Simulation Analysis of the Mutual Influence of the Stress Intensity Factor on the Multiple Blisters Caused by Hydrogen Induced Damage

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Abstract. Hydrogen blisters are taken as the research object by using the finite element software ABAQUS. The stress intensity factors of blister cracks are numerically calculated at varying depths and different edge distances for established three-dimensional finite element models of single-blister and double-blister s, respectively. The mutual influence of the stress intensity factors of the multiple blisters is obtained. It shows that the blister crack is easier to expand when the crack is closer to inner wall of the cylinder. What’s more, the crack growth rate increases firstly and then decreases as the increasing of the distance between two blisters cracks. The investigated result is of great reference value for predicting the trend of blister crack growth.

1. Introduction
With the rapid development of modern industry, many chemical devices are running in a typical wet H₂S environment. In this environment, hydrogen atom is made from the electrochemical corrosion and gets together, which lead to hydrogen-induced damage in the equipment, such as hydrogen-induced cracking, hydrogen blister and so on. Especially hydrogen-induced damage usually occurs on the surface of chemical equipment [1]. Due to hydrogen originally in the metal or from hydrogen sulfide in the medium reacting with some components (such as Fe) in the metal, the mechanical properties of the material will decline which will result in brittle fracture or cracking. Therefore, it is particularly important to study the hydrogen-induced damage for chemical equipment. The literature [2, 3] introduced the finite element simulation of the hydrogen blister in the steel of 16MnR in moist H₂S and the influence of MnS(inclusion) on the diffusion of hydrogen atoms in the matrix. C.Q. Yan [4] simulated the expansion of the hydrogen blisters in gas pipelines by the finite element software ABAQUS. Literature [5] studied the microstructure of hydrogen blister cracks in the gathering transmission pipeline and analyzed the formation of blisters due to the crack passivation. There were many blisters in the reflux tank of the solvent regeneration tower through the internal macroscopic examination in regular maintenance of the refining equipment in a refinery company and some blisters were cracked. In this paper, the models of reflux tanks with single-blister and double-blister are created and analyzed by the finite element analysis software ABAQUS. The stress intensity factors of cracks in different depths and with different edge-distances are comparing. At last, the mutual influences of stress intensity factor on multi-blister are studied.
2. The finite element model and boundary conditions of the blisters

According to the equivalent elliptic method [6] commonly used in engineering, hydrogen blister cracks can be equivalent to elliptical cracks. In order to research the stress intensity factors $K$ of blister cracks in the different paths conveniently, the quarter model of the blister crack is divided into ten parts and there are eleven paths, as shown in Fig.1. Path 1 and path 11 represent semi-major axis and semi-minor axis of the elliptical crack respectively and the stress intensity factors along the 11 paths are extracted later.

![Figure 1. The eleven different paths of elliptical crack](image1)

In order to analyze the cylinder expediently, the cylinder is equivalently reduced to a thin-wall cylinder with a blister crack and a semi-cylinder is taken due to symmetry. Trepanning, pipe and other factors of the Tower top reflux tank are ignored. The major axis of the elliptic crack is parallel to axial of the cylinder [4]. Fig.2 shows a quarter model of a single elliptical crack and fig.3 is the partial diagram of the cylinder with single-blister. The ratio of the minor axis and the major axis of elliptic blister cracks in inner-wall of the cylinder is 0.5, that is, $b/a=0.5$. The length of the major axis is 20mm, the distances between the single-blister and the inner surface are 2mm, 5mm, 7mm respectively.

![Figure 2. Quarter model of the blister crack](image2)

The C3D8R linear and reduced integration element is selected because the grid at the crack tip can bend and deform. The elliptical blister cracks in the cylinder are tiny defects, so the meshes should be generated finely especially near the crack tip and the model is segmented structurally and differently in different parts of it. It can be seen that the grid of crack tip is fine and of good quality from figure 3, so the accuracy and veracity of the calculated results are guaranteed. After the model is established, the hydrogen pressure in the blister crack is applied on the crack surface.

The finite element model of double-blister is established, in which one of the blister cracks is set as a circular one with a radius of 5mm, and internal pressure of the blister cracks is the same as that of the initial single-blister crack. In order to study the influence of the distance between the two blisters on cracks, the edge distance $L$ between them is set as 5mm, 10mm and 20mm respectively. The double-blister is 2mm distant from the inner-wall of the cylinder, as shown in Fig.4.
Figure 4. The mesh model of double-blister crack

According to the crack parameters provided by the case and the empirical formula of hydrogen concentration $C_H$ given by Hirth et al. [7] and the internal hydrogen pressure of the cylinder blister is calculated to be 500 MPa, so the hydrogen pressure applied to the surface of the blister is 500 MPa. Symmetrical constraints were applied to the crack-end of the cylinder which is a simplified symmetry model: $U_3=U_{R1}=U_{R2}=0$. The film stress of 5.16 MPa and displacement constraints ($U_1=U_2=U_3=0$) in three directions (X, Y, and Z) are applied on the other end of the cylinder. Symmetrical restraint is applied to the axial section of the cylinder: $U_2=U_{R1}=U_{R3}=0$. The working pressure applied to the inner-wall of the cylinder is 0.35 MPa.

3. Results and discussion

The stress intensity factors $K$ are parameters that consider the effect of stress and crack size on the crack growth under the influence of stress, which reflect the strength of stress intensity near the tip of the crack. Different types of crack growth have different stress intensity factors, where $K_I$ is the open-type stress intensity factor and $K_{II}$ is the slip-type stress intensity factor. $K_I$ of single-blister is extracted under 500MPa as shown in Fig.5.

Figure 5. The $K_I$ distribution of blister crack under 500MPa

When the hydrogen pressure is 500MPa, $K_I$ is minimal at $h=5$mm; $K_I$ are both larger and nearly the same at $h=2$ mm and $h=7$ mm, which indicates that the blister crack is more likely to propagate near the cylinder wall surface and consistent with the reality.

As shown in Fig.6, when the hydrogen pressure is 500MPa, double-blister cracks’ Mises stress is extracted at $L=5$mm.
Figure 6. The Mises stress of double-blister crack

The stresses of the double-blister crack tips both reach higher value and the stress distribution of the double-blister cracks is similar, and the stress in the bulged part of the blister crack is larger than in its surrounding area. The stress of the blister lying in the location farther away from the blister cracked region is lower, and the region stress is lower between two blisters as well.

As shown in Fig. 7, $K_I$ of double-blister with different edge distances is compared with $K_I$ of single blister.

Figure 7. The $K_I$ of single and the $K_I$ of double blister crack of three different edge distances

For double-blister, the function relationship of the edge distance L and the $K_I$ is approximately parabolic. When the edge distance L is smaller, the $K_I$ goes up as the edge distance L increases because of the mutual inhibition of the blister cracks. When L reaches to the critical value, $K_I$ decreases gradually with the increase of L, which eventually the $K_I$ value of a single-blister.

The $K_{II}$ of single-blister and double-blister crack are extracted and the curves are drawn in Fig. 8.

Figure 8. The $K_{II}$ of single-blister and the $K_I$ of double-blister at different edge distances
The distance $L$ between the double-blister crack has a dual effect on the $K_{II}$ of the original elliptical crack. When the edge distance $L$ is relatively small, the slip-type crack growth augments as the edge distance $L$ increases. However, when edge distance $L$ reaches to a certain value, slip-type crack growth slows down.

4. Conclusion

Based on the finite element simulation and analysis of single-blister and double-blister, it can be seen that the growth trend of cracks increases as the depth $h$ decreases in the same blister size and under the same hydrogen pressure; the distance between the double-blister crack has a dual effect on the crack propagation tendency. The crack propagation tendency becomes strong firstly and then weak with the increase of the crack distance. It is of great reference value to explore the law of mutual influence of 3D hydrogen blister cracks.

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