Strain limit dependence on stress triaxiality for pressure vessel steel

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Abstract. In this paper, the failure characteristics of pressure vessel materials were investigated, and measurement and analysis approaches for ductile fracture strains were studied. Based on uniaxial tensile tests of notched round bar specimens, combined with finite element analyses and microscopic observations of fracture surface, the relationships between the stress triaxiality factor and the ductile fracture strain are proposed for three typical Chinese pressure vessel steels, 16MnR, Q235 and 0Cr18Ni9. The comparison of experimental fracture strains with the multiaxial strain limit specified in ASME Ⅷ-2 2007 shows that the strain limit criterion of ASME is suitable for carbon steels but not suitable for austenitic stainless steels for Chinese pressure vessel steels. To improve the calculation accuracy for fracture strain of materials and to develop the strain limit criterion for Chinese pressure vessel materials, more experimental studies and numerical analyses on fracture strain are necessary.

1. Introduction

Based on many experimental results of material properties, Bridgman[1] concluded in 1952 that the ductility of materials is related to the stress state and can be significantly improved by applying a higher pressure. In 1959, Davis and Connelly[2] investigated the effect of the stress state on the fracture strain of cylinders subject to internal pressure and tensile loads, and proposed the concept of stress triaxiality factor. In damage mechanics the stress triaxiality factor is a very important concept, defined as

\[ TF = \frac{\overline{\sigma}}{\sigma_m} = \frac{(\sigma_1 + \sigma_2 + \sigma_3)^3}{\sqrt{(\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_3 - \sigma_1)^2}} / 2 \]  

(1)

where \( TF \) is the stress triaxiality factor, \( \sigma_m \) is the average stress, \( \overline{\sigma} \) is the Mises
equivalent stress, $\sigma_1 \sim \sigma_3$ are the principal stresses. McClintock[3] in 1968, and Rice and Tracey[4] in 1969, investigated the mechanical mechanisms of the growth of a cylindrical hole and spherical hole respectively. In these two papers, they gave the quantitative relationship between the growth of holes and stress triaxiality factor, which are recognized as a milestone for the development of damage mechanics of materials. Void initiation, growth, and coalescence are three typical processes in the ductile fracture of metal materials[5]. The fracture strain of materials directly correlates with the critical size of voids.

Hancock and Mackenzie[6], and Mackenzie[7] performed uniaxial tension tests on the same batch of notched round bar specimens and carried out the microscopic and macromechanical analyses of the specimens with an assumption of uniform stress and strain distributions at the notch root of the specimens. Experimental results showed that the equivalent stress dropped rapidly after reaching a maximum value on the equivalent stress vs. equivalent strain curve. If unloading started immediately after the maximum equivalent stress, cracks were observed from microscopic analyses; if unloading started before the maximum equivalent stress, discrete voids was observed. Therefore, the equivalent strain corresponding to the maximum equivalent stress was considered as the fracture strain of materials. Macromechanical behaviour analyses showed that there existed a nonlinear relationship between the stress triaxiality factor and the fracture strain, the bigger the stress triaxiality factor the smaller the fracture strain was.

Whether it is global plastic instability or local ductile fracture, the failure of materials is determined by the stress state of structures. The possibility for both failure modes should be investigated in the prediction of the failure mode of structures.

In this paper, we present a pilot study on the ductile fracture of pressure vessel materials by using three typical Chinese pressure vessel steels.

2. Specimens for ductile fracture measurement of pressure vessel materials

2.1 Experimental specimens
The ductile fracture of materials often occurs locally. Normally, the equivalent strain is used as a measurement of the ductility of materials, it is a material parameter related to the stress triaxiality factor but independent of specimens. Since the ductile fracture under triaxial stress states is very complicated, there is no unified conclusion made and no standard available for measuring the ductile fracture strain of materials under triaxial stress states. The notched round bar tension specimen is simple, easy to test and can be used to obtain different stress triaxiality factors by changing the notch radius. Therefore, the tension test on the notched round bar has been widely employed by researchers as a standard method to develop the relationship of the stress triaxiality factor and the strain.

Bridgman[1] made a milestone contribution to the stress analysis of notched round bar tension tests. He investigated the stress distribution of a round bar tension specimen near the neck before fracture. Bridgman’s method has been widely used for the stress analysis of notched round bar tension specimens, often referred to as Bridgman notch specimens or the Bridgman model. In the Bridgman model, it was assumed that near the neck the specimen profile along the longitudinal direction was a circle-like shape with a diameter of $R$, the deformation of its cross section was uniform with a radius of $a$, as shown in Fig.1.

The centre of the round bar has the maximum stress triaxiality factor written as[1]
where \( a \) is the root radius of the notch, and \( R \) is the notch radius. With an assumption of uniform stress and strain distributions at the cross section of the notch root, the effective strain and stress are written as

\[
\tilde{\varepsilon} = 2 \ln \frac{a_0}{a} \\
\tilde{\sigma} = \frac{P}{\pi a^2}
\]

where \( \tilde{\varepsilon} \) is the efficient strain at the cross section of the notch root, \( a_0 \) is the initial radius of the notch root before loading, and \( a \) is the notch root radius changing with the tension load. In this paper, we employed notched round bar tension specimens to measure the equivalent strain of materials at ductile fracture under triaxial stress states.

2.2 Materials of specimens

Three typical pressure vessel materials were tested, 16MnR, Q235, and 0Cr18Ni9. The technical specifications and chemical compositions of the materials are listed in Table 1.

| Standard | Material  | No. | Element proportions by weight (%) |
|----------|-----------|-----|-----------------------------------|
| GB6654   | 16MnR     | 1   | C 0.18 | Mn 1.51 | Si 0.353 | S 0.002 | P 0.011 | Ni 0.006 |
| GB6654   | Q235      | 2   | C 0.151 | Mn 0.45 | Si 0.201 | S 0.003 | P 0.013 | Ni 0.150 |
| GB/T 4237| 0Cr18Ni9  | 3   | C 0.046 | Mn 1.198 | Si 0.477 | S 0.003 | P 0.022 | Ni 8.13 | Cr 18.35 |

Six different notch radii were chosen: 0.25mm, 0.5mm, 1.0mm, 1.5mm, 2.0mm, 2.5mm and 3.0mm. The root radius of the notched round bars was 4 mm. 2 to 3 specimens were fabricated for each size.
3. Experimental result analysis for ductile fracture of pressure vessel materials

The tension test was performed with an MTS-880 tensile test machine under displacement controlled loading. The loading speed was 0.5mm/min, which was considered to be a quasi-static load, that is, the loading speed effect could be neglected[8,9]. In the test, the load was recorded, the change of the notch radius at the neck was measured by a horizontal extensometer and the length change of specimens was measured by a vertical extensometer.

Since pressure vessel materials exhibit good ductility, plastic instability may still occur in a notched round bar tension test. Combined with experimental results, finite element analyses (FEAs) were used to investigate whether the failure mode of the specimen was ductile fracture. ANSYS 9.0, a commercial FE program, was used for all FEAs in this study. Due to the symmetry of the geometry, axisymmetric models with Plane82, an 8-node quadrilateral element type, were employed. The isotropic material with an isotropic hardening law was assumed. The arc-length method, large deformation and the Von Mises yield criterion are employed for stress and strain analyses.

From notched round bar tension tests, we can directly obtain $P-\Delta$ curves, where $P$ is the tensile load and $\Delta$ is the radius reduction at the neck of specimens. Using Eqs (3) and (4), we can convert $P-\Delta$ curves to equivalent stress and strain curves, $\bar{\sigma}-\bar{\varepsilon}$. Based on FEA results from the node of the outer surface at the neck, we can plot $P-\Delta$ curves. Fig.2(a) and Fig.2(b) show the comparison of experimental and FEA $P-\Delta$ curves for specimens with notch radius of 0.5mm and 2.0mm respectively. No-notched round bar tensile tests were performed on 3 specimens for each kind of material, and 3 true stress-strain curves were obtained for the same material. Therefore, three sets of material parameters corresponding to 3 true stress-strain curves of tensile test data were used in FEM analysis. In another words, 1-05-11, 1-05-12, and 1-05-13 shown in Fig.2(a) are FEM analysis results for notch radius 0.5mm corresponding to 3 sets of material parameters respectively, whereas 1-20-11, 1-20-12, and 1-20-13 in Fig.2(b) are results for notch radius 2.0mm.

As shown in Fig.2(a), the experimental curve at the earlier loading stage matches well with that from FEAs, while the experimental curve at the late stage of loading drops much quicker than that from FEAs. Due to the assumption of a continuous body in FEAs, the maximum value of $P$ on FEA curves corresponds to the load at plastic instability. For
experimental specimens, the void initiation after plastic deformation will reduce the real net cross-section area at the neck, resulting in a decrease of the load-carrying capacity of specimens. The maximum value of $P$ on the experimental curve in Fig.2(a) is less than that on the FEAs curve, that is, less than the load at plastic instability from FEAs. In addition, $\Delta$ value corresponding to maximum $P$ from test is less than that obtained from FEAs. The reason that $\Delta$ from test is smaller is: during the test, before sample met the plastic instability, ductile fracture damage arising while lack of material ductility. Therefore, the failure mechanism for the specimens with 0.5mm notch radius is ductile fracture.

Fig.2(b) shows that the $P-\Delta$ curve from FEAs has a reasonable match with the experimental curve. The difference between the experimental curve and the FEAs curve may come from the real net cross-section area reduction at the neck due to the void initiation in the test, which cannot be considered via FEA unless damage mechanics is included in the model. $\Delta$ value corresponding to maximum $P$ from test is close to that obtained from FEAs. The two $\Delta$ values went through a large plastic deformation process after the maximum load, and the $P-\Delta$ curve from the test and that from finite element analyses are still very close, which indicates that plastic instability is reached first before the damage, that is the plastic instability failure. Therefore, the failure of the specimen with 2mm notch radius is plastic instability, and the experimental results from this specimen cannot be used for ductile fracture criterion studies.

The optical microscopic images of the fracture surfaces for the two specimens are illustrated in Fig.3. Dimples are observed on the fracture surfaces of both specimens; these are evidence of voids before fracture. The dimple distribution of 1-05-1 specimen with a notch radius of 0.5mm is very dense and linked together to form cracks causing fracture in materials; the dimple distribution of 1-20-1 specimen with a notch radius of 2.0mm is relatively loose, their existence may only reduce the load-carrying capacity of materials, and the failure of the specimen is plastic instability due to its insufficient strength.

![Fig.3 Detailed inspection of fracture surfaces of tensile specimens](image)

(a) notch radius 0.5mm  (b) notch radius 2.0mm

4. The relationship of stress triaxiality factor and strain under ductile fracture

Until now, although more studies are still required the Bridgman’s approach is still a widely used method for calculating the equivalent strain (Eqs.(3)) and the stress triaxiality factor (Eq. (2)) in engineering applications. Using the approach described in Section 3 we investigated
the relationship of the stress triaxiality factor and the equivalent strain of materials under ductile fracture by analysing more than 60 notched round bar tension tests and comparing them with FEA results. It was found that, for 16MnR and Q235 specimens, the failure mode was ductile fracture when the notch radii of round bar specimens were less than or equal to 1.5mm, and the failure mode of specimens was plastic instability when the notch radii of specimens were greater than 1.5mm; for 0Cr18Ni9 specimens, the failure mode was ductile fracture when their notch radii were less than or equal to 2.0mm, and the failure model was plastic instability when their notch radii were greater than 2.0mm. By using the relationship of $\varepsilon_f = A \cdot \exp\left(-B \cdot TF\right)$, we obtained the relationships of the stress triaxiality factor and the equivalent strain under ductile fracture for the three materials, as follows:

16MnR: $\varepsilon_f = 0.633 \cdot \exp\left(-0.510TF\right)$, $1.18 \leq TF \leq 2.53$

Q235: $\varepsilon_f = 1.133 \cdot \exp\left(-0.813TF\right)$, $1.18 \leq TF \leq 2.53$

0Cr18Ni9: $\varepsilon_f = 1.398 \cdot \exp\left(-0.882TF\right)$, $1.01 \leq TF \leq 2.53$

In ASME VIII-2 2007[10] pressure vessel and boiler standard, the strain limit to protect against local failure is introduced and written as:

$$\varepsilon_f = \varepsilon_{Lw} \cdot \exp\left[-\left(\frac{\alpha_d}{1 + m_2}\right)\left(TF - \frac{1}{3}\right)\right] \tag{5}$$

where $\varepsilon_f$ is the limiting triaxiality strain, i.e. the fracture strain $\varepsilon_f$; $\varepsilon_{Lw}$ is the uniaxial strain limit, i.e. fracture strain $\varepsilon_u$, which is the maximum value among $m_2$, specified elongation and specified reduction area; $m_2$ is related with $\sigma_s/\sigma_b$, for ferritic steel, $m_2 = 0.6 \cdot \left(1 - \sigma_s/\sigma_b\right)$ and $\alpha_d = 2.2$, for austenitic stainless steel, $m_2 = 0.75 \cdot \left(1 - \sigma_s/\sigma_b\right)$ and $\alpha_d = 0.6$. Using Eq. (5), the fracture strain under triaxiality stress states, $\varepsilon_f$, can be easily obtained from a round bar uniaxial tension test by measuring $\sigma_s$, $\sigma_b$, specified elongation and specified reduction area.

To verify the reliability of the strain limit, three materials, 16MnR, Q235 and 0Cr18Ni9, were investigated. For facilitating the comparison with experimental results, we rewrote the strain limit, Eq. 5, as

$$\ln\left(\frac{\varepsilon_f}{\varepsilon_{Lw}}\right) = -\left(\frac{\alpha_d}{1 + m_2}\right)\left(TF - \frac{1}{3}\right) \tag{6}$$

If the rewritten form of the strain limit, Eq. (6), is plotted in the coordinates, $\ln\left(\frac{\varepsilon_f}{\varepsilon_{Lw}}\right)$ vs. $TF - 1/3$, then it is a straight line with a slope of $\frac{\alpha_d}{1 + m_2}$. Fig.4(a-c) show the comparison of experimental results and Eq (6) for the three materials. As shown in Fig.4(a & b), the experimental curves of two ferritic steels, 16MnR and Q235, are above the strain limit line defined by Eq.(6). That is, it is safe and conventional to use the strain limited specified in ASME VIII-2 2007 for 16MnR and Q235. Fig.4(c) shows that the experimental curve of 0Cr18Ni9, an austenitic material, is below strain limit line defined by Eq.(6). That is, it is not safe to use the strain limited specified in ASME VIII-2 2007 for 0Cr18Ni9.

5. Conclusion

The notched round bar tension specimen can be used for the fracture strain measurement of materials, but the failure mode of specimens, such as plastic instability or ductile fracture, should also be determined.

Based on a large amount of experimental data from notched round bar tension tests, combined with FEA results and microscopic observations of fracture surface, the
relationships between the stress triaxiality factor and the strain under ductile fracture for three steels commonly used in Chinese pressure vessel are proposed.

The fracture strains of 16MnR, Q235 and 0Cr18Ni9 were calculated from the strain limit specified in ASME VIII-2 2007, and they were compared with experimentally measured failure strains. It was found that the strain limit criterion of ASME VIII-2 2007 was safe and quite conservative for 16MnR and Q235 steel but not safe for 0Cr18Ni9 steel. Therefore, the
strain limit criterion of ASME VIII-2 2007 can be used directly in carbon steels for Chinese pressure vessels, and more research will be needed before the strain limit criterion is used for austenitic steels for Chinese pressure vessels.

To improve the calculation accuracy of fracture strains for different materials and to develop the strain limit criterion for Chinese pressure vessel materials, more experimental studies and numerical analyses on fracture strain are necessary. The experimental principle, measurement method and analysis methods used in this study provided a foundation for further studies on ductile fracture of pressure vessel materials.

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