Modelling of mode-I stable crack growth under hydrogen assisted stress corrosion cracking

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ABSTRACT

The paper presents a new strategy based on combined analytical and finite element (FE) solution to hydrogen assisted stress corrosion crack growth. The diffusion process is solved analytically through both one-and two-dimensional modelling. These solutions are adopted with two-dimensional FE based cohesive zone model of crack extension study. The results fit well with published experimental data and show improvement over the predictions by full FE approach. The new solution approach helps to reduce time required for simulation/computation. The study has produced a relationship between concentration dependent reduction in cohesive strength and plastic strain rate.

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1. Introduction

Machines or structural components working in hydrogen environment can fail prematurely without forewarning. Such failures are observed commonly in marine and nuclear applications. To improve upon operational safety, quantitative methods are required for assessing the crack growth. Hydrogen in the presence of external loading or internal stresses (such as residual stresses in welds) can damage materials through cracking, blistering, reduction of ductility, and/or by formation of brittle hydrides [1]. The source of hydrogen can be the acidic environment, corrosion reaction, electrolysis, thermal processing, etc. Hydrogen-assisted stress corrosion cracking (HASCC) is a process of accelerated crack growth under combined action of stress and hydrogen. Lynch [2] has reviewed the principal mechanisms leading to HASCC and other types of hydrogen damage. Three important mechanisms supported by significant experimental and theoretical work are: hydrogen enhanced localised plasticity (HELP), hydrogen induced decohesion (HEDE) and adsorption induced dislocation emission (AIDE).

Different approaches have been considered to predict the stable crack growth under HASCC viz., fictive tensile specimen model by Boellinghaus and Hoffmeister [3], cohesive zone model (CZM) by Scheider et al. [4] and Olden et al. [5], mesoscale fibre bundle model by Dietzel et al. [6], and three dimensional multiscale model by Rimoli and Ortiz [7], just to mention a few. The CZM is of concern here.

The CZM can easily incorporate the effects of mechanical phenomena occurring within the process zone around a crack tip. The CZM was introduced by Barenblatt [8] to simulate cracking of brittle materials and was then developed to study metal tearing process. Essentially, it represents decohesion of atomic lattice using traction separation law (TSL) which

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Nomenclature

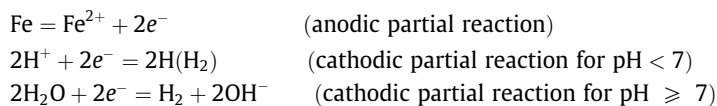|	
$B_{m,n}^i$	Fourier coefficients for 2D solution
C	normalised hydrogen concentration
D_{eff}	effective diffusivity
E	modulus of elasticity
E_m^i	Fourier coefficients for 1D solution
H	height of domain
K	stress intensity factor
L, L_1	length of domain
T_0	cohesive strength
W	width of specimen
a_0	initial crack length
Δa	crack extension
$a_1, a_2, \dots$	coefficients of polynomial for 2D solution
$b_0, b_1, \dots$	coefficients of polynomial for 1D solution
t, t_1	time
v_{pl}	plastic component of crack mouth opening displacement
x, y	Cartesian coordinates
z	distance between load-line and measuring position for v
Γ_0	cohesive energy
δ	separation in cohesive element
δ_0	critical separation
δ_1, δ_2	intermediate separations used to define traction separation law
δ_5	displacement of two points 2.5 mm above and below starter crack tip
ϵ_{pl}	plastic strain
$\dot{\epsilon}_p$	crack tip plastic strain rate
μ	cohesive strength reduction factor
v	Poisson's ratio
σ_u	ultimate strength
σ_y	yield strength

correlates cohesive stress with displacement within material. The CZM model is applied to a narrow region along the path of crack propagation. The progressive damage to the load carrying capacity of material and subsequent formation of crack surfaces take place inside the cohesive zone.

The CZM is a phenomenological model. It avoids evaluation of the stress singularity at the crack tip which simplifies the numerical handling of crack growth calculations. The material damage is represented by using any two of the parameters: cohesive energy Γ_0, cohesive strength T_0, and critical separation δ_0. The cohesive energy represents the amount of energy supplied to the material during the period of crack initiation to the end of crack extension. The damage due to hydrogen is quantified in terms of the extent of reduction in the cohesive energy proportionate to local hydrogen concentration [9]. The effect of reduction can be incorporated through a concentration-related term in the expression for TSL.

Typical anodic and cathodic reactions for corrosion of iron in water are as follows.

$$Fe = Fe^{2+} + 2e^- \qquad \text{(anodic partial reaction)}$$
$$2H^+ + 2e^- = 2H(H_2) \qquad \text{(cathodic partial reaction for pH} < 7)$$
$$2H_2O + 2e^- = H_2 + 2OH^- \qquad \text{(cathodic partial reaction for pH} \geqslant 7)$$

While a hydrogen atom generated will generally combine with other hydrogen atom to form a hydrogen molecule (gas bubble) that will escape as it is too large to diffuse into metal, some hydrogen atoms diffuse into the metal (before getting an opportunity to combine with other atom). Such hydrogen atoms lodge themselves at several high energy locations, particularly at the high stress location immediately ahead of the crack tip. This transport of hydrogen atoms into metal is influenced by pressure, temperature, metal microstructure, hydrostatic stress, and plastic strain. The amount of hydrogen inside trap sites is related to the number of trap sites. This number depends on the magnitude of plastic strain; the quantum of hydrogen inside lattice sites is governed by the hydrostatic stress. Although the peak concentration of lattice hydrogen occurs at a distance little ahead of crack tip, the distribution of total hydrogen (at trap sites and within lattice) is governed by the variation of plastic strain. Since the strain is highest at the crack tip, so is the total hydrogen concentration [10]. It is obvious that the plastic strain has the predominant role in this scheme whereas the hydrostatic stress has a minor influence on the distribution of total hydrogen at/around the crack tip. So, it is reasonable to neglect the latter for diffusion of hydrogen and subsequent damage calculations. The plastic strain can be incorporated in the diffusion calculations by introducing a