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A Fracture Mechanics Approach to Characterizing Hydrogen Embrittlement of Fasteners

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ABSTRACT

This paper elaborates on a method previously reported that characterized a materials susceptibility to hydrogen embrittlement in a seawater environment under CP by monitoring the crack growth rate of ASTM ⁽¹⁾ E1820¹ pre-cracked CT specimens at various constant stress intensity (K-levels) and at varying cathodic protection potentials. For the fastener grade ASTM A320 L7 & L43² grade carbon alloy material the initial reported results showed that the material susceptibility to hydrogen embrittlement followed a pattern influenced by the yield strength level of the material, specifically that material susceptibility is distinguished by the response to varying CP potential & applied K levels. Intermediate yield strength (< 930 MPa) for example, showed multiple K_{IEAC} threshold responses; while known susceptible material with very high strength levels showed reduced threshold response and insensitivity to more positive CP potentials.

The paper presents additional results from those previously reported covering the yield strength levels between 725 MPa (105ksi) and 964 MPa (140ksi) and highlighting the transition between non-susceptibility to susceptibility right about 939 MPa (135ksi) and close to the hardness limit of HRC 34 identified in API² 20e³. These results can be represented graphically and can serve to establish design operating limits for the materials in a seawater environment under CP.

Key words: hydrogen embrittlement, environmental assisted cracking, HISC, fracture mechanics, cathodic protection, Oil & Gas Subsea production, fasteners, riser bolts

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INTRODUCTION

Characterizing Hydrogen Embrittlement Susceptibility – Methodology Overview

Materials properties that are used in specific oil and gas environments are de-rated due to the risks associated with hydrogen embrittlement cracking. In oil production environments the concern is for the onset of stress corrosion cracking (SCC), while in seawater environments the concern is for Hydrogen Induced Stress Cracking (HISC). Both are hydrogen embrittlement phenomena with the distinction being the source of hydrogen for each.

In SSC the source of hydrogen is from the presence of H_2S in the oil production fluids, and in HISC the source of hydrogen is from the dissociation of water from the cathodic protection system. This paper is focused on the latter phenomena and aims to characterize the susceptibility of carbon alloy steels as applied in fastener applications, in a seawater environment under cathodic protection.

The chosen method to characterize the susceptibility of the material to cracking uses pre-cracked compact tension specimens in accordance to ASTM E1820 to monitor and record the crack growth rate as a function of constant loading and varying cathodic protection potentials. Because the methodology is tracking and documenting crack growth rates, stress loading is now measured as applied K ($ksi\sqrt{in}$) at the crack tip⁴.

One of the key ideas that will be explored by this method is that the assessment of a materials susceptibility to hydrogen cracking involves more than characterizing materials' parameters such as the heat treatment, microstructure, strength & hardness levels. What determines susceptibility of a material in a seawater environment under cathodic protection; is better described by the interaction of these materials parameters with the CP potential levels and the design applied K stress parameters of the components. One of the goals is to map the three variables of design (applied K), environment (CP potential level) & materials(strength/hardness) to provide an engineering application guideline.

Since hydrogen activity at a crack tip is intensified when compared to the bulk of the material, tracking the crack growth rate (CGR) becomes a very sensitive parameter that can be used to characterize the interactions. The data will be presented and discussed in the context of a hydrogen activated cracking model introduced by Ted Anderson⁵ & Rick Gangloff⁶. In a nutshell, the guiding philosophy for this approach is evaluating the interaction of applied stresses with the CP environment, in order to characterize a materials' susceptibility to hydrogen embrittlement as a function of a materials yield strength/hardness level.

For the fastener grade ASTM A320 carbon alloy steels tested and previously reported as detailed in NACE⁽³⁾ paper 12785 (Corrosion 2019)⁷; those material conditions that were less susceptible evidenced a decrease in CGR when more positive CP potentials were applied at any given Applied K level. In other words, the more positive potentials could compensate for the increased stresses that are experienced by increasing the Applied K levels. Contrariwise, for those materials that were investigated beyond the recognized hardness/yield levels considered acceptable per API 20e; the effect of the more positive CP potential levels had little effect if any on the resultant CGR.

The goal of the present research was to fill in the regions with an intermediate yield strength material building on the previous data with a material in the range of hardness values close to HRC 34 (the maximum hardness limit identified by API 20e) in order to characterize susceptibility as a function of increasing yield strength levels and to explore the region where the transition between susceptibility and non-susceptibility occurs.

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Background & Context - Hydrogen Assisted Cracking; the effects of the interaction of CP potential and Stress levels & Design Guidelines

In hydrogen activated cracking, the crack propagation occurs because the higher local concentration of hydrogen at the crack tip embrittles the area. This embrittlement and crack propagation are due to the fact that at the crack tip there is a high degree of triaxial stress concentration which works to open up the crystal lattice and, in the process, increases the solubility of hydrogen at the crack tip.^{4&5} Compared to the bulk of the material, the generated atomic hydrogen is then attracted preferably to the crack tip. Due to this, monitoring the crack growth rate (CGR) at the crack tip, is therefore a very sensitive monitor of the effects of the CP potential level. This model is represented by Figure 1 and is based on Anderson.⁴

In accordance to this model, low relative yield strength levels will be less susceptible to hydrogen embrittlement when compared to a relative higher yield strength carbon alloy steel. The higher the relative yield of the material, the greater the amount of triaxial stresses at the crack tip leading to the expansion of the crystal lattice. As the crystal lattice expands, the solubility of hydrogen increases at that crack tip as compared to the bulk material, and with that the embrittlement effect increases. One of the focal points of this research is to characterize the susceptibility of the material as a function of the yield strength.

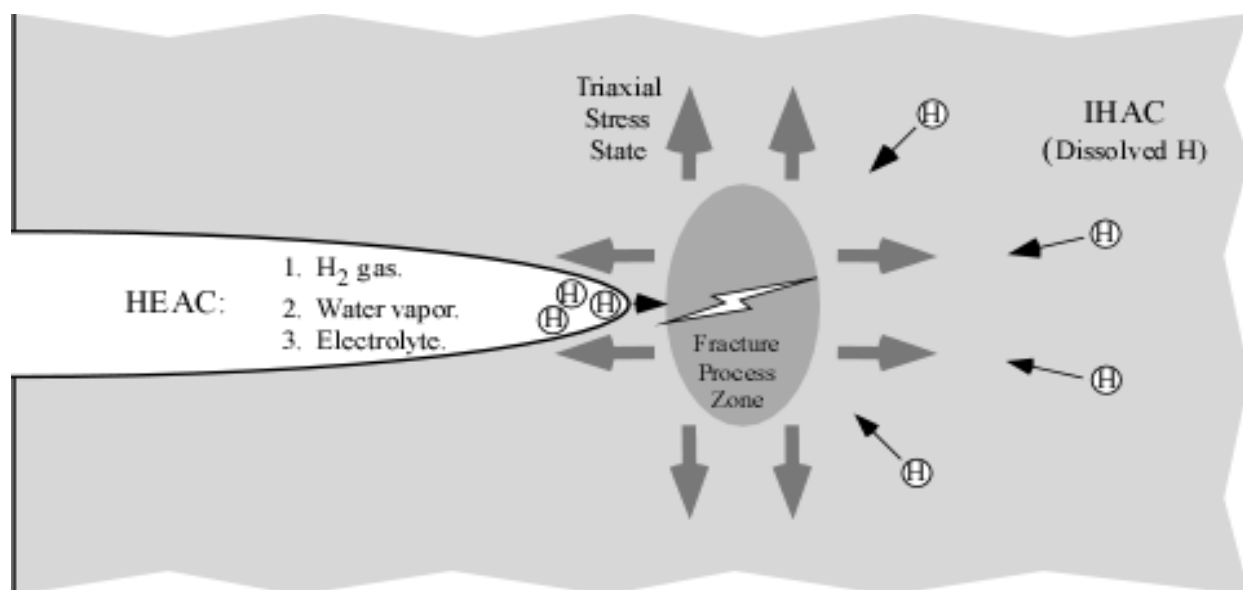


Figure 1:⁵

The triaxial stresses at the crack tip open the lattice structure attracting atomic hydrogen to the crack tip and facilitating the crack propagation process.

Another focal point of the research is to characterize the effect of increasing applied K stress levels at any given yield strength. Increasing applied K stress has the same effect as outlined above for the increases of yield strength; specifically that as the applied K stress level is increased, the solubility of hydrogen will also be increased, resulting in a greater crack growth rate and hence an increased susceptibility of the material to embrittlement. Exploring susceptibility at various applied K stress levels and varying CP potentials allows mapping out a design operational parameter for the application of the material in terms of applied K stress parameters.

These types of effects as represented by the model can be a very effective means of testing and explaining on an experimental basis, the hardness & yield limits that have been set in specifications such as API 20e for carbon alloy (HRC 30 to 34) steel fasteners used in seawater and under CP. Field experience has indeed shown, that as the hardness is increased beyond the identified levels with a metallurgically acceptable microstructure, that the risk for hydrogen embrittlement rises. The results of this research confirm these limits and show how monitoring stable static crack growth rates is then a very sensitive way to characterize the interaction of stress and CP levels that define susceptibility to hydrogen embrittlement.

Table 1 shows represents the range of crack growth rates that have been encountered in the present work as well as the previously reported work. The crack growth rates have been extended to include the length of a crack after 10 & 20 years to show applicability of the how the data can be used in design. This extrapolation can be done because the crack growth rate that is occurring is in the region of stable static crack growth.

For design purposes, the maximum crack growth allowed during the design life of the fasteners is the minimum flaw size detectable by non-destructive techniques such as penetrant or magnetic particle testing. This will be discussed more at length in the discussion section of this paper.

Note that the low CGR of 10^{-8} mm/sec represents the K_{1EAC} which is a parameter defined as the threshold stress intensity below which the anticipated crack growth is negligible.⁸ The data that will discussed in the latter part of this paper shows that the achievable K_{1EAC} values where crack growth is negligible is influenced by the by the interaction of Applied K & CP potential levels at each of the specific yield strength levels tested.

Table 1
Crack growth rate (CGR) & Design Life Calculations

Predicted Crack Growth mm			
CGR (mm/sec)	1 year (mm)	10 years (mm)	20 years (mm)
10^{-5}	3,153.6	31,536	Way too much!
10^{-8}	.31536	3.1536	≈ 6.3mm (1/4 ")

From practical experience, oil industry specifications have limited maximum strength levels by establishing maximum hardness levels ranging from 34 to 35 HRC. What has not been clearly established is identifying the corresponding yield strength level where the transition occurs? Hardness has been chosen as a quality control parameter to define the limits of application, but in the specifications at present, there is no direct correlation to maximum yield strength levels that the hardness limits correspond to. One of the stated goals of this research work is to help identify the transition.

Though hydrogen embrittlement per se does not need a crack to be initiated, the key point is that if it does occur, the probability that the crack is formed will be at the highest stress concentration area. It follows then, that it is at these high stress concentration areas that materials factors such as hardness, yield strength & microstructure become highly relevant. What the study of hydrogen activated cracking facilitates, is the opportunity to characterize the interaction of applied stresses in the highest stress state, with the varying CP potential levels that a component could be exposed to in operation.