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Numerical Simulation and Safety Assessment Analysis for Pressure Pipe with Incomplete Penetration Defects

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Abstract. A head of a gas collecting pipe used in ammonia refrigerating system dropped off during applications. The cause for head fracture was investigated by means of numerical simulation and safety assessment analysis. The results indicate that the fracture reason of welded joint is also influenced by the brittle fracture behavior under low stress.

1. Introduction
The head of a collecting pipe in ammonia refrigerating system dropped off during use. This accident resulted in liquid ammonia leakage. The serious incomplete penetration defects were found in the weld joint based on the macro and micro analysis of fracture. The gap left due to unmelted by arc between the weld metal and base metal is known as incomplete penetration. The incomplete penetration defects may be classified into surface defects and internal defects [1]. The effective weld area is decreased and the strength is dropped because of the incomplete penetration defects. It can even cause stress concentration and may be the crack source. This will seriously reduce the fatigue strength of weld and maybe the important reason of weld fracture.

Pressure pipe containing defects bears on the safety and economy of pipe operation. The safety assessment should be made scientifically using the fracture mechanics method. At present, there are many safety assessment methods for pressure pipe containing defects, such as the plastic failure criterion method using limit load, the safety assessment method of J-integral, R6 two-criteria approach and ASME standard assessment method [2-5]. In China, GB/T 19624-2004 <Safety assessment for in-service pressure vessels containing defects> was promulgated in 2004. This criterion is applicable to the safety assessment of pressure pipe.

In this paper, numerical simulation and safety assessment analysis for pressure pipe with incomplete penetration defects are studied. The reason of the head fracture is illustrated.

2. Finite Element Model
The outer diameter and thickness of the gas collecting pipe studied in this paper are 159mm and 5mm, respectively. The weld penetration thickness and depth unevenly distributed along the circumference based on the measurements. The smallest and biggest effective thicknesses of the weld are 2.5mm and 6.7mm, respectively. The cross-section sketch map of the weld with incomplete penetration defects including pipe and head is shown in Fig. 1.
Figure 1. The cross-section sketch map of the weld with incomplete penetration defects.

The collecting pipe and head are analyzed using the finite element software Abaqus. In the design condition, the structure and load are all symmetric. Then, the section of structure is used to establish the finite element model. The finite element mesh is generated as shown in Fig. 2.

Figure 2. The finite element mesh used in the analysis.

The internal walls of gas collecting pipe and head is under uniform internal pressure of 0.8MPa. The bottom of gas collecting pipe is constrained by the axial displacement. The detailed application of boundary condition is shown in Fig. 3.

Figure 3. The boundary condition and load of the finite element model.

The value of -20℃ is chosen as the fracture temperature because that the weld joint fractured under ductile-brittle transition temperature curve. The maximum working pressure is no greater than 0.8MPa during defrost process. Thus, the value of 0.8MPa is chosen as the internal pressure in this model to carry out the failure assessment. The safety assessment for pressure vessel with defects is evaluated based on the GB/T 19624-2004 <Safety assessment for in-service pressure vessels containing defects> [6].
3. Results and Discussions

3.1. Calculation and Analysis of Static Strength
The head went off along axial direction because of the axial stress generated by the pipe media. It can be inferred that the weld fracture stress during the defrosting process should be greater than the average tensile strength tested at -20°C by the unfailed weld joint.

\[
\sigma = \frac{PD}{4\delta} = \frac{P \times (159 - 5.0)}{4 \times 5.0} \geq 331 MPa
\]  

where \( P \) is the internal pressure of pipe, \( D \) is the out diameter of pipe and \( \delta \) is the wall thickness. Then the Eq. (1) should be satisfied by the following condition:

\[
P \geq 43.84 MPa
\]  

The design pressure of gas collecting pipe is less than 1.0MPa. It is considerably lower than the pipeline internal pressure of above mentioned condition. In theory, the head weld shouldn’t fracture based on the calculation of static strength criterion. Obviously, the failure reason can’t be explained only through the static strength checking. Although the vessel or pipeline is designed according to strength criterion, this refers to the condition under ductility and without serious stress concentration. For brittle material or the condition under stress concentration, the fracture of pipeline doesn’t only depend on the strength. The material may fracture instantaneously due to the lack of ductility.

Thus, the analysis of weld fracture behavior couldn’t only depend on the calculation of static strength, but also consider the incomplete penetration or void defects. But beyond that, the brittle fracture behavior under low stress also should be considered.

3.2. Fracture Mechanics Analysis of Weld Considering Structural Discontinuity
The Mises stress distribution of the collecting pipe is shown in Fig. 4. The axial stress distribution of the collecting pipe is shown in Fig. 5. The axial stress distribution of the incomplete penetration weld of the head is shown in Fig. 6. Through simulation, the structure discontinuity is formed because that the discrepancy of the wall thickness among the weld joint, incomplete penetration zone neighbouring head and pipeline is greater. This produces stress concentration in this area. The axial stress of incomplete penetration part is greatly beyond the neighbouring head.

Figure 4. Mises stress distribution of the collecting pipe.
3.3. Safety Assessment

The safety factor is unsuited to the assessment process because the structure has fractured. The failure assessment diagram obtained through calculating is shown in Fig. 7. The data point lies out of the safe range of failure assessment curve. It can be inferred that the structure can’t be guaranteed safe in the above-mentioned working conditions. Based on the calculation results, the head will drop off when the internal pressure of pipeline reaches 2.8MPa.

4. Conclusion

The structural discontinuity of weld causes larger stress concentration. This results in the insufficient safety margin of anti-rupture for structure under low temperature and stress conditions. The brittle fracture failure happened in the head weld. The weld defects and low temperature brittleness are the internal reason of brittle fracture. However, the occurrence of fracture needs the fluctuations or rapid rise in pressure.
Acknowledgments
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