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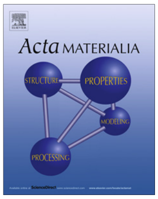

Corrosion fatigue crack growth behavior of pipeline steel under underload-type variable amplitude loading schemes

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ABSTRACT

This investigation attempts to rationalize various near-neutral pH corrosion fatigue (CF) failure scenarios found during pipeline operations, which continues to be a major consideration in pipeline integrity. The phenomenon is often referred to as stress corrosion cracking (SCC) but as will be discussed is more properly considered as CF. Existing CF (SCC) models predict a service life of more than 100 years for gas pipelines, as compared with the 20–30 years typically seen in the field when these mechanisms are operative. It has been identified from analyzing pressure fluctuations recorded in the field that the underload-type variable amplitude loading schemes often found within 30 km downstream of a compressor station are the most prone to crack growth, and these locations comprise more than 70% of all-service and hydrostatic-test failures attributed to stress cracking. In this investigation, underload-type variable amplitude loading schemes were designed and used for crack growth measurements in pipeline steel in near-neutral pH environments. Crack growth enhancement by a factor of 10 was found under the underload-type variable amplitude cyclic loading, as compared with the constant amplitude cyclic loading. There also exist two distinct regimes of crack growth behavior over the range of loading frequency from 5.0×10^{-1} Hz to 10^{-5} Hz under such variable amplitude fatigue. Crack growth rate was found to increase with decreasing loading frequency down to 10^{-3} Hz, while it remained constant below 10^{-3} Hz. This critical loading frequency was successfully modeled based on the crack growth mechanisms identified. The outcome of the investigation agrees well with the failures experienced in the field.

1. Introduction

This investigation gives an explanation for the various corrosion fatigue (SCC) failure scenarios found during pipeline operations. In particular, it will focus on the crack growth behavior over a wide range of loading frequency found in service considering both gas and liquid pipelines. The corrosion fatigue failure of pipeline steel in near-neutral pH environments was described as stress corrosion cracking when first reported in 1985 [1]. Although three decades have passed, the models governing the crack growth still cannot predict failure time accurately, and pipeline failures caused by corrosion fatigue continue imposing a significant threat to the safety of the operation of the pipeline network [2,3].

Corrosion fatigue is often classified into three categories: cyclic dependent, time dependent, and time and cycle dependent [4]. Crack growth in the first category of corrosion fatigue is not loading frequency dependent, while the latter two are frequency dependent. The frequency-dependent growth in essence is attributed to time-dependent processes that contribute either directly or indirectly to the crack growth, which may include:

(i) The time-dependent process of surface passivation or oxide film formation, which usually yields an inverse dependence of crack growth rate on loading frequency [4,5]. But this is not the case for the near-neutral pH corrosion system as no passivation or oxide films are observed in near-neutral pH environments [1].
(ii) The time-dependent process of corrosion where lower loading frequencies give rise to a higher crack growth rate per cycle.

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(iii) Both time- and cycle-dependent processes, for example, may correspond to a maximum segregation of hydrogen to the crack tip that is both time and cycle dependent [6–8].
(iv) Time-dependent mechanical property attributes, such as room temperature creep [9–11] and high temperature creep [12], both of which could lead to crack tip blunting and mechanical damage to the crack tip materials. Although blunting can be beneficial as it reduces stress enhancement at the crack tip, it can cause mechanical damage such as void formation (either the ductile dimples or the creep voids), which accelerates crack growth.
(v) Many other specific conditions that could enhance or reduce the time-dependent crack growth, such as temperature [12], chemistry of materials and electrolytes [6, 13], mechanical characteristics [3,6, 14], and electrolyte dynamics [6].

Corrosion fatigue of pipeline steel in near-neutral pH environments is very complicated because it involves 4 (that is, ii–v) of the 5 aspects of time-dependent processes defined above. For the physical mechanisms of crack growth, it is generally believed that crack growth proceeds by either or all of the following processes: (1) by dissolution at the crack tip only, which is primarily a process of major influence in the earliest stage of crack growth when the crack is shallow, for example, up to 1 mm in depth, and during the growth of these small cracks on the pipe surface; (2) by direct cracking of the crack tip through hydrogen embrittlement mechanisms, which is primarily the mechanism of crack growth following the dissolution mechanism in the initial stage; (3) by direct cracking caused by cyclic loading which results from the pressure fluctuations during normal pipeline operation.

In addition to the above considerations, the complexity of corrosion fatigue of pipeline steel in near-neutral pH environments also arises from the following unique situations:

(a) The range of loading frequency is very large, typically in the range from 10^{-1} to 10^{-6} Hz [15]. Crack growth behavior in the low range (lower than 10^{-3} Hz) of loading frequencies has not been well studied [6,16].
(b) The pressure fluctuations are dictated by unpredictable supply and consumption of fluid media and the location relative to the pumps which are used to transport the fluids. This variability of loading and the cycle interactions can lead to large variations in crack growth as will be shown. However existing life prediction models of either fatigue or corrosion fatigue [6,16,17] do not adequately account for these effects.

Both of the above two unique conditions will be dealt with in this investigation. The crack growth rate in the frequency range higher than 10^{-3} Hz under constant amplitude fatigue loading has been well studied. It is generally believed that the fatigue crack growth rate increases with lowering frequency, because of the increased time either for the interaction of corrosive chemicals with the metal or for hydrogen diffusion [6,7]. However, such a conclusion could not be extended to the frequency range lower than 10^{-3} Hz, within which there is always sufficient time for hydrogen to diffuse to the weakest link in the material ahead of the crack tip, in accordance with the change of stress. For these lower frequencies, the effect of room temperature creep may also become significant. However, only a few investigations have been reported for the corrosion fatigue crack growth at loading frequencies lower than 10^{-3} Hz [16,18].

Pipelines are operated under variable pressure fluctuations. All existing crack growth models were developed based on results obtained from tests either under constant load for the case of SCC or under constant stress amplitude loading for the case of fatigue or corrosion fatigue. These models generally yield a prediction that fails to accurately predict real crack growth because they fail to consider the effects of both the load history-dependent and the time/frequency-dependent load interactions on crack growth during the variable pressure fluctuations. Such predictions may under predict or over predict, depending on the loading schemes. These load interaction situations are essential to the nature of stress-cracking of pipeline steel in near-neutral pH environments and may be summarized as follows:

(1) Scenario 1: A previous cyclic loading with an R-ratio different from the current cyclic loading may condition the crack tip mechanically to either increase or decrease the crack growth rate of the current cycle and/or the future cycles, which is the so-called load history-dependent load interaction [19,20].
(2) Scenario 2: The rate of pressure fluctuations, often referred as loading frequency, produces variable pressure fluctuations, which may yield different time-dependent contributions to the crack growth, which is categorized as time/frequency-dependent load interaction. These time-dependent contributions may include: the rate of corrosion, the rate of hydrogen segregation by diffusion to the crack tip [7], and the degree of crack tip blunting caused by room temperature creep [7,9–11] and interactions between hydrogen and dislocations [21,22].
(3) Scenarios (1) and (2) can also mutually interact, for example, crack tip blunting caused by the situations described in Scenario 2 which may lead to different stress states at the crack tip and therefore yield different load history-dependent load interactions considered in Scenario 1.

The pressure fluctuations in the field could be roughly categorized into the following three types: Type I – underload pressure fluctuations, Type II – load fluctuations above and below the mean, and Type III – overload fluctuations. Type I is typically seen within 30 km downstream of a pump station and is the harshest pressure fluctuations in terms of crack growth rate because the maximum pressure of the variable pressure fluctuations is generally highest and often controlled to be at or close to the design limit. The maximum pressure, however, is reduced as the fluids move away from the discharge site of a pump station because of the friction between the fluids inside the pipeline and the pipeline internal surface. Type III exits at the suction section of a pipeline and is usually associated with a reduced potential

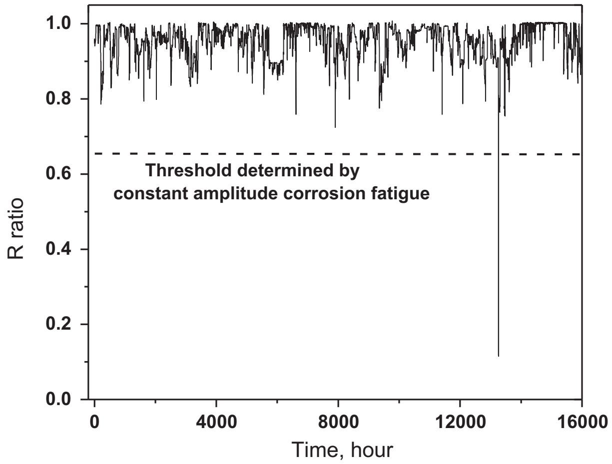

Fig. 1. Pressure fluctuations recorded for a high-pressure gas transmission pipeline (SCADA data).