed. In brief, the modelling approach proposed herein uses Fatigue Crack Growth Rate (FCGR) data of virgin steels to estimate the Hydrogen-Assisted Fatigue Crack Growth Rate (HA-FCGR) for that steel. HA-FCGR behaviour is then considered in terms of three parameters, namely: a lower bound and an upper bound the rate of reduction of material toughness and stress intensity factor range respective to these bounds. The final part of the paper provides examples and a discussion of the results.

2. Hydrogen concentration ahead a moving crack tip

In this section diffusion of hydrogen from a moving crack tip is considered. The aim is to estimate the hydrogen concentration

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ahead the crack tip. The hydrogen concentration so obtained is then used to evaluate the level of embrittlement ahead the moving crack in a HA-FC process.

Hydrogen diffusion is driven by the gradient of chemical potential [22]. Several factors influence the gradient, including the extent of local plasticity, the rate of plastic strain, the presence of hydrogen trapping sites and the local stress field [24–27]. Only one-dimensional diffusion is considered herein. Diffusion in the direction normal to the crack plane has been reported as not influential in the distribution of hydrogen concentration ahead of the crack tip and thus is not of major influence in governing diffusion ahead of the crack tip [22,28,29].

Simple form of one-dimensional diffusion is:

$$\frac{\partial u}{\partial t} = D\frac{\partial^2 u}{\partial x^2} \tag{1}$$

in which:

u: Relative concentration of hydrogen in the metal, defined as $\left(\frac{\text{Number of hydrogen particles in a unit volume of the metal}}{\text{Number of hydrogen particles in a unit volume of the environment}}\right)$

t: Elapsed time, starting from formation of a new crack tip

D: Apparent diffusivity of hydrogen in the metal

x: Distance in the direction of the crack, from the crack tip to the point where the hydrogen concentration is being considered

For simplicity let the relative concentration of hydrogen at the tip of the crack, where the metal is in direct contact with hydrogen, be assumed to be unity irrespective of the hydrogen pressure in the surrounding environment. Also, it is assumed that hydrogen concentration in the environment is constant. $u = 1$ at the crack tip means that hydrogen concentration in the metal at the crack tip is equal to the concentration of hydrogen in the environment (the number of particles in a unit volume is the same in the metal and environment). This means the boundary conditions are assumed to move with the crack as it grows. Thus, to solve Eq. (1) under moving boundary conditions the origin of the coordinate system is reset to be at the crack tip for each incremental step. In consequence, the boundary conditions for each increment of crack growth are:

$$u_n(0,t) = 1 \tag{2}$$

$$\lim_{x\to\infty} u_n(x,t) = 0 \tag{3}$$

in which u_n is the relative concentration of hydrogen in the metal after the occurrence of the nth increment.

Considering the moving boundary condition problem to solve Eq. (1), the initial condition for the next increment is the solution of the previous increment. Recalling that the origin is set at the crack tip, the initial condition for nth increment is as follows:

$$u_n(x,0) = u_{n-1}(x + x_n, t_n) \tag{4}$$

where x_n and t_n are the crack growth and the time between the n-1th and nth increments, respectively. According to the solution of one-dimensional homogeneous boundary-value problems of diffusion in a semi-infinite region when $u_n(0,t) = 0$ and under initial condition (4) the solution for u_n will be [30]:

$$u_n(x,t) = \sqrt{\frac{D}{4\Pi t}}\int_0^\infty u_{n-1}(x + x_n, t)\left(e^{\frac{-D(x-z)^2}{4t}} - e^{\frac{-D(x+z)^2}{4t}}\right)dz \tag{5}$$

Also, when $u_n(0,\ t) = 1$ and the initial condition is zero, u_n will be:

$$u_n(x,t) = erfc\left(\sqrt{\frac{1}{4Dt}}x\right) \tag{6}$$

Thus when boundary conditions (2) and (3) and initial condition (4) are applied, due to linearity of (1), the total solution for $u_n(x,t)$ will be:

$$u_n(x,t) = erfc\left(\sqrt{\frac{1}{4Dt}}x\right) + \sqrt{\frac{D}{4\Pi t}}\int_0^\infty u_{n-1}(x + x_n, t)\left(e^{\frac{-D(x-z)^2}{4t}} - e^{\frac{-D(x+z)^2}{4t}}\right)dz \tag{7}$$

In the formulation in Eq. (7) it is assumed that crack tip jumps instantaneously in a cycle. In reality the crack tip might grow continuously or have a more gradual movement, somewhere between jumping and a continuous movement. Evidently, the formulation in Eq. (7), which is based on discontinuous movement (jump) of the crack tip will estimate a lower hydrogen concentration than would be obtained by the solution for continuous movement of the crack tip. To support the following arguments about concentration of diffused hydrogen ahead the crack tip, let Eq. (7) be used for estimating hydrogen concentration. Fig. 1 shows the hydrogen concentration ahead of the crack tip when the crack growth rate varies between 10^{-8} (m/cycle) and 10^{-6} (m/cycle). The crack growth rates of 10^{-8} (m/cycle) and 10^{-6} (m/cycle) are associated with the $\Delta K = 8$ (MPa m$^{1/2}$) and $\Delta K = 18$ (MPa m$^{1/2}$) in the HA-FCGR curve for X-70–80 grade steel, (Fig. 3). The hydrogen diffusivity (D) is taken as 7.5×10^{-11} (m^2/s) in Fig. 1, adopted from [31], and loading frequency is taken as 1 Hz in all diagrams. Thus the time between two subsequent jumps is one second.

The trend lines in Fig. 1 show that for a realistic range of crack growth rates the relative hydrogen concentration is close to unity. It follows that hydrogen concentration is quite close to that of the surrounding environment along the path followed by the crack tip in the metal. Fig. 1 is obtained under a constant hydrogen diffusivity of 7.5×10^{-11}(m^2/s). However, the local apparent diffusivity can be significantly greater under the influence of a metal fatigue process. For example, it has been shown that the apparent hydrogen diffusivity under fatigue is some five orders of magnitude greater than the standard hydrogen diffusivity for type 304 austenitic stainless steel exposed to 10 MPa of hydrogen pressure [32]. It follows that the real hydrogen concentration ahead the crack tip can be even closer to unity than that suggested by Fig. 1. To support this argument and show the influence of increasing hydrogen diffusivity on the hydrogen concentration ahead the crack tip, a crack growth rate of 10^{-7}(m/cycle) under varying hydrogen diffusivity is considered in Fig. 2. Hydrogen diffusivity, D varies between 2×10^{-11}(m^2/s) and 100×10^{-11}(m^2/s) in this case. The crack growth rate of 10^{-7}(m/cycle) is associated with the

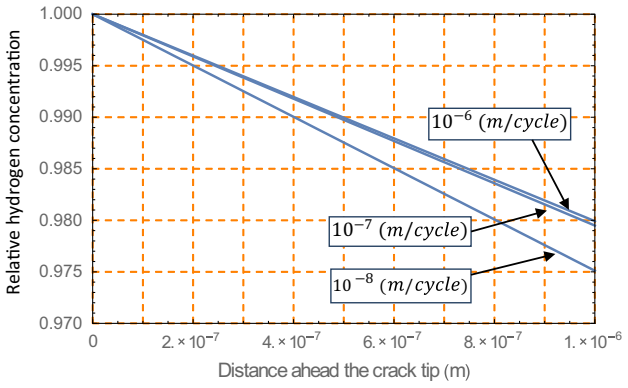

Fig. 1. Relative hydrogen concentration ahead the crack tip with different crack growth rates. Hydrogen diffusivity is 7.5×10^{-11} (m^2/s). Loading frequency = 1 Hz.