Reliability Analysis for Degradation Effects of Pitting Corrosion in Carbon Steel Pipes

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Abstract

Corrosion is a major cause of failure in some metals with adverse effects on reliability of components and structures made from such metals. For example in carbon steel pipes various forms of localized corrosion, pitting corrosion, and stress corrosion cracking (SCC) cause sudden and catastrophic failures due to the absence of any external sign of damage in the system. Studying the growth of pit depth and pit densities at different temperatures and stress conditions with respect to time is critical in monitoring the localized corrosion damage and preventing the system downtime. A new probabilistic physics-of-failure (PPOF) model is developed to determine the temperature and stress dependencies of pit depth growth with respect to time. In doing so, microscopic methods are used to determine the pit depths produced on X-70 carbon steel samples subjected to accelerated corrosion tests. The pit depths and densities are measured in unstressed and stressed samples exposed to a solution of Sodium thiosulfate and water at different times and temperatures to ascertain the temperature and stress dependencies of pit depths that propagate during the pitting corrosion process. The stress and temperature dependency of the new model follows the exponential law (Arrhenius law), which allows estimating the activation energy of pitting corrosion process. Moreover, the pit size and intensity under different temperatures and stress conditions, estimated at different times, appear to follow the lognormal distribution. The uncertainty associated with the proposed models due to scattering of pit data and also the autocorrelation among such data are accounted for.

Keywords: Pitting Corrosion; Pit Depth; Lognormal Distribution; Reliability; Uncertainty Analysis; Autocorrelation; Bayesian inference.

1. Introduction

Corrosion is considered a significant factor in the failure and damage of metals, including carbon steel pipes. According to a study, the annual direct cost of corrosion, in the U.S. oil industry exceeds $5.1 billion per year [1]. One of the most destructive forms of corrosion is pitting corrosion. Oil and gas steel pipelines are mostly subjected to this type of corrosion, resulting from the corrosive medium that flows inside the pipes and causing notable cracks. This has fuelled the study of the behavior and impact of this phenomenon on specimens from pipes used in
the industry. Experiments performed in this study focused mainly on measuring the pit depths, pit densities after exposing samples of X-70 carbon steel to corroding Sodium thiosulfate for different time and temperature (with and without applied stress). Statistical methods and tests were used to find the distribution of pits over the specimen surface and the Bayesian inference for evaluation the parameters.

Nomenclature

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
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<tbody>
<tr>
<td>a</td>
<td>Pit depth</td>
</tr>
<tr>
<td>r</td>
<td>Pit radius</td>
</tr>
<tr>
<td>t</td>
<td>Time (immersion)</td>
</tr>
<tr>
<td>C, C_p</td>
<td>Material constants</td>
</tr>
<tr>
<td>a, d, f, u, w</td>
<td>Constant parameters</td>
</tr>
<tr>
<td>n</td>
<td>Time exponent</td>
</tr>
<tr>
<td>T</td>
<td>Temperature [K]</td>
</tr>
<tr>
<td>ĭ</td>
<td>Applied stress</td>
</tr>
<tr>
<td>Q</td>
<td>Activation energy</td>
</tr>
<tr>
<td>[H₂S]</td>
<td>Hydrogen sulphide concentration</td>
</tr>
<tr>
<td>s</td>
<td>Standard deviation of pit depth</td>
</tr>
<tr>
<td>R</td>
<td>Gas constant = 8.314472 J/mol·°K</td>
</tr>
</tbody>
</table>

2. Theoretical Background

2.1. Introduction to Corrosion

Corrosion is the degradation of a metal or alloy and its properties due to a chemical or electrochemical reaction with the surrounding environment [2]. Many variables influence the behavior of a metal in its environment. Acidity (pH), oxidizing power, mechanical stress, temperature, fluid flow and the concentration of the corroding medium are important factors that affect the corrosion process. The most common types of corrosion are: general-, galvanic-, crevice-, creep-, and pitting- corrosion and this paper focused only on pitting-corrosion.

2.2. Pitting Corrosion (Hydrogen Sulphide Corrosion)

Pitting corrosion is a localized form of corrosion that occurs when a corrosive medium attacks a metal at specific points causing small holes or pits to form. This happens when a protective coating or oxide film is perforated, due to mechanical damage or chemical degradation. Hydrogen sulphide (H₂S), also known as sour corrosion, is an aggressive agent of corrosion. Wells with only 10 ppm or above are labelled as sour and corrosive [3].

2.3 Models for Pitting Corrosion

Some of the most important models of pitting corrosion are summarized below:

- **Hoeppner (1971)** [4] proposed a model to determine critical pit depth required to nucleate a crack under pitting corrosion fatigue conditions. The time required to reach this critical pit depth can be determined by:
1932

M. Nahi et al. / Procedia Engineering 10 (2011) 1930–1935

\[ t = \left( \frac{a}{C} \right)^3 \rightarrow a = C t^{1/3} \]  

(1)

b. Kondo (1989) [5] applied a transition model to simulate the process from corrosion pit to fatigue crack nucleation. Pit diameter (assuming hemispherical pit depth) was measured intermittently during corrosion fatigue tests. From these experimental results, the corrosion pit growth law was expressed as:

\[ 2a \approx C_p t^{1/3} \]  

(2)

3. Experimental Set-up, Materials and Methodology

3.1 Pitting Corrosion Tests

Strip samples (50x25x2.5-3 mm) were machined from a section of X-70 carbon steel pipe. The samples were polished on SiC sand paper with different grits and finally, fine polished with Al₂O₃ powder in order to obtain a shiny mirror surface without any pits present. A dial gauge was attached at the center of the static-stressed specimens in order to read the amount of bending and the corresponding applied stress was calculated according to the ASTM standard relation [6].

The specimen was submerged vertically in a bath of 250 ppm weighed Sodium thiosulfate (Na₂S₂O₃, 5 H₂O) for a predetermined amount of times and temperatures. Tsujikawa et al. proposed that (Na₂S₂O₃, 5H₂O) is a good substitute for hazardous H₂S [7, 8, and 9]. The pit sizes, pit depths and distributions were measured by using an optical microscopy and SEM.

4. Results and Discussion

4.1 Temperature and Stress Dependency of Pit Depths

The pit depths were measured using optical microscopy by focusing and defocusing method [10]. The difference between the focused and unfocused portions was divided by the magnification used to determine the pit depth. Temperature and stress dependency of pith depth versus time in figure 1 show nearly the power law tendency given in Hoeppner and Kondo model (\(a \approx C t^n\), with \(n=1/3\) for Aluminum alloys).

\[ a = C t^n \]

\[ a = e^{d\sigma} e^{-Q/RT} e^{u-\gamma T-f\sigma} \]

Fig. 1. (a) pit depth vs. time (unstressed X-70 carbon steel samples) in 250 ppm Hydrogen thiosulfate (H₂S similar) at different Temperatures; (b) pit depth vs. time (stressed samples) at 318 K in 250 ppm in Hydrogen thiosulfate solution

Activation energy of the pitting process was estimated from the temperature dependency of the coefficient C, which follows the Arrhenius law. Exponent n (in the relation \(a \approx C t^n\)) shows a linear dependencies with both temperature and stress. Therefore pit depth becomes the following general form:

(3)
All the parameters for the general empirical model were estimated using the Bayesian Markov Chain Monte Carlo (MCMC) analysis [10] and the results and probability estimations are given in the Fig. 2. Therefore the final relation with the mean values substituted for unstressed condition at different temperatures and stressed samples at (318 K) is given by:

\[
\alpha = 0.04635 e^{0.0125 - 695.4/T - 0.00024T + 0.00492}
\]  

(4)

Fig. 2. parameters estimated by Bayesian posteriors estimated using sophisticated sampling approach MCMC [11].

4.2 Pit Intensity Distribution

Pit intensity is a measurement of the number of pits per unit surface (square millimetre in this case). The number of pits increases when the samples were subjected to higher stresses or temperatures. Pit intensity measured randomly on the sample-surface which followed lognormal distribution.

The following observations for the pit intensities were made:

- Mean pit intensity, \( \rho \), for the unstressed samples increases logarithmically with the temperature and immersion time. This tendency (for samples immersed in Sodium thiosulfat) is shown in Figure 3.

![Fig. 3. mean intensity, \( \rho \), vs. Temperature (unstressed samples) immersed for different times in 250 ppm in Hydrogen thiosulfate solution](image)

- Mean pit intensity, \( \rho \), for the stressed samples increase logarithmically with time for different applied stresses 6, 13,1nd 17 MPa at 318K. These tendencies (for samples immersed in Sodium thiosulfat) are shown in Figure 4.
Pit intensities for unstressed and stressed X70-carbon steel samples followed a lognormal distribution at different temperatures 308 K, 318 K, 348 K and 363 K and for different times. This tendency is shown in figure 5 after 30 hrs immersion in the corrosive medium. They showed the same behaviour after 5 and 10 hours immersion times.

The mean intensity of unstressed is expressed by \( \mu (318 \text{ K}) = \ln(\mu = 6.75, \sigma = 0.14) \), and for stressed \( \mu (17 \text{ MPa, 318 K}) = \ln(\mu = 6.72, \sigma = 0.10) \).

In this part of research the effect of pit depth dependency on different \( \text{H}_2\text{S} \) concentrations (100, 150, 200, 300, and 400 ppm) and immersion times (5, 10, 24 hrs, at 323 K) has been estimated. Further, experiments for extension of these results to higher temperatures are under investigation. The results are given by:

\[
\alpha = 0.0057 \ [\text{H}_2\text{S}]^{0.1419} t^{-0.017}[\text{H}_2\text{S}] + 0.355
\] (5)

In order to justify the use of a lognormal distribution for the pit intensities, Kolmogorov-Simirnov test was applied and the distribution was not rejected [12]. Autocorrelation among the data points was also considered in this study. It was shown that the adjacent data points for pit depths for 308 K and 318 K are correlated and one can be predicted from the other by knowing the corresponding autocorrelation factor.

By assuming a Poisson distribution for the number of defects with a pith depth intensity of 3.82 per mm\(^2\), the total probability of failure of a pipeline (250 meter long, 1 mm thick), estimated for 25 years, is 0.7025, which corresponds to 28 failures per year. The related probability densities are given in Figure 6.
5. Conclusions

Pit depth models of Hoeppner and Kondo for the pitting corrosion were expanded in this study. An empirical model that captures the depth of the pits on the surface of the pipelines subjected to corrosive medium was developed. The temperature dependency had the form of Arrhenius law, which allows for the estimation of the activation energy required for pitting corrosion process. The stress dependency showed an exponential tendency. The linear temperature and stress dependency of the time exponent was estimated. The pit intensity followed a lognormal distribution and showed logarithmic dependency with temperature and time. Bayesian inference was applied to estimate the probability distributions of parameters.

References