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Corrosion fatigue crack growth modelling for subsea pipeline steels

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ABSTRACT

Based on the recent development of research for environment-assisted cracking (EAC), a crack growth model for the corrosion fatigue (CF) of subsea pipeline steels is proposed in this paper. The model adopts a two-component structure in consistence with the physical fact that CF is a mixed process of stress corrosion (SC) and hydrogen-assisted cracking (HAC). Anodic dissolution (AD) and hydrogen embrittlement (HE) are believed to be responsible for SC and HAC and their models are integrated in the general model within a framework of fracture mechanics. The model is then applied to modelling the CF crack growth of X65 pipeline steel and the results show that the shape of the modelled crack propagation curve can be controlled well using the proposed model, and both the exacerbated cracking rate and behavior features can be captured with appropriate consideration of the effects of mechanical and environmental parameters, such as loading frequency, stress ratio, temperature, and hydrogen concentration, etc.

1. Introduction

Subsea pipelines are safety critical structures primarily used to carry oil or gas. They occupy the most extension through space in offshore oil and gas production systems, and often encounter harsh working conditions. As a strategy to guarantee safe operation (DNV-OS-F101, 2013), fracture mechanics based engineering critical assessment (ECA) or fitness-for-service (FFS) has been widely applied in offshore engineering in recent years. However, subsea pipelines are vulnerable to severe environmental assisted crackings (EACs) which lack attention in current mainstream ECA guidelines such as BS 7910 (2013) and API 579 (2009). To acquire high-quality ECAs, it is necessary to develop proper crack growth models for subsea pipelines to account for EAC effects. Depending on the loading profile, there are two major categories of EAC: Corrosion fatigue (CF) and stress corrosion cracking (SCC). CF is the environment enhanced cracking under fatigue loads and SCC represents the cracking induced by the combined influence of a corrosive environment and a static load. Usually both CF and SCC are thought to be able to cause substantial life reduction of subsea pipelines. However, it is doubtable if SCC can be realized in real service conditions since engineering structures are normally exposed to complex operations with varying working stresses that are usually mixture of static and cyclic components. Some researchers even argued that SCC is a special case of CF with the stress ratio being unity (Shipilov, 2002). Although theoretical and experimental studies on SCC are relatively ample, CF is receiving more and more attention in recent years. A number of models have been developed for CF of metals in aqueous environments (Kim et al., 1998). However, most of them are just phenomenological because the material's CF cracking behavior is quite complicated and considerable variables can impose their impacts, while the involved mechanisms are not very clear.

Based on the recent research on the mechanisms and modelling of EACs (Rhodin, 1959; McEvily and Wei, 1972; Gerberich et al., 1988; Parkins, 1992; Rhodes, 2001; Gangloff, 2003; Wang et al., 2013), a two-component CF crack growth model for subsea pipeline steels is proposed in this paper, in which the anodic dissolution (AD) model and the hydrogen embrittlement (HE) model newly established by authors (Cheng and Chen, 2017) are integrated within a framework of fracture mechanics. The model is then applied to modelling the CF crack growth of X65 pipeline steel and the impact of loading frequency, stress ratio, temperature, and hydrogen concentration on the model performance is discussed.

Abbreviations: AD, Anodic dissolution; AIDE, Adsorption Induced Dislocation Emission; CF, Corrosion fatigue; CP, Cathodic protection; DBT, Ductile-brittle transition; EAC, Environment assisted cracking; EAZ, Environment affected zone; ECA, Engineering critical assessment; FFS, Fitness for service; HAC, Hydrogen assisted cracking; HE, Hydrogen embrittlement; HEDE, Hydrogen Enhanced De-cohesion; HELP, Hydrogen Enhanced Localized Plasticity; LEFM, Linear elastic fracture mechanics; SC, Stress corrosion; SCC, Stress corrosion cracking; SIF, Stress intensity factor

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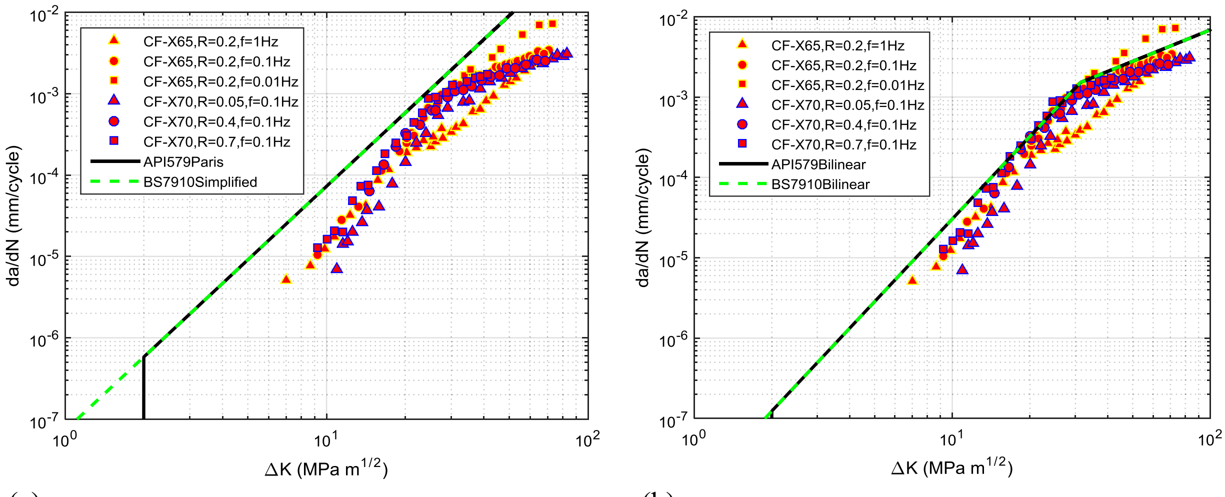
2. Corrosion fatigue mechanisms

Subsea pipelines are exposed to potentially aggressive service environments both the inside and outside. The chemical composition of product fluid may vary from field to field, while the outside environment roughly stays the same. Either tenting of tape or coating at the long-seam welds or under tape wrinkles can create space for seawater contacting and further corroding the bare metal. Also, pre-existing external flaws such as as-built pipeline defects including grooves and weld defects, or dents caused by third-party interference may act as initiating sites for EACs. The research interest of this paper exists in the corrosive effect of seawater on cracks in the external steel surface of subsea pipelines. The influence from environment to the CF crack growth is multi-aspect and complicated. For example, the deep-sea environment may impose huge external hydrostatic pressure and cold temperature. Meanwhile subsea pipelines may also suffer loads from intervention vessels, current and other met-ocean events. Additional attentions should be paid to the possible thermal and pressure expansion and contraction. The related loading frequencies, stress ratios and even temperature may vary in rather big ranges. Besides, as cathodic protection (CP) technique is widely adopted nowadays, intensive hydrogen pick-up may happen due to over protection, which often results in a high hydrogen concentration in the bulk material. All the factors above mentioned may play a role in the CF process of subsea pipelines. Due to the complicated nature of CF, current simplified CF crack growth models often provides predictions that are either over-conservative or under-estimated. For example, as shown in Fig. 1(a), the over conservatism in predictions by linear models from API 579 (2009) and BS 7910 (2013) is obvious. While in Fig. 1(b), both bilinear models provided by API 579 (2009) and BS 7910 (2013) fail to predict the CF crack growth rate of X65 pipeline steels in seawater conservatively. The CF data under a loading frequency of 0.01 Hz and a stress ratio of 0.2 go beyond the prediction at relatively high SIF ranges. More attentions should be paid to such problems since the lost CF crack growth rates are fairly high, thus greatly increasing the risk of sudden failure of the component.

No metal is immune from some reduction of its resistance to cyclic loading if the metal is put in a corrosive environment. But different environment-material systems may exhibit distinct CF cracking behaviours. According to McEvily and Wei (1972), those behaviours belong to three types, type A, type B, and the mixed type. Each type is schematically plotted in Fig. 2. Type A describes the behavior where the threshold K_{th} is reduced and crack growth rate is enhanced by the presence of the corrosive environment at all levels of K. Type B represents the behavior typified by the enhanced crack growth beyond the K_{ISCC} and is characterized with a plateau in crack growth rate. The mixed type, where type B behavior happens above K_{ISCC} with type C behavior superimposed on at all K levels below, is exhibited by a broad range of material-environment systems, and is typical of pipeline steels in seawater.

BS 7910 (2013) defines CF as a type of damage similar to fatigue, except the environment is corrosive instead of inert or dry air. Fatigue failure process of a component or specimen usually begins with the initiation of cracks (stage I), and with continued cyclic loading the cracks grow (stage II), sequentially comes the rapid crack growth leading to the final rupture (stage III). A corrosive environment causes degradation of the material, the most common visible effect being pitting or surface roughness (etching). These notch-like regions act as stress raisers and are generally the sites of crack nucleation (Ellyin, 2012). The corrosive environment thus shortens the crack nucleation stage. Once cracks are initiated, subsequent crack growth may be enhanced by the corrosiveness. Quite a number of fundamental questions regarding the possibility, severity and rate of CF cracking remain unanswered. Foremost among these questions is the problem of the CF mechanism. In contrast to CF, relatively extensive and fruitful research has been performed on the mechanism of SCC (Parkins, 2000; Beavers and Harle, 2001; Woodtli and Kieselbach, 2000; Fang et al., 2003). SCC is the crack growth in a corrosive environment under a sustained load. Crack growth of SCC is a result of the combined and synergistic interaction of corrosion reactions and mechanical stress. In the most general situation, cracks initiate from the bottoms of pits and crevices or other surface blemishes, and propagate into the material either transgranularly, intergranularly or sometimes in a mixed type. For high-pH SCC, the crack often grows along an intergranular path. This is thought to be associated with the strong environmental influence it receives. Local corrosion has been well accepted as its driving mechanism. But for near-neutral pH SCC, it has been suggested that the mechanism is associated with the hydrogen ingress as a byproduct of corrosion, as well as the dissolution at the crack tip. That is to say near-neutral pH SCC is mixture of two damage modes, namely stress-assisted corrosion or stress corrosion (SC) and hydrogen-assisted cracking (HAC). Interestingly, CF usually shows the same transgranular fracture surface as near-neutral pH SCC. The similar morphologies indicate that CF and SCC may have similar cracking mechanisms. Some experimental investigations on the near-neutral pH SCC even used a cyclic loading to initiate cracks from pit bottoms (Parkins, 2000). Further studies confirm that the mechanisms, which have generally been proposed to explain SCC, are also responsible for



(a) (b)

Fig. 1. Experimental CF data in comparison with model predictions of API 579 and BS 7910: (a) Simple linear model; (b) Bilinear model. (X65 and X70 data by Vosikovsky (1975, 1981).