Life prediction of multi-pit-crack interaction in pressure vessel

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Abstract: During the service of pressure vessel, there are many kinds of structural damage. The main defect is pitting caused by corrosion of loaded materials, cracks are formed because of stress concentration in the pit position, and crack propagation leads to crack leakage. As an important parameter to characterize cracks, fatigue life is widely used in engineering to judge the safety and reliability of mechanical structures. In this paper, based on the two-parameter pit-crack model, the fatigue life of pressure vessel with multiple pits-cracks is discussed by using ANSYS finite element analysis software. The results show that the fatigue life of pressure vessels decreases with the existence of multiple pits and cracks, but with the increase of pit-crack spacing, the effect decreases gradually until it returns to a stable state. The effect of pit parameters and the ratio of crack length to depth on fatigue life has obvious interval effect. This paper can be used as a reference for failure assessment of multi-pit-crack pressure vessels.

1. Introduction

Point corrosion pits of different sizes and shapes will be formed on the inner surface of pressure vessel due to the corrosion of gas or solution. These pits will cause local stress concentration in the vessel, and stress concentration is the main cause of crack formation\textsuperscript{[1-4]}. The existence of these cracks will lead to the decrease of local deformation resistance of pressure vessel, even damage and leakage failure, which greatly affects the safety and reliability of the equipment\textsuperscript{[5-7]}. Fatigue life, as an important index of crack evaluation, directly affects the crack propagation mechanism and fracture failure criterion\textsuperscript{[8-10]}. Li Xiubo et al.\textsuperscript{[11]} innovatively put forward a two-parameter pit-corrosion fatigue crack model in the study of crack life prediction of corrosion pits in offshore engineering structures, and found that the location parameters of corrosion pits will determine the location of the initiation cracks. Newman et al.\textsuperscript{[12]} studied the variation of stress intensity factors of cracks in cylindrical pressure vessel. The results show that the pressure vessel is mainly affected by open-mode crack growth under internal pressure. Yu Jianxing et al.\textsuperscript{[13]} Through the analysis of stress intensity factor of pit-crack on pipeline surface, the conclusion that pit can obviously reduce the threshold of crack growth is obtained, and the influence trend of pit parameters on stress intensity factor is different. Yao Anlin et al.\textsuperscript{[14]} used finite element method to explore the influence of crack interaction on stress intensity factor in high pressure gas pipeline, and used the concept of nominal stress intensity factor to demonstrate the relationship between the numerical value and the related parameters of crack.

Because of the existence of pits, the change rule of stress intensity factor and the propagation mechanism of cracks will change in some properties, especially in the case of multiple pits and cracks, how cracks propagate at the same time needs to be studied. Therefore, on the basis of defining the reliability of finite element simulation calculation, this paper establishes a multi-pit-crack model, which is devoted to discussing the influence of pit-crack parameters on nominal stress intensity factor. This provides a theoretical reference for safety assessment and failure identification of pressure vessels with defects in practical engineering applications.
2. Establishment of Finite Element Model

In order to explore the law of interaction between multiple pits and cracks in pressure vessels, a finite element model of pressure vessels with inner diameter of 600 mm and wall thickness of 60 mm was established by SolidWorks according to the actual dimensions of common cylindrical pressure vessels in engineering. The material parameters of the model are shown in Table 1. Because the model is a continuous symmetrical and uniform entity, in order to reduce the computational workload of the finite element method, the pressure vessel is divided into four parts along the central symmetry, and one fourth of them is imported into ANSYS for finite element simulation. In this paper, a two-parameter method is used. \( \alpha = \frac{d}{f}, \quad \beta = \frac{b}{f} \). A pit model \([11]\) is established on pressure vessel, which treats pits as uniform ellipsoidal pits. The model schematic is shown in Fig. 1.

![Pressure Vessel Model](image)

![Erosion Pit Model](image)

Fig. 1 Pressure vessel and its pit geometry

Among them, the radius of the inner wall of the pressure vessel is \( r \), the thickness of the wall is \( t \), the height of the vessel is \( H \), the depth of the pit is \( f \), the radius of the pit is \( d \), the distance between the two pit centers is \( s \). The vertical position of ellipsoid center is changed by changing the value of \( \beta \) \( \left( \frac{b}{f} \right) \); and the curvature of pit bottom is changed by changing the value of \( \alpha \) \( \left( \frac{d}{f} \right) \); thus different pit models are obtained.

According to Yu Jianxing's research, when the parameter is less than 0.2, the maximum stress concentration always appears at the bottom of the pit. Because stress concentration is the main cause of local cracking of components, this paper mainly aims at adding different length-depth ratio \( \left( \frac{a}{c} \right) \) cracks at the bottom of the pit under the condition of \( \beta = 0 \). The crack schematic is shown in Fig. 2.

| Material       | Modulus of elasticity (MPa) | Poisson's ratio | Yield strength (MPa) | Ultimate strength (MPa) |
|----------------|----------------------------|----------------|----------------------|-------------------------|
| 15MnMoVN       | 200000                     | 0.3            | 690                  | 750                     |

Tab.1 Material Properties of Pressure Vessels
When meshing the model in ANSYS, because the model is a complete uniform continuum, the model is meshed by the sweeping meshing method and two-node SOLID186 element. At the same time, the CONTACT174 contact element is used to ensure the connection between the crack mesh and the whole mesh. In order to ensure the accuracy of crack stress intensity factor calculation, six integral contours are set up; displacement along the y-axis at the bottom of pressure vessel is restrained, and friction-free constraints are set at the two cutting surfaces of the vessel as boundary conditions for finite element calculation; 10 Mpa pressure is fixed on the inner surface. Its meshing is shown in Figure 3.

![Fig. 2 crack geometry](image)

3. Analysis of the interaction between double pit-cracks

3.1 Parameter Setting of Pit-Crack Model

When studying the influence of different pit parameters and the ratio of crack length to depth on the life of pressure vessel, we can change the parameters by fixing the pit depth to change the radius of the pit; fixing the crack depth to change the length of the crack, so as to change the ratio of the length to depth of the crack; and changing the distance between the two pits and cracks (to ensure that the two pits and cracks are independent intact bodies which do not cross each other, and the value needs to start from 5) to obtain the value of stress intensity factor under different conditions. The related parameters are shown in Table 2.

| Tab. 2 Pit-Crack Parameters |
|-----------------------------|
| pit parameter | Dept of pit | Crack depth | Crack length-depth ratio | Pit-crack spacing |
| parameter | f | c | a/c | s (mm) |
| β (mm) | 0.9, 1.0, 1.1, 2 | 0.6, 0.8, 1.0, 1.2, 1.4 | 5, 6, 7, 8, 9, 10, 11, 12, 13 |
| α | 0.9, 1.0, 1.1, 2 | 0.6, 0.8, 1.0, 1.2, 1.4 | 5, 6, 7, 8, 9, 10, 11, 12, 13 |
| s (mm) | 5, 6, 7, 8, 9, 10, 11, 12, 13 | 5, 6, 7, 8, 9, 10, 11, 12, 13 | 5, 6, 7, 8, 9, 10, 11, 12, 13 |
3.2 Fatigue Life Analysis of Pit-Crack Interaction

The fatigue life of pressure vessel with single and double pits-cracks is calculated and analyzed in the range of pre-set pit parameters and crack length-depth ratio. In order to embody the principle of data normalization, the nominal fatigue life $K_{IN}$ is defined as:

$$K_{IN} = K_{UN} / K_{0}$$

Among them, the fatigue life of pressure vessel in the presence of double pits and cracks is $K_{UN}$ (MPa. mm$^{1/2}$) and that of pressure vessel in the presence of single pit and crack is $K_{0}$ (MPa. mm$^{1/2}$).

By comparing the finite element results of single pit-crack fracture parameters and double pit-crack fracture parameters, the curves of fatigue life varying with pit-crack spacing under different pit parameters are obtained as shown in Fig. 4.

![Fig. 4 Nominal fatigue life $K_{IN}$ curve of pressure vessel with spacing](image)

It can be seen from the graph that the fatigue life of the pressure vessel with damage under the interaction of pit and crack is similar to that of the pressure vessel with pit parameters, the ratio of crack length to depth is less than 1, equal to 1 or greater than 1, and the trend of change with the spacing $S$ is basically similar, showing a gradual increase and the final fluctuation is stable. The results show that the effect of pits and cracks on the life of pressure vessel is affected by the distance between them, and the larger the distance, the smaller the effect until stability. However, the nominal fatigue life is always less than 1. It can be inferred that due to the existence of double pits-cracks, the effect of each other on the fatigue life of pressure vessels is always affected, resulting in a decrease in the numerical value, reducing the service life of pressure vessels, and making pressure vessels more vulnerable to structural failure. In addition, with the increase of pit parameters, the pit-crack spacing required for the nominal fatigue life of pressure
vessels to stabilize gradually increases. That is to say, the larger the distance, the longer the distance is needed to achieve a stable state.

In summary, the interaction between pits and cracks promotes the effect of cracks on the fatigue life of pressure vessels, and the effect decreases gradually until stable with the increase of pit-crack spacing. In addition, the pit parameters will determine the spacing required for the transition to a stable state, and the larger the spacing, the larger the spacing required.

In order to clarify the effect of crack parameters on fatigue life of pressure vessels, it is necessary to study the variation of nominal intensity factor with the ratio of crack length to depth under different pit parameters, as shown in Fig. 5.

![Figure 5](image)

Figure 5 nominal fatigue life curve of pressure vessel with crack length-depth ratio

It is found that the nominal stress intensity factor decreases first, then increases and then decreases under the condition of pit parameters, and tends to a straight line under the condition of > 1. It shows that with the increase of pit parameters, the effect of crack length-depth ratio on stress intensity factor becomes smaller and smaller, and when it increases to a certain value, it has almost no effect. In addition, the spacing between adjacent curves becomes smaller and smaller with the increase of the pit-crack spacing, which indicates that when the pit-crack spacing increases to a certain value, the change of the stress intensity factor of the crack will not be affected.

4. Summary

Based on the two-parameter pit-crack model, the distribution of local stress and the change trend of nominal stress intensity factor of pressure vessel in the presence of multi-pit-crack are discussed by using ANSYS finite element analysis software. Through comparative analysis, the following conclusions are drawn:

1) The fatigue life of pressure vessel varies with the distance s, showing a trend of decreasing gradually and finally fluctuating smoothly. The larger the crack parameters are, the larger the spacing required to reach a stable state is.
The ratio of crack length to crack depth has a significant effect on nominal stress intensity factor, but has little effect on nominal stress intensity factor at $> 1$.

5. References

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