Study on fatigue crack growth rate of 15CrMo steel based on stress ratio and corrosion environment

Wang Jing1*, Guo Chong2, Huang Kuichao3 and Shao Xiaolin4

1Department of Engineering Mechanics, Beijing University of Technology, Beijing, 100124, China
2Department of Engineering Mechanics, Beijing University of Technology, Beijing, 100124, China
*Corresponding author’s e-mail: wjing@bjut.edu.cn

Abstract. In this paper, the fatigue crack growth rate of 15CrMo steel, a typical gas cylinder material, is studied under the condition of simulating the actual working condition of gas cylinder. The low-frequency corrosion fatigue tests with stress ratio of 0.1 and 0.5 are carried out in air and different concentrations of wet hydrogen sulfide environment. The relationships between \(\frac{da}{dN}\) and \(\Delta K\) are expressed by Paris equation. The results show that the crack growth rate in hydrogen sulfide environment with concentration of 200 ppm is 27 times higher than in air. The addition of corrosion environment greatly fasts the crack growth rate of 15CrMo steel. With the increase of H2S concentration, the crack growth rate increases exponentially. With the increase of stress ratio, the average stress increases, the crack closure effect decreases, the crack tip is fully opened, and the contact area with corrosion medium increases, which results in the increase of crack growth rate.

1. Introduction
With the adjustment of national energy policy and the attention of the society to the living environment, clean energy represented by natural gas and hydrogen is more and more widely used in various fields [1]. Long tube trailer is a natural gas storage and transportation equipment, its main working part is gas cylinder. Because the gas inside the cylinder is usually high-pressure, flammable, explosive, and even corrosive, it has a higher safety risk [2]. Natural gas needs to be desulfurized and dehydrated before it is filled into the gas cylinder, but there are still H2S and CO2 residues. In practical applications, gas cylinders are often filled and deflated. So the working condition of the cylinder is a typical fatigue condition. The wet hydrogen sulfide environment and the pressure of cyclic rise and fall form a corrosive fatigue environment in the gas cylinder. In the process of production and use, the gas storage bottle will inevitably produce some small cracks. The corrosion fatigue environment will greatly accelerate the crack growth. Once an accident occurs, it will cause huge loss of life and property and adverse social impact. Therefore, it has great economic and social value to ensure its safety and reliable operation [3].

15CrMo steel is a kind of pearlitic structure heat-resistant steel with good hydrogen corrosion resistance property, which is often used to produce gas cylinders for storage and transportation of natural gas. In recent years, Chinese scholars have made a comprehensive description of the corrosion resistance properties of this material. However, under the coupling effect of corrosion and fatigue, it can often cause rapid failures of equipment. In this paper, the fatigue crack growth rate of 15CrMo steel under different concentration of hydrogen sulfide and different stress ratio is studied, and the corresponding
expression of crack growth rate is obtained, which provides a basis for the prediction of crack growth of 15CrMo steel cylinder in corrosive environment.

2. Material and experiment procedures

2.1. Experimental material
The experimental material is 15CrMo steel, the chemical composition and the mechanical properties are shown in Table 1 and Table 2.

| element | mass fraction /% |
|---------|-----------------|
| C       | 0.12~0.18       |
| Si      | 0.17~0.37       |
| Mn      | 0.40~0.70       |
| Cr      | 0.80~1.10       |
| Mo      | 0.40~0.55       |
| P, S    | ≤0.035          |
| Cu, Ni  | ≥0.30           |

| $E$ (GPa) | $R_{p0.2}$ (MPa) | $R_m$ (MPa) | A% | Z% |
|-----------|------------------|-------------|----|----|
| 200       | 396              | 522         | 21.9 | 73.1 |

2.2. Shape of Specimen
According to GB/T 6398-2017[4], method for fatigue crack growth of metallic materials, modified WOL specimen is used for the study, and the diagram of specimen is shown in figure 1.

2.3. Experimental procedures
By using Paris formula (1), the relationship between crack growth rate $\frac{da}{dN}$ and stress intensity factor range $\Delta K$ can be accurately expressed as follow.

$$ \frac{da}{dN} = C(\Delta K)^n $$  \hspace{1cm} (1)

The crack length $a_i$ of each cycle can be calculated by using the compliance equation.

$$ \frac{\Delta V_i}{\Delta P_i} = \frac{C_i(a_i/W)}{EB} $$  \hspace{1cm} (2)

After crack length $a$ is calculated, the $a-N$ curve of crack length $a$ varying with the number of cycles $N$ can be drawn, and the fitting values of fatigue crack growth rate $\frac{da}{dN}$ and crack length are determined by national standard.

According to the national standard GB12445.3-1990[5] the stress corrosion test method of high strength alloy Pre-crack specimen under wedge opening load (WOL), the stress intensity factor range $\Delta K$ at the crack tip of modified WOL specimen is:

$$ \Delta K = \frac{\Delta P \cdot C_i(a/W)}{B \cdot \sqrt{a}} $$  \hspace{1cm} (3)

In the test process, the alternating load $\Delta P$ is a constant value, so as long as the crack length $a_i$ of
each cycle is known, $\Delta K_i$ of each cycle can be obtained.

2.4. Experimental environments

Tests are carried out under H$_2$S concentrations of 200ppm, 1000ppm and 2000ppm. The stress ratios of the tests are 0.1 and 0.5. The test frequency is 0.01Hz.

3. Test results

3.1. Test results in air

The fatigue test of 15CrMo steel was carried out in air, the frequency was 0.01Hz and stress ratio was 0.5. The $a-N$ curve and crack growth rate $da/dN$-$\Delta K$ curve is shown in figure 2 and figure 3.

3.2. Crack growth rate curve in different concentration of hydrogen sulfide at $R=0.5$

The corrosion fatigue tests of 15CrMo steel were carried out under 200ppm, 1000ppm and 2000ppm respectively. The stress ratio was 0.5. The crack growth rate $da/dN$-$\Delta K$ curve is shown in figure 4.

3.3. Crack growth rate curve in different concentration H$_2$S at $R=0.1$

When the stress ratio was chosen as 0.1, the experiments were carried out under 2000 ppm and 200 ppm, and the $a-N$ curve and crack growth rate curve are shown in figure 5.

3.4. Paris fitting of crack growth rate curve

According to the curves in figures 2, 3, 4 and 5, the expressions of crack growth rate expressed by Paris equation are fitted, as shown in Table 3.
4. Discuss

4.1. Effect of different concentration of corrosive medium on crack growth curve

4.1.1. Effect of corrosion environment on crack growth rate curve.

As can be seen from the figure 6, when the stress cycle reaches 3000 times, the crack growth of the sample in the hydrogen sulfide environment with a concentration of 200 ppm was at least 10mm, and the propagation in the air was only 1mm. In figure 7, when the concentration was 200ppm, the crack growth rate was about 27 times that in the air.

The addition of hydrogen sulfide in the solution forms a sulfide film on the surface of the steel, which increases the self-corrosion potential and promotes the cathodic reaction. The characteristic adsorption of \( H_2S \) and its \( S^{2-} \), \( HS^- \) ionized in water on the steel surface will inhibit the reaction of hydrogen bonding of cathode to \( H_2 \), thus increasing the concentration of atomic hydrogen on the surface. The embrittlement sensitivity of the steel increases with the infiltration of atomic hydrogen into the material, which shows that the crack growth rate increases greatly with the addition of corrosion environment.
4.1.2. Effect of hydrogen sulfide concentration on crack growth rate.

When \( R = 0.5 \), the crack growth rates are 1.27 and 1.9 times faster while the concentrations of hydrogen sulfide are 5 and 10 times greater (from 200ppm to 1000ppm and 2000ppm). When \( R = 0.1 \), the crack growth rate is about 1.6 times faster while the concentration of \( \text{H}_2\text{S} \) 10 times greater.

The change of crack growth rate is nonlinear with the change of hydrogen sulfide concentration. According to the hydrogen permeation formula 6, with the same applied load, hydrogen content in the specimen has an exponential relationship with the initial environmental concentration, which shows an exponential relationship with the degree of hydrogen embrittlement.

\[
C = C_0 \exp \left( \frac{V_H \sigma_H}{RT} \right)
\]

In 2014, Liu Changhai [6] and others studied the mechanical properties of 2.25Cr-1Mo-0.25V steel in hydrogen sulfide environment, and the result shows that the concentration of corrosive solution doubled, the crack growth rate increased by 20%. Literature [6] tells the same law as the results of this paper, which further verifies the reliability of the above conclusions.

According to the curve shape in the figure and the Paris expression in Table 3, in the double log space, the parameters \( n \) indicating the curve slope are all about 2.8, each line is parallel. There is no significant difference between the curves, indicating that the effect of corrosion hydrogen damage on the crack growth rate is only to change the physical properties of the material.

4.2. Effect of different stress ratio on crack growth curve

In the double log space, the crack growth rate curves with \( R = 0.5 \) are all on the upper left of the curve with \( R = 0.1 \), that is, the crack growth rate with stress ratio \( R = 0.5 \) is greater than that with \( R = 0.1 \). There are three reasons for this phenomenon:

1. The higher the stress ratio \( R \), the higher the average stress, the more hydrogen in the metal, the lower the fatigue resistance of the metal and the faster the crack growth.
(2) Corrosion medium is easy to form a passivation film on the metal surface. The effect of cyclic stress causes the passivation film to be damaged. The greater the stress ratio $R$, the greater the average tensile stress, the greater the plastic strain at the crack tip, and the more likely the passivation film of the exposed metal at the crack tip is to be damaged, which makes hydrogen ions easier to enter and accelerate the anodic dissolution, thus accelerating the crack growth.

(3) When $R=0.1$, the stress ratio is relatively small, crack closure effect exists at the crack tip, and the corrosive solution is not easy to contact with the exposed metal at the crack tip; when $R=0.5$, the crack closure effect basically disappears, the crack tip is fully opened, and the corrosive solution is fully in contact with the exposed metal surface, which accelerates the corrosion of the metal at the crack tip.

5. conclusion

(1) The corrosion fatigue crack growth rates of 15CrMo steel under three H$_2$S concentrations of 200ppm, 1000ppm and 2000ppm, two stress ratios of 0.1 and 0.5 were tested. The $a-N$ curves and $da/dN-\Delta K$ curves were obtained. The expressions of crack growth rate were fitted by Paris equation.

(2) Corrosion medium has great influence on the crack growth rate. The addition of minor corrosion environment can greatly improve the crack growth rate. The $da/dN$ in 200 ppm H$_2$S environment is 27 times higher than in air. With the increase of the concentration of corrosive environment, the crack growth rate accelerated, but there is not a linear relationship between the two. According to the hydrogen permeation formula, the hydrogen permeation amount and the hydrostatic stress show an exponential relationship.

(3) In high and low concentration corrosion media, the fatigue crack growth rate increases with the increase of stress ratio. The main reasons are: the high stress ratio makes the crack stress closure effect decrease, the average stress increases, the crack tip fully opens, the contact area with the corrosion medium increases, and the hydrogen diffusion behavior intensifies. At the same time, under the coupling effect of high concentration and high stress ratio, the hydrogen permeation is more significant, which results in the acceleration of crack growth rate.

Acknowledgement
This study was supported by National key research and development program (2016YFC0801905-16).

References
[1] Dong, H.L., Li, B.X., Bo, K. (2014) Review of the Development of Tube Trailer Cylinder on Safety Technology. Safety of special equipment in China, 30: 1-5.
[2] Zhang, X.J., Zhang J.P., Bo, K. (2017) Analysis and exploration of safety application technology of long tube trailer. China Equipment Engineering, (15): 42-43.
[3] Wang, Q., (2019) Review of potential safety hazards in the use of long tube natural gas trailers. Chemical machinery, 46: 372-374.
[4] Fatigue crack propagation method of metal material fatigue test: GB/T 6398-2017 [S], 2017. (In Chinese)
[5] Test method for stress corrosion of precracked specimens of high strength alloy under wedge opening load (WOL): GB / T 12445.3-1990 [S] (In Chinese)
[6] Liu, C.H., Deng, W.B., Gao, J. (2014) Experimental study on hydrogen sulfide stress corrosion of 2.25Cr-1Mo-0.25V steel. Pressure vessel, (2): 9-13.