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# Fatigue crack growth modelling for pipeline carbon steels under gaseous hydrogen conditions

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A B S T R A C T

A corrosion-crack correlation model is proposed for the hydrogen embrittlement (HE) influenced fatigue crack growth modelling of pipeline carbon steels under gaseous hydrogen conditions. The model is developed primarily based on the correlation of environment-affected zone (EAZ) and plastic zone. In the model, fatigue crack growth rate is predicted by Forman equation to take into account the influence from fracture toughness. The critical frequency and the "transition" stress intensity factor (SIF) are derived based on stress-driven hydrogen diffusion and Hydrogen-Enhanced De-cohesion (HEDE) hypothesis, which provides reasonable explanation on the frequency dependence of fatigue crack growth for pipeline carbon steels in hydrogen gas. Furthermore, an approximation formula involving threshold the SIF range and the stress ratio is established to describe the phenomenon of crack growth rate plateau. In addition, a formula is proposed to estimate the equilibrium fracture toughness according to the equilibrium between crack growth and hydrogen delivery rates. A series of experimental data from different grades of carbon pipeline steels (including high-strength grades such as X70 and X80) are utilized for demonstrate the validity of the proposed formulae and model effectiveness. The comparison between model predictions and experimental data shows that the proposed model is capable of capturing the essence of pipeline carbon steels' fatigue crack growth process under gaseous hydrogen conditions.

## 1. Introduction

It has been well known that the cracking process of metals such as carbon steels can be severely aggravated due to aggressive environment. This phenomenon is usually called environment-assisted cracking (EAC). Depending on the loading profile, there are two major categories of environment-assisted damage: stress corrosion cracking (SCC) and corrosion fatigue (CF). Considerable theoretic and experimental studies [34] have been conducted on SCC. Based on the difference in crack morphology and environment conditions, it has been pointed out that for the two basic SCC modes, i.e. high-pH and near-neutral pH, the latter shares a similar morphology sometimes as well as the environmental conditions with those of CF. On the other hand, engineering structures are normally exposed to complex operations with varying working stresses that are usually a mixture of static and cyclic components [41]. Thus it was suspected that both two phenomena undergo identical EAC mechanisms. Some researchers even claimed SCC is only a special case of CF at the stress ratio equal to unity [42]. Further studies indicated that the two phenomena are actually both mixtures of two crack-tip damage modes, namely the stress-assisted corrosion/stress corrosion (SC) and hydrogen-assisted cracking (HAC) [51,4]. In the case of SC, the primary driving force for crack growth comes from the localized chemical corrosion processes occurring at the crack tip, which is usually explained by the theory of anodic slip dissolution [35,26]. Various models for estimating the crack growth rate were proposed based on either theoretical formulae such as Faraday's law or experimental tests or both [13]. As for HAC, crack growth is associated with absorbed hydrogen in the material. Those hydrogen may come from corrosion in aqueous solutions, cathodic protection, or high-pressure hydrogen gas, and then diffuse to a pre-existing flaw in the atomic state with stresses applied. Consequently, enhanced crack growth occurs and fracture happens at a lower stress level compared to that of the same material measured in air or inert gas. This phenomenon is called the hydrogen embrittlement (HE). Numerous mechanisms have been raised to account for the degradation of mechanical properties observed in experiments. At present, three of them have been widely accepted: Hydrogen Enhanced De-cohesion (HEDE), Hydrogen Enhanced Localized Plasticity (HELP), and Adsorption Induced Dislocation Emission (AIDE). Arguments supporting each are not definitive, even not exclusive. A critical review has been

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provided by Lynch [28]. But a consensus is emerging that HEDE is likely to be the dominant mechanism [17]. There is still controversy centring on the extent to which HAC explains subcritical crack growth in metals stressed in environments that support concurrent crack tip dissolution, passive film formation, and atomic hydrogen production. Nevertheless, an agreement has been reached that HE normally prevail for subsea metal structures with cathodic protection (CP) as well as those exposed to gaseous hydrogen [3].

As nowadays the renewable energy such as wind and solar is booming in its development, the corresponding energy storage technology is attracting more and more attention. In a possible scheme proposed, the fresh energy is converted into gaseous hydrogen by separating water, and then stored and transmitted by pipelines [24]. This idea is especially practical for offshore wind and solar farms where water supply is not a problem. Modern pipelines are usually made of medium or low strength steels and often designed by use of defect-tolerant principles, where knowledge of defect size and fatigue crack growth rate can be used to determine the remaining service life of a component. Several comprehensive reviews on the fatigue crack growth behaviour of pipeline carbon steels exposed to gaseous hydrogen were performed by Lam [23], Nanninga et al. [29], and Liu and Atrens [25].

As seen from above literature review, it is clear that HE has a significant impact on fatigue crack growth behaviour of carbon pipeline steels, especially under high hydrogen pressures and varying loading frequencies. Although both corrosion fatigue and hydrogen influenced fatigue cracking show some frequency dependence, Nanninga et al. [29] pointed out that the mechanisms and models used to predict hydrogen influenced fatigue cracking in hydrogen may still differ significantly from those used for statically loaded applications or in fatigue situations where the hydrogen derives from aqueous liquids, which usually accompanies corrosion or/and negative potential. Moreover, unlike the situation for sustained load cracking in hydrogen environments, it was found that medium- even low-strength pipeline steels are highly susceptible to HE influenced fatigue cracking [25]. However, there is still a lack of such models that can rationally account for the mechanisms of HE influenced fatigue cracking, just as what is mentioned in API RP 579 [47], equations/models that describe fatigue crack growth behaviour in aggressive environments are only available for limited stress intensity ranges and most often intended for aqueous liquids.

In order to solve this problem, a corrosion-crack correlation model is developed based on the concepts of environment-affected zone (EAZ) and plastic zone. In the model, fatigue crack growth rate is predicted by Forman equation to take into account the influence from fracture toughness. The critical frequency and the "transition" stress intensity factor (SIF) are derived from theoretical basis of stress-driven hydrogen diffusion and HEDE. Furthermore, an approximation formula involving the threshold SIF range and stress ratio is established to describe the phenomenon of crack growth rate plateau. In addition, a formula is proposed to estimate the final fracture toughness determined by the equilibrium between crack growth and hydrogen delivery rates.

## 2. Hydrogen embrittlement influenced fatigue cracking process

A brief description for the HE influenced fatigue cracking process of pipeline carbon steels is presented in this section with the purpose of providing theoretical basis and clarifying physical meaning to the mathematical equations given in the next section.

As Oriani claimed [31], the basic notion of HEDE is that HE cracking occurs when the local opening tensile stress in front of crack tip exceeds the maximum-local atomic cohesion strength, which has been lowered by the presence of hydrogen. Based on this notion, Wang et al. [50] established a model that can predict the degradation of fracture toughness for alloy steels exposed to gaseous hydrogen. Good agreement was observed between the prediction and experimental data. The success of this model indicates that HEDE works well on explaining the HE of pipeline carbon steels. However, it should be noted that the degraded fracture toughness was measured by testing pre-cracked specimens under sustained loading condition [19], where there is sufficient time for hydrogen atoms to diffuse to the maximum tensile stress location. Thus fracture resistance is degraded and cracking is enhanced to the same extent corresponding to the hydrogen pressure along the whole test. The fracture toughness measured in such a way is called the saturated fracture toughness for the ambient hydrogen pressure.

However, if crack propagation goes beyond a specific speed (usually around the point when rapid unstable crack propagation begins), diffusing hydrogen cannot keep pace with the growing crack, resulting in an increased resistance against the rapid crack propagation and in turn the rate itself slows its acceleration to establish an equilibrium with the hydrogen delivery rate. Subcritical crack growth may then continue along the equilibrium rate toward an "equilibrium fracture toughness" API RP 579 [47]. Such a HE influenced fatigue crack process can be observed in fatigue tests performed in hydrogen gas for pipeline steels spanning from low grades such as X42 [9] to grades as high as X100 [1].

If hydrogen damage is viewed as a special case of corrosion, then the foresaid process is a description on the corrosion-crack correlation mechanism existing in HE influenced fatigue cracking. Based on the typical process description, for a specimen tested in high-pressure hydrogen gas with fatigue loading, three specified types of fracture toughness are defined, namely the inherent fracture toughness, $K_{\mathrm{IN}}$, which is measured in a non-aggressive environment with the same loading conditions; the saturated fracture toughness, $K_{\mathrm{IH}}$, which is obtained under high hydrogen pressure using procedures defined in ASTM E 1820 [2]; the equilibrium fracture toughness, $K_{\mathrm{IE}}$, namely the final fracture toughness displayed in the fatigue test.

## 3. Hydrogen embrittlement influenced fatigue crack growth modelling

For normal fatigue cracking (where aggressive environment is not applicable), in principle, crack propagation starts from the "stage I" (the "initiation" phase), mainly being "short crack", and continues with the "propagation" phase of stage II and stage III

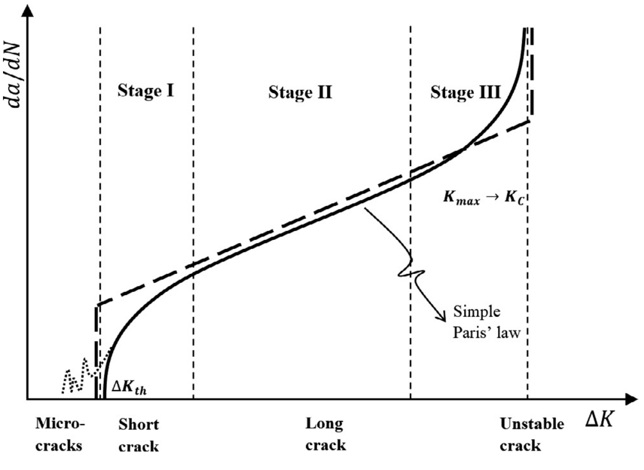

**Fig. 1.** Schematic diagram of a normal fatigue cracking process.