Fatigue life prediction of gasoline storage tank considering varying current density and weld stress

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Abstract
In the field of corrosion fatigue crack research, how to couple corrosion and fatigue under various conditions is a problem worthy of discussion. According to the electrochemical corrosion principles and the superposition principles, studies have been made on the interaction between corrosion and fatigue, and the relationship model between the corrosion fatigue crack size and the corrosion fatigue remaining life in the Corrosion of Hydrogen evolution (COHE) fatigue long crack growth stage is established. The feasibility of the model is verified by using the experimental data. According to the specific structure of the dislocation butt weld of large storage tank, the stress at the crack is calculated. Based on the above model and the experimental data, the corrosion fatigue residual life of large storage tank is predicted. The feasibility of the model is verified, which provides a new method for corrosion fatigue life prediction of large storage tanks.

Keywords
Fatigue life, COHE, weld stress, crack size, storage tank

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Introduction
In real life, the materials of many machines and pressure vessel components are metal. The good physical properties of metal make it the mainstream of the era. However, in actual engineering practice, although the designer has no problem with the fatigue strength design, metal fatigue can still cause metal fracture to fail.1

Corrosion fatigue is the result of the interaction of corrosion and fatigue loading, which is influenced by the corrosive environment, load magnitude and load frequency. Corrosion fatigue has been widely reported for testing in air and various environments.2 In 2008, the Corrosion fatigue behavior of extruded magnesium alloy was discovered that corrosion fatigue crack initiation and crack initiation in an inert medium were completely different.2,3 The corrosion fatigue life was quantitatively evaluated by dividing the corrosion fatigue process into two phases, that is, the corrosion pit growth phase before crack initiation and the corrosion pit growth phase before specimen damage.2 Studies were made on the influence of environmental factors on the corrosion fatigue of aluminum alloys, and based on fracture mechanics, crack growth was quantitatively characterized.4,5 In 2017, the mechanism of corrosion fatigue cracking was proposed.6

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In the corrosion fatigue crack growth stage, the interaction model believes that the rate of crack growth under the interaction of corrosion and fatigue will produce an additional crack growth rate.\textsuperscript{7–10} The competitive model considers the crack growth rate to be the one with the largest rate among them, but the independent superposition model considers them to act independently, the latter of which is difficult to establish in most cases. For instance, when electrochemical corrosion is Corrosion of Oxygen evolution (COOE), after the material produces a passivation film,\textsuperscript{11–13} the corrosion rate will be greatly reduced. Only fatigue cracks the passive film, and there must be a rate of interaction in this process.\textsuperscript{14–16} However, COHE does not produce a passivation film, and the independent superposition model is found to be applicable after verification in the case of COHE. In the research of corrosion fatigue, many people express the corrosion rate by Faraday’s law.\textsuperscript{17,18} Many scholars set the current density in Faraday’s law to be constant, but as the crack grows, Newman found that the current density changes,\textsuperscript{9} but it needs to be determined by continuously measuring the corrosion potential. It can be done when doing corrosion fatigue experiments, but it is obviously unrealistic to measure low-cycle corrosion fatigue at all times for decades.\textsuperscript{12,19} This article studies the corrosion potential through the chemical properties of the corrosion solution.

In the stress analysis of thin-walled cylindrical pressure vessels, many people think that the stresses received by cracks in different directions are hoop stress and axial stress,\textsuperscript{20–24} the calculation method is adopting the analysis method of thin-walled cylinders. Some people would also think that the crack stress analysis of large liquid storage tanks is still obtained by the analysis method of thin-walled cylinders.\textsuperscript{25–27} However, this method is based on the condition that the pressure in the cylinder is equal everywhere. However, the pressures of different liquid levels in large-scale liquid storage tanks are completely different, and there is no pressure on the upper surface, so the thin-walled cylinder method is not suitable for calculating the stress of large-scale liquid storage tanks.\textsuperscript{28–30} In this paper, the stress state at the crack is studied based on the combined cylinder method.

This article is structured as follows: Firstly, by analyzing the difference between the two kinds of electrochemical corrosion of COHE and COOE, it is analyzed that the principle of independent superposition is different in the two cases; Secondly, according to the chemical properties of the solution, based on Paris formula and Faraday’s law, combined with the principle of independent superposition, the relationship model between corrosion fatigue crack growth rate and crack size is established; Then, based on the combined cylinder method, the relationship between the stress at the crack and the crack size is established, and the life of the oil tank is predicted; Finally, some conclusions are drawn.

**Research method**

**Process of corrosion fatigue**

The corrosion fatigue life of materials is divided into two main periods. The first period is from the smooth specimen to the formation of corrosion pits and growth to the critical pit depth. At this time, fatigue small cracks are generated under the effect of stress concentration, and the multiple small cracks expand and coalesce into long cracks. This stage is the initial corrosion fatigue life of materials. The second stage is the stage from the appearance and propagation of long fatigue crack to the fatigue fracture failure, which is the corrosion fatigue long crack propagation life of materials.\textsuperscript{15} In this paper, the growth of long cracks is mainly studied. Schematic diagram of corrosion fatigue process is shown in Figure 1.

**Corrosion rate of COHE during fatigue long crack growth**

Different from the electrochemical corrosion in the crack initiation stage, the fatigue crack growth rate in the crack propagation stage is faster, and the surface of the fresh crack tip is constantly exposed. Electrochemical corrosion is divided into two types: COOE and COHE. COOE will produce a passivation film, that is, the commonly known rust, whose chemical composition is $\text{Fe}_2\text{O}_3$, but COHE does not produce a passivation film. The corrosion rate of COOE will be greater than that of COHE, which requires that the passivation film is destroyed fast enough, because once the passivation film is produced, the corrosion rate will get lower. This requires pure mechanical fatigue to destroy the passivation film and crack it to expose the fresh metal surface that will continue to be corroded.\textsuperscript{31}

![Figure 1. Corrosion fatigue process.](image)
The corrosion rate is usually measured by Faraday’s law\textsuperscript{13,14}:
\[
\left(\frac{da}{dN}\right)_{SCC} = \frac{IM}{nFp}
\]  
(1)
where \(i\) is current density, \(M\) is molar mass, \(p\) is density of the corroded metal, \(n\) is ion valence of the corroded metal, \(F\) is faraday’s constant.

**Fatigue growth at the long crack growth stage**

The fatigue crack propagation stage generally refers to the process of material crack propagation in the air to rapid fracture.\textsuperscript{17} The crack growth rate in this stage is very regular. The Paris model is a well-known and recognized crack growth rate model in the fatigue crack growth stage:\textsuperscript{32}
\[
\left(\frac{da}{dN}\right)_{F} = C(\Delta K)^m
\]  
(2)
where \(C\) and \(m\) in the air is the material constant. \(\Delta K\) is the stress intensity factor in the case of tensile stress, and the expression is as follows.
\[
\Delta K = Y\Delta \sigma \sqrt{\pi a}
\]  
(3)
where \(Y\) is a geometric correction. \(\Delta \sigma\) is the difference between the maximum and minimum stress. \(a\) is the length or depth of the crack.

Generally, the metal material will have a stress intensity factor threshold value for crack growth \(\Delta K_{th}\). In the case of \(\Delta K > \Delta K_{th}\), it will quickly enter the crack propagation stage. If the threshold value of stress intensity factor of the material is known by experiment or consulting data \(\Delta K_{th}\), then you can know the initial crack size within a certain stress range \(a_0\).
\[
a_0 = \frac{1}{\pi} \left(\frac{\Delta K_{th}}{Y\sigma_{-1}}\right)^2
\]  
(4)

Of course, this crack growth stage will also end. When the crack size reaches a certain value, it will enter a rapid fracture period. At this stage, the crack grows very rapidly, and this crack size is called the critical crack size \(a_c\), whose estimated formula is as follows.
\[
a_c = \frac{1}{\pi} \left(\frac{K_{IC}}{Y\Delta \sigma}\right)^2
\]  
(5)

Thereinto \(K_{IC}\) is the fracture toughness. It is related to elastic modulus and yield strength. According to the formula Hahn – Rosenfield\textsuperscript{18}:
\[
K_{IC} = A_0 \sqrt{\varepsilon_f E\sigma_y n_0}
\]  
(6)

**Figure 2. Corrosion of oxygen evolution.**

where \(E\) is the modulus of elasticity. \(\sigma_y\) is the yield strength. \(n_0\) is the strain hardening index of the material. \(\varepsilon_f\) is true strain of fracture. And it is only applicable to materials only alloy steel. Since the elastic modulus and yield strength vary with temperature, it can be written as follows.
\[
K_{IC} = \sqrt{AE\sigma_y}
\]  
(7)

Bringing into the above formula is as follows.
\[
a_c = \frac{1}{\pi} \frac{AE\sigma_y}{(\Delta \sigma \times Y)^2}
\]  
(8)

where \(a_c\) is proportional to \(E\sigma_y\), but temperature has an effect on elastic modulus and yield strength, so the critical crack size changes with temperature.

**COHE fatigue long crack growth rate**

Electrochemical corrosion is divided into COHE and COOE.COOE has a fast corrosion rate, but produces a passivation film that slows the corrosion rate. COHE will not produce a passivation film to reduce the corrosion rate, but the corrosion rate is slower.\textsuperscript{19} The superposition model of interaction assumes that there is an interaction between corrosion and fatigue, resulting in an additional rate of interaction. For example, COOE will produce a passive film, the composition of which is \(Fe_2O_3\). As shown in the Figures 2 and 3, the corrosion rate tends to zero during the period from the formation of the passive film to the rupture, which can only be cracked by pure mechanical fatigue, and the fatigue acts on the passive film.\textsuperscript{31–33}

The rate of this period is not a simple sum of the two, because the corrosion rate is 0, and the fatigue rate acts on another material, with the rate unknown, so the passive film will certainly produce a corrosion fatigue interaction rate \(\left(\frac{da}{dN}\right)_{COHE}\).

The current density is the decisive factor, and the rest are constant. Due to factors such as corrosion deposits and metal activity, the current density of the crack wall is much smaller than the current density of the crack.
tip,21 and the constantly exposed surface of the fresh crack tip becomes the target of corrosion. Therefore, the corrosion current density generally refers to the current density of both the anode crack tip and the cathode coating.9 Many scholars regard the current density as a constant, that is, the corrosion rate will not change from beginning to end. But the metal loses electrons from the anode through the solution to the cathode, and the cracks become deeper and deeper, so the length of the solution will also become longer, and the resistance of the electrons will also become larger. The crack tip displacement will also change with the crack depth and stress, which will affect the current density.27 Stress and crack depth will affect the current density, and there will be no passivation film after COHE, so there is no need to quickly dissolve the width of the crack tip.

So during COHE, the stress also has an effect on the corrosion current. This also creates an interaction, which accelerates the rate of crack expansion. The superposition of the corrosion fatigue interaction rate and the corrosion rate is expressed as27:

$$\frac{da}{dN} = \frac{da}{dN}_{SCC} + \frac{da}{dN}_{F} + \frac{da}{dN}_{CO}$$

(9)

where \(Mg/(mol)\) is Molar mass, \(\sigma_0(MPa)\) is flow stress, the mean value of yield stress and tensile strength. \(\Delta\phi(V)\) is the potential difference between the crack tip and the outer surface, which can be obtained from the potential diagram. \(n\) (dimensionless) is corroded metal ion valence \(F(C/mol)\) is the Faraday constant, \((96500C/mol)\), \(\rho(g/mm^3)\) is density of corroded metal. \(\sigma(MPa)\) is stress level. \(v\) is loading frequency. \(a_b(mm)\) is crack depth.

Therefore, the total rate of corrosion fatigue is:

$$\frac{da}{dN} = \left(\frac{da}{dN}\right)_{SCC} + \left(\frac{da}{dN}\right)_{F} + \left(\frac{da}{dN}\right)_{CO}$$

(10)

where \(4M\sigma_0\Delta\phi\) is the product of the Molar mass and the current density, and \(nFpf\sigma_b\ln(1 + \frac{4a_b}{\sigma})\) is the product of the Faraday constant and the potential difference between the crack tip and the outer surface.

However, we know the current density changes, but we need to constantly measure the current density or voltage. It may be possible to do it in experiments, but if there lie ahead decades of low-cycle corrosion fatigue, it is difficult to make measurements all the time. The PH-potential diagram of \(Fe - H_2O\) is Figure 4, which can determine the potential difference between cathode and anode.19

**Model validation**

In engineering practice, there are many failures of mechanical parts when they work, mainly due to defects caused by corrosion, fatigue and corrosion fatigue.34,35 Therefore, in the process of mechanical component design and acceptance, it is necessary to evaluate and modify according to the actual situation. For example, when the wall of a large storage tank has defects, the remaining service life should be evaluated based on corrosion fatigue cracks for repair and replacement.36 If it is working at a high temperature, the theoretical strength should be improved. It can be seen from the Paris formula that the fatigue growth rate increases exponentially as the crack size increases.

If the current density is constant in Faraday’s law, then \(\frac{da}{dN} = \left(\frac{da}{dN}\right)_{SCC} + \left(\frac{da}{dN}\right)_{F}\), which is considered as a linear model. If the current density is not constant in Faraday’s law, then \(\frac{da}{dN} = \left(\frac{da}{dN}\right)_{SCC} + \left(\frac{da}{dN}\right)_{F} + \left(\frac{da}{dN}\right)_{CO}\), which is considered as a nonlinear model.

According to data from the literature,37 compare the data it gets with the data in Figure 5.

It can be seen that in the case of corrosion fatigue with only COHE, the nonlinear model is closer to the
test data, while the linear model and the test data have larger errors. Compared with the three curves in the graph, the nonlinear model is closer to the experimental data, which verifies that the nonlinear model is more reasonable.

**Life prediction of liquid storage tank**

The material of oil storage tank is Q245R, which is low carbon steel. Schematic diagram of tank wall and surface crack is shown in Figure 6. Both elastic modulus and yield stress are related to temperature. The relationship between elastic modulus and temperature is shown in Figure 7. And the relationship between yield stress and temperature is shown in Figure 8.17

The relationship between yield stress and temperature is as follows:

\[
\sigma = \frac{1978E \sigma_s}{D_s^3 Y^2} \left( \frac{11}{Y} \right)
\]

When it is known that at 25°C the fracture toughness of Q245R is 110.7 MPa, the expression of critical crack size of Q245R can be obtained from the Figures 7 and 8 and equation (8):

\[
a_c = \frac{1}{\pi} \frac{K_{IC}^2}{(\Delta \sigma Y)^2} = \frac{1}{\pi} \frac{0.1978E \sigma_s}{(\Delta \sigma Y)^2}
\]  

(11)

The temperature of this area is about 40°C in summer, and the critical crack depth \(a_c\) is calculated to be 16.87 mm (Table 1).

The oil tanks in this article have been tested and all of the crack defect locations is shown in Figure 9. The Figure 10 shows the deepest flaw on the tank wall. In order to obtain the size of the crack, we polish it off, which is shown in Figure 11.

**Tank wall stress calculation of liquid storage tank**

Most storage tanks are equipped with floating roof seals. This kind of internal pressure storage tank is regarded as a thin-walled cylinder by some scholars.39 The axial stress is \(\sigma = \frac{pR}{2t}\). The circumferential stress is \(\sigma = \frac{pR}{t}\).

The detection crack is horizontal, so it is not subject to circumferential stress. The pressure of the tank wall changes with the height of the liquid storage. The pressure of each place is different, so the stress of different height also varies. Schematic diagram of the pressure distributions of large oil storage tank shell is shown in Figure 12. The bottom plate is separated from the tank bottom according to the shear effect of the upper side wall plate on the lower side wall plate.38 These are considered to be a long cylindrical shell wall plate, the model as shown in Figure 13, on the edge of the unit force and under the action of hydraulic pressure, the deflection equation, respectively.
where $F_i = \left( \frac{E_i}{R_i} \right)^{0.25}$, $K_i = \frac{E_i}{R_i}$. $t_i$ is the thickness of the tank wall of the $i$ layer. $\rho$ is the liquid storage density. $x_A$ is the distance from the weld on the $i$ layer of the wall plate. $h$ is the height of the weld between the two plates from the liquid level. $H_i$ is the calculated height of water level at the connection between the $i$ layer and the $i + 1$ layer.

\[
y_A = \frac{2F_i}{K_i} e^{-F_i x_i} \left[ -Q_i \cos(F_i x_A) - F_i M_i (\cos(F_i x_A) - \sin(F_i x_A)) \right] + \frac{\rho g (H_i + x_A)}{K_i}
\]

(12)

\[
y_B = \frac{2F_{i+1}}{K_{i+1}} e^{-F_{i+1} x_B} \left[ -Q_i \cos(F_{i+1} x_B) - F_{i+1} M_i (\cos(F_{i+1} x_B) - \sin(F_{i+1} x_B)) \right] + \frac{\rho g (H_i - x_B)}{K_{i+1}}
\]

(13)
where $y_B$ is the deflection of the \(i+1\) layer of the wall plate, $x_B$ is the distance from the weld on the \(i+1\) layer of the wall plate.

When $x_A = x_B = 0$, $y_A = y_B$, $y_A^0 = y_B^0$, which gives the equation:

$$
2F_i + 1K_i + 2F_i^2K_i + 2F_i^2K_i/\gamma^0 + 2F_i^2K_i/\gamma^0 - 4F_i^2K_i/\gamma^0 - 2F_i^2K_i
\begin{equation}
2F_i^2K_i + 2F_i^2K_i/\gamma^0 - 2F_i^2K_i/\gamma^0 - 4F_i^2K_i/\gamma^0 - 2F_i^2K_i
\end{equation}

Considering that the result of calculation of the bending moment $M_i$ is small, it is ignored. Shear force $Q_i$ on the upper surface of the \(i\)-layer plate per millimeter:

$$Q_i = \left[ \frac{1}{K_i} - \frac{1}{K_{i+1}} \right] \rho g H_i$$

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Therefore, the shear force on the tank wall whose width is the crack length ($B = c$) is $Q = Q_c$. Schematic diagram of tangential stress of the crack is shown in Figure 14. The shear stress at the crack is:

$$\sigma = \frac{Q}{A}$$
Schematic diagram of crack surface length and depth is shown in Figure 15. The crack section is generally a semi-ellipse, where $A$ is the remaining area after removing the crack area:

$$A = ct - \frac{1}{4} \pi ac$$  \hspace{1cm} (17)

For cracks in storage tanks, the relationship between crack length and depth can be introduced:

$$c = 0.75a^{1.43}$$  \hspace{1cm} (18)

The stress intensity factor is:

$$K = Y \Delta \sigma \sqrt{\pi a}$$  \hspace{1cm} (19)

where $a$ is the crack size. $\Delta \sigma = \sigma_{\text{max}} - \sigma_{\text{min}}$ is the stress range. $Y$ is the geometric correction factor, which generally is $Y = 1.12$.

Generally, the deepest and longest cracks detected are at the weld seam, and the butt joint of the weld seam will cause stress concentration. Schematic diagram of weld place is shown in Figure 16, so the stress concentration factor of the butt weld seam is introduced:

$$K_t = 1 + 0.27(\tan \theta)^{1.3} \left(\frac{1}{Y}\right)^{1.5}$$  \hspace{1cm} (20)

$\theta$ is the welding toe angle. $r$ is the root radius of the notch.

The maximum shear stress is:

$$\sigma_{\text{max}} = K_t \sigma$$  \hspace{1cm} (21)
where $\Delta t$ is the thickness difference of the steel plate. $t$ is the thickness of the steel plate with a smaller thickness.

The deepest part of the crack is at the welding point between the first and second tank wall. Apply the model to calculate the stress at the deepest part of the oil tank wall crack, which is 121.04 MPa.

In order to enhance the accuracy of the calculation, the finite element method is used to calculate the stress here. Stress analysis nephograms are shown in Figures 17 and 18. The establishment of the finite element solution shows that the stress between the first wall and the second wall is 123.076 MPa, and the error is only 1.6%. This calculation result verifies the accuracy of the model. When predicting the life of an oil tank, the model is used to calculate the stress of cracks at different depths.

The parameters of the oil tank are brought into the corrosion fatigue of the material of the model Q245R. It can be seen from Table 2 that the theoretical remaining service life of the pressure vessel is about 9.78 years, which is basically the same as the design remaining service life of 10.25 years, and the error between the design service life of the gasoline storage tank and the measured data is only 4.51%.

**Table 2. Comparison of predicted life and actual service life.**

| Initial crack size (mm) | Critical crack size (mm) | Extended life (cycle) | Usage time (year) |
|-------------------------|--------------------------|-----------------------|-------------------|
| 5                       | 16.87                    | 714.5                 | 9.78              |

**Conclusion**

In this paper, based on the Paris formula, the relationship between corrosion solution current density and crack depth in the corrosion fatigue process is investigated in the COHE case, and a nonlinear crack expansion model is established. Comparing the steel corrosion fatigue crack expansion rate under linear and nonlinear models, the results show that the nonlinear model is more suitable for the prediction of corrosion rate. Establish the relationship between crack stress and crack size at the weld seam according to the actual tank condition. The applicability of the model is verified by predicting the remaining service life of the tank, and the error is within 5% from the actual situation. A new method for reservoir life prediction is proposed.

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