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ARTICLE

Effect of Pre-strain on Failure Assessment of Titanium Pressure Vessel with Crack

Dai Qiao[1,2], Wang Fei[1], Zhang Jian[1], Chen Xiaoyang[1], Zhou Jinyu[1], Zhou Changyu[3]

[1] Jiangsu University of Technology, Changzhou 213001, China; [2] Jiangsu Key Laboratory of Green Process Equipment, Changzhou 213164, China; [3] Nanjing Tech University, Nanjing 211816, China

Abstract: To understand the effect of pre-strain on the integrity assessment of titanium structure with crack, the dependence of tensile mechanical parameters, fracture toughness, failure assessment diagram (FAD) on pre-strain was focused. Firstly, tensile tests reveal that with increasing the pre-strain value, the yield stress and the yield-ultimate strength ratio increase, but the ductility decreases, and the fracture toughness decreases. Then, based on finite element (FE) analyses of compact tension (CT) specimen and titanium pressure vessel with crack, the plastic zone near the crack tip decreases with increase of pre-strain, resulting in the decrease of *J*-integral. Moreover, the BS 7910:2013 failure assessment curves (FAC) of Options 1 and 3 vary with pre-strain, and the acceptable area decreases. Therefore, with increase of pre-strain, the reserve factor of yield stress increases but that of fracture toughness decreases significantly. In brief, the pre-strain affects the failure assessment of titanium pressure vessel with crack, and needs to be considered in the integrity assessment.

Key words: pre-strain; failure assessment curve; crack; commercially pure titanium; pressure vessel

Titanium and titanium alloys have excellent mechanical properties, including high strength-to-weight ratio, creep resistance and corrosion resistance[1,2], and exhibit good deformability and weldability[3]. So they are excellent candidates for the manufacturing of petrochemical and chemical process equipment. During the manufacturing process, the materials are plastically deformed[4,5], and mechanical properties of the plastically deformed materials are different from those of as-received materials[6]. Min[7] and Chang[8] found that the yield stress and uniform elongation value of titanium alloy strongly depended on the pre-strained value. Moreover, it is reported that the pre-strain affects the fatigue property[9] and the fatigue crack growth behavior of titanium alloys[10]. Therefore, the pre-strain significantly affects the mechanical properties of titanium alloys, and its effect on the fracture parameter needs to be studied.

Crack defect will appear on equipment, due to material and weld defects, manufacturing process, service process and applied load, which threaten the safe operation of equipment. It is necessary to evaluate the structure with crack to determine whether it is safe, and the fitness-for-service method based on engineering critical analysis is desirable[11,12]. Practical codes and standards for the assessment of structure with crack have been established by different countries, such as R/H/R6-Revision 4 and GB/T 19624, and the failure assessment diagram (FAD) is used in all codes. In the FAD, the failure assessment curve (FAC) and the assessment points are considered, which are strongly correlated with tensile properties and fracture toughness. For assessing the pre-strain treated structure with crack, it is needed to understand the influence of pre-strain on the FAD. Based on the experimental study of pre-strain X65 pipe steel with crack, Baek et al[13] found that the assessment points in FAD of the structure with crack move with pre-strain value. But the impact of pre-strain on the FAC is neglected. Therefore, it is necessary to reveal the effect of pre-strain on

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Corresponding author: Dai Qiao, Ph. D., Lecture, School of Mechanical Engineering, Jiangsu University of Technology, Changzhou 213001, P. R. China, Tel: 0086-519-86953210, E-mail: daiqiao@126.com

the integrity assessment for titanium structure with crack by considering both FAC and the assessment point.

To study the effect of pre-strain on the integrity assessment for titanium structure with crack, tensile tests, finite element (FE) analyses and FAD were studied in this work. The effects of pre-strain on tensile parameters, fracture toughness, plastic zone near the crack tip and *J*-integral were analyzed. Moreover, the effects of pre-strain on FAC and assessment point were discussed based on BS 7910:2013. This work can provide reference for the integrity assessment of pre-strain treated CP-Ti structure with crack.

1 Experiment and FE Analysis

Hot rolled CP-Ti plate with the thickness of 5 mm was used, with chemical composition (wt%) of 0.08 Fe, 0.02 C, 0.01 N, 0.001 H, 0.13 O, and balance Ti, which meet the requirement of GB/T 3620.1 according to the material quality specification from the material supplier. Standard tensile specimen with a rectangular cross section was processed by wire electro-discharge machining, in accordance with ASTM E8M-04. The test section of the specimen had the width of 6 mm and the length of 50 mm. The pre-strain of 4%, 9%, 13%, 18% and 23% was conducted for CP-Ti, which were applied at the strain rate of 5×10^{-4} s^{-1} by MTS 810 material test system, and the pre-strain value ε_{pre} is estimated as:

$$\varepsilon_{pre} = \frac{L_{pre} - L_0}{L_0} \quad (1)$$

where L_0 is the initial gauge length, and L_{pre} is the gauge length of the plastically treated specimen. Tensile tests were carried out on the as-received and pre-strain treated specimens using the MTS 810 material test system with a strain rate of 5×10^{-4} s^{-1}, and the strain was measured by the MTS strain extensometer.

The FE method with the commercial software ABAQUS[14] was used to analyze the compact tensile (CT) specimen and a titanium pressure vessel with crack. In order to understand the effect of pre-strain on the integrity assessment of titanium structure with crack, as-received material and materials with 4%, 9%, 13%, 18% and 23% pre-strain were considered in the FE analyses. The geometry of the CT specimen used for FE calculation is shown in Fig.1a. The half-crack plane strain model was adopted, due to the symmetry of structure and load, as illustrated in Fig.1b. 8-node quadratic plane strain quadrilateral element was selected, and the mesh near crack tip was refined.

The typical titanium pressure vessel with an inside radius R_i of 100 mm, a wall thickness *B* of 10 mm and an axial length *W* of 600 mm was applied in this work, as shown in Fig.2a. And an axially extended internal surface crack with the ratio of crack depth *a* to wall thickness of 0.6 was considered. Due to the geometry and load characteristics, the FE analysis was simplified to plane strain problem, and half-crack model was adopted, as illustrated in Fig.2b.

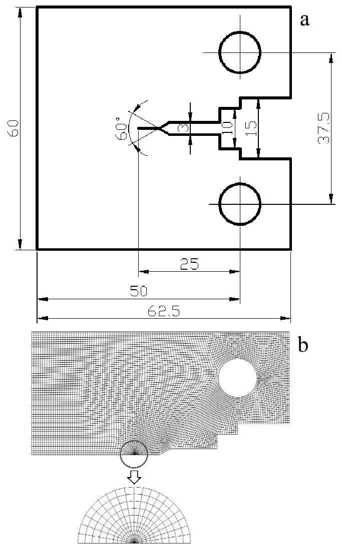

Fig.1 CT specimen dimension (a) and FE analysis model (b)

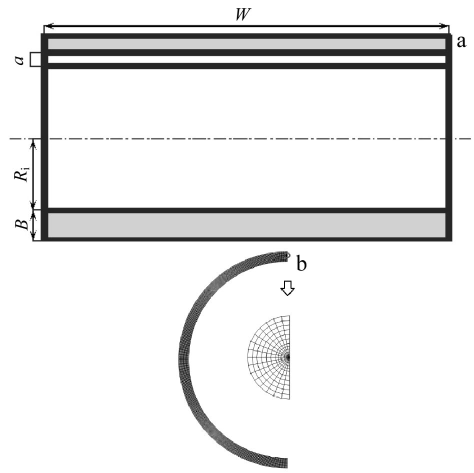

Fig.2 Titanium pressure vessel with crack (a) and FE analysis model of the titanium pressure vessel with crack (b)

2 Results and Discussion

2.1 Effect of pre-strain on stress-strain model of CP-Ti

True stress-strain curves of as-received and pre-strain treated materials by tensile tests are shown in Fig.3. It is obvious that there is no significant difference between as-received material and pre-strain treated materials in the initial elastic stage, but the elastic stage is significantly enlarged with increasing the pre-strain. Moreover, the yield stress significantly increases with pre-strain, and the work hardening stage narrows. It is worth noting that the fracture strain decreases with pre-strain, implying that the material ductility decreases after pre-strain treatment. Moreover, the ultimate strength is independent on the pre-strain value, since the ultimate strengths of different materials are similar. Therefore,

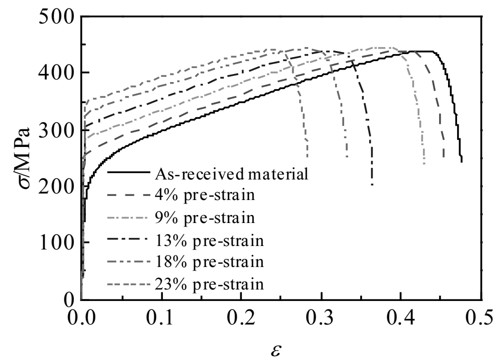

Fig.3 True stress-strain curves of CP-Ti with different pre-strain values

the yield-ultimate strength ratio increases with pre-strain. The effect of pre-stain on the stress-strain curve for CP-Ti agrees with that for austenitic stainless steel and structure steel[15,16].

As mentioned above, tensile properties of CP-Ti vary with pre-strain value. To quantitatively describe the true stress-strain curves of pre-strain treated CP-Ti, Ramberg-Osgood relationship is used, as below:

$$\frac{\varepsilon}{\varepsilon_0}=\frac{\sigma}{\sigma_0}+\alpha\left(\frac{\sigma}{\sigma_0}\right)^n \tag{2}$$

where σ_0 is the reference stress, normally equal to the yield stress, and ε_0 is the reference strain, correlated with the yield stress and elastic modulus E; α is the material constant, and n is the strain hardening exponent. According to the experimental true stress-strain curve of as-received CP-Ti, the parameters of Ramberg-Osgood relationship can be obtained by data fitting, as listed in Table 1.

The strain of as-received material is defined as ε^{AR}, and that of pre-strain treated material is defined as ε^*, while the pre-strain value is defined as ε_{pre}. Therefore, the relationship between the strain of pre-strain treated material and that of as-received material is as follows:

$$\varepsilon^*=\varepsilon^{AR}-\varepsilon_{pre} \tag{3}$$

For the pre-strain treated materials, the stress and strain at the yield point are different from those of as-received material, which are denoted as σ_0^* and ε_0^*. According to the experimental true stress-strain curves at different pre-strain values in Fig.3, the yield stresses of pre-strain treated CP-Ti can be obtained, as listed in Table 2. It can be drawn from

Table 1 Ramberg-Osgood parameters of as-received CP-Ti

σ_0/MPa	E/MPa	α	n
158	99510	5.33	3.85

Table 2 Yield stress of pre-strain treated CP-Ti

Pre-strain value	4%	9%	13%	18%	23%
σ_0^*/MPa	256	285	308	329	345

Fig.3 that the elastic modulus value is independent on the pre-strain value, and can be described as:

$$E=\frac{\sigma_0}{\varepsilon_0}=\frac{\sigma_0^*}{\varepsilon_0^*} \tag{4}$$

Moreover, the relationship between the pre-strain value and the yield stress of pre-strain treated material can be expressed as:

$$\frac{\varepsilon_{pre}}{\varepsilon_0}=\alpha\left(\frac{\sigma_0^*}{\sigma_0}\right)^n \tag{5}$$

Consequently, the stress-strain model of the pre-strain treated material is related to that of as-received material, which can be described as follows (for $\sigma^*\geq\sigma_0^*$)[17]:

$$\frac{\varepsilon^*}{\varepsilon_0}=\frac{\sigma}{\sigma_0}+\alpha\left(\frac{\sigma}{\sigma_0}\right)^n-\frac{\varepsilon_{pre}}{\varepsilon_0}=\frac{\sigma^*}{\sigma_0}+\alpha\left(\frac{\sigma^{*n}-\sigma_0^{*n}}{\sigma_0^n}\right) \tag{6}$$

Therefore, Ramberg-Osgood relationship of pre-strain treated material can be determined by that of as-received material according to Eq.(6).

2.2 Effect of pre-strain on fracture toughness

Fracture toughness is required for the failure assessment of structure with crack, and it is related with the dominant microscopic fracture processes at the crack tip. The fracture process is driven by the stress-strain field near crack tip, and it can be represented by J-integral, which is widely used to represent the ductile fracture process.

Hutchinson[18] and Rice[19] proposed the HRR singularity to derive the stress and strain fields around the crack tip through an asymptotic solution. Through this theoretical analysis, the J-integral is as follows (SINTAP):

$$J=\frac{\alpha I_n r}{E}\left(\frac{\varepsilon_{ij}E}{\alpha\tilde{\varepsilon}_{ij}}\right)^{\frac{n+1}{n}}\sigma_0^{\left(\frac{n-1}{n}\right)}=\frac{\alpha I_n r}{E}\left(\frac{\sigma_{ij}}{\tilde{\sigma}_{ij}}\right)^{\frac{n+1}{n}}\sigma_0^{-(n-1)} \tag{7}$$

where I_n is related with the strain hardening index n, r is the radial distance to crack tip, σ_{ij} and ε_{ij} are stress tensor and strain tensor. $\tilde{\sigma}_{ij}$ and $\tilde{\varepsilon}_{ij}$ are related with n and the angular position θ around the crack tip, which are dimensionless as follows:

$$\frac{\sigma_m}{\sigma_e}=\frac{\tilde{\sigma}_m}{\tilde{\sigma}_e} \tag{8}$$

where σ_m is the hydrostatic stress, and σ_e is the equivalent von Mises stress.

According to the stress-modified critical strain-controlled model developed by Ritchie and Thompson[20], when the value of J-integral equals fracture toughness J_{IC}, microvoid coalescence occurs, leading to ductile fracture. And the local equivalent plastic strain exceeds a critical value ε_c, which is related to the stress state. Based on the void growth model[21], the relationship of the critical equivalent plastic strain and the stress state is as follows:

$$\varepsilon_c=\ln\left(\frac{\overline{R}_c}{R_o}\right)\left(\frac{2}{3}e^{\frac{5}{3}}\right)\exp\left(-\frac{3}{2}\frac{\sigma_m}{\sigma_e}\right) \tag{9}$$

where R_o is the radius of initial spherical void, and $\overline{R}_c$ is the critical mean void radius. When the average void radius reaches $\bar{R}_c$, rupture occurs. Therefore, the fracture toughness is related with the local fracture criteria. And the critical equivalent plastic strain can be determined by the stress state based on the void growth model. Then, the fracture toughness of the as-received material can be determined as[16]:

$$J_{IC} = \frac{\alpha I_n r_c}{E}\left(\frac{\sigma_c}{\tilde{\sigma}_{\theta\theta}}\right)^{\frac{n+1}{n}} \sigma_0^{-(n-1)} \tag{10}$$

where $\tilde{\sigma}_{\theta\theta}$ is a dimensionless stress in HRR equations, r_c is the critical distance from crack tip, σ_c is the critical stress, and the failure occurs when the equivalent von Mises stress equals σ_c and r equals r_c.

As discussed in Fig.3, pre-strain has a significant influence on the tensile property of CP-Ti. Therefore, the stress and strain field near crack tip and the fracture processes will be affected by pre-strain treatment. Then, the fracture toughness will also be affected by pre-strain. It is assumed that, the changes in n and α are neglected, and the pre-strain will not affect I_n and $\tilde{\sigma}_{\theta\theta}$. Hence, the relationship between the fracture toughness of the pre-strain treated material and that of the as-received material is expressed by[16]:

$$\frac{J_{IC}^*}{J_{IC}} = \left(\frac{\sigma_c^*}{\sigma_c}\right)^{n+1}\left(\frac{\sigma_0}{\sigma_0^*}\right)^{n-1}\left(\frac{r_c^*}{r_c}\right) = \left(\frac{\sigma_c^*}{\sigma_c}\right)^{n+1}\left(\alpha\frac{\varepsilon_0}{\varepsilon_{pre}}\right)^{\frac{n-1}{n}}\left(\frac{r_c^*}{r_c}\right) \tag{11}$$

Based on the theory derived model in Eq.(11) by Cosham[17], the fracture toughness of pre-strain treated materials can be obtained by that of as-received materials. This method is also applied and verified for the fracture toughness of pre-strain treated line pipe steels[22]. According to the fracture toughness of as-received CP-Ti obtained by fracture experiment[23] and the parameters of Ramberg-Osgood model determined by Fig.3, the fracture toughness of pre-strain treated materials can be obtained. And the variations of the fracture toughness with pre-strain are shown in Fig.4. The pre-strain has a significant effect on fracture toughness, which declines with increasing the pre-strain, especially at low pre-strain values.

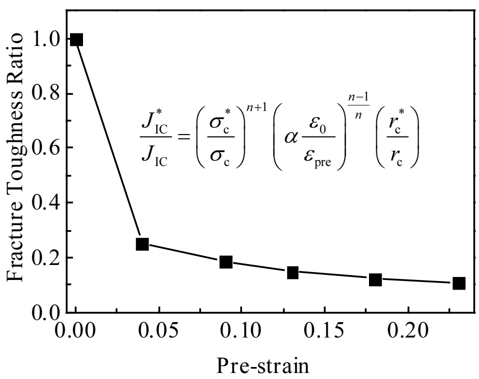

Fig.4 Effect of pre-strain on fracture toughness

3 Effect of Pre-strain on Failure Assessment

FAD is an effective method for the failure assessment of structure with crack. The vertical axis is the fracture ratio K_r of the stress intensity factor K to the fracture toughness K_{mat} for brittle fracture judgment, while the horizontal one is the load ratio L_r of the load P to the plastic collapse load P_L for plastic collapse judgment. The assessment line FAC is the curve of K_r with load, while the assessment point (L_r, K_r) can be determined by the calculation of structure with flaw. The assessment point is compared with FAC to assess the safety of the structure. The position of FAC and the values of assessment point (L_r, K_r) are related with material properties, structural geometry, and defect size. Since the pre-strain affects the material properties shown in Fig.3, it will have an effect on the FAC and assessment point.

3.1 Effect of pre-strain on FAC of Option 1

Several integrity assessment codes in service give the establishment method of FAC. BS 7910:2013 gives three alternative choices, Options 1, 2 and 3. The higher the option number, the more complex for the required material and stress analysis data, and the more accurate results (BS-7910). The FAC established by Option 1 in BS 7910:2013 is appropriate for materials without yield discontinuity, and it only needs little material data, described as follows:

$$\begin{cases} f(L_r) = \left(1+\frac{1}{2}L_r^2\right)^{-1/2}\left[0.3+0.7\exp\left(-\mu L_r^6\right)\right] & \text{for } L_r \le 1 \\ f(L_r) = f(1)L_r^{(N-1)/(2N)} & \text{for } 1 < L_r \le L_{r\max} \\ f(L_r) = 0 & \text{for } L_r > L_{r\max} \end{cases} \tag{12}$$

where μ=min(0.001E/σ_y, 0.6), N=0.3(1−σ_y/σ_u), L_{max}=(σ_y+σ_u)/2σ_y. In previous versions of normal assessment curves such as Level 2A in BS 7910:2005 and Option 1 in R6-Revision 4:2001, the yield stress and tensile strength are only considered to determine the permitted limit L_{rmax}, rather than the whole curve of Option 1. With the version update of defect assessment standard, the yield stress and tensile strength are considered in whole curve of Option 1 of BS 7910:2013, because the parameters μ and N are related to yield stress and tensile strength. Since the pre-strain has a significant effect on the yield stress, it has effect on the FAC established by Option 1 of BS 7910:2013. According to the yield stress and tensile strength under different pre-strain values shown in Fig.3, the FACs of CP-Ti are established by Option 1, as shown in Fig.5.

As shown in Fig.5, the pre-strain has an effect on the FAC obtained by Option 1 of BS 7910:2013, and it is obvious at low pre-strain value. Due to the influence of pre-strain on the yield stress, when L_r is less than 1, the FAC will move up with increasing the pre-strain. However, when L_r is greater than 1, the FAC will move down with increasing the pre-strain, and L_{rmax} decreases owing to the increase of yield stress with

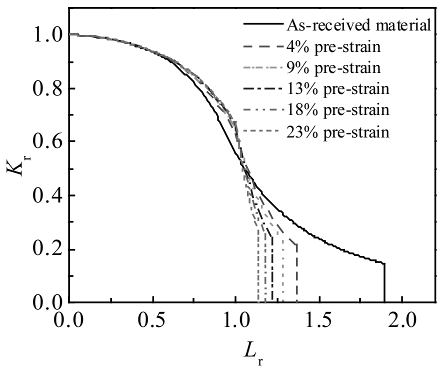

Fig.5 Effect of pre-strain on FAC established by Option 1 of BS 7910:2013

pre-strain. Comparing the FAC of different pre-strain treated material, the acceptable area decreases with pre-strain, which will affect the failure assessment results.

3.2 Effect of pre-strain on FAC of Option 3 for CT specimen

For a particular material and structure, the Option 3 of BS7910:2013 provides the most accurate FAC, which needs the J-integral values obtained by both elastic and elastic-plastic analyses of the structure with crack (BS-7910). The FAC is described as follows:

$$\begin{cases} K_r = \sqrt{\dfrac{J_e}{J}} & \text{for } L_r \le L_{r\max} \\ K_r = 0 & \text{for } L_r > L_{r\max} \end{cases} \tag{13}$$

where J_e is the elastic component. The FE method is widely used to analyze structures with cracks, and the J-integral value can be obtained by FE analyses. Based on the stress-strain curves of as-received and pre-strain treated materials shown in Fig.3, FE analysis was performed on standard CT specimens. The strain field near crack tip is shown in Fig.6, and the J-integral values of different pre-strain treated materials are given in Fig.7.

As shown in Fig.6, there is a plastic zone at the crack tip, and the elastic zone is outside the plastic one. Due to the influence of pre-strain on the tensile property, the area of plastic zone near the crack tip varies with pre-strain. It is clear that the area of plastic zone decreases with increasing the pre-strain. Therefore, the pre-strain not only increases material strength, but also weakens its plastic deform ability. Subsequently, the effect of pre-strain on stress and strain fields leads to the changing of J-integral with pre-strain. During the FE analysis for J-integral, six contours' integral output is needed. The value of the first contour around the crack tip is ignored, and the value of J-integral is the average value of other five contours. The effect of pre-strain on J-integral for CT specimen is shown in Fig.7. It can be observed that when the load is small, the J-integral value is independent on the

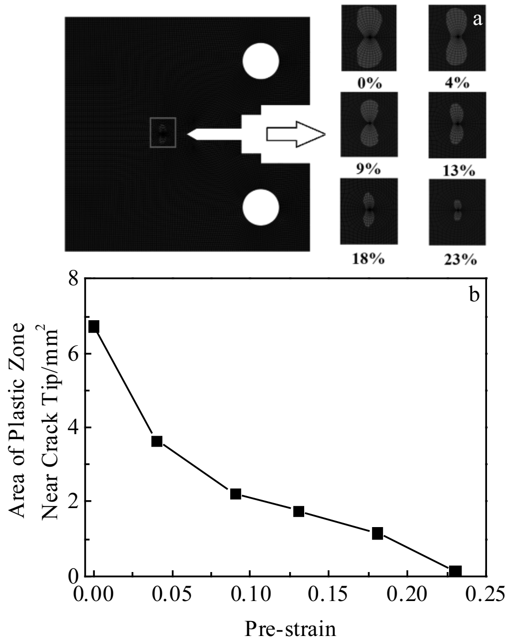

Fig.6 Effect of pre-strain on the strain field near crack tip for CT specimen (a) and variation of plastic zone area near crack tip with pre-strain (b)

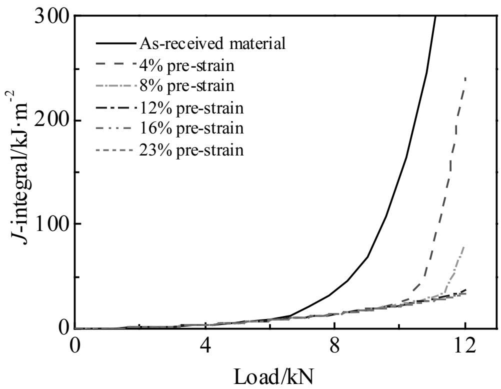

Fig.7 Effect of pre-strain on J-integral for CT specimen

pre-strain, but when the load is large, the J-integral value significantly decreases with the increase in the pre-strain value. The reason is that the small load just causes small range of yielding and the crack tip is dominated by the elastic zone, and then the value of J-integral is mainly composed of elastic component; however, the large load causes large area of yielding, and the crack tip is dominated by the plastic zone, and then the value of J-integral is mainly composed of plastic component. Since the yield stress increases with pre-strain, the area of plastic zone around the crack tip decreases with pre-strain. Therefore, the plastic component of the J-integral decreases with pre-strain, which leads to a reduction of the total J-integral.

According to the values of J-integral obtained by FE analysis for CT specimens, Option 3 curve of BS 7910: 2013 is adopted, and the FACs at different pre-strain values are established, as shown in Fig.8. It can be found that the pre-strain has a significant influence on the FAC established by Option 3 of BS 7910:2013, and FAC moves down with increasing the pre-strain value. Compared to the pre-strain dependence of Option 1 curve shown in Fig.5, the pre-strain dependence of Option 3 curve in Fig.8 is more sensitive.

3.3 Effect of pre-strain on the failure assessment for titanium pressure vessel with crack

To study the effect of pre-strain on the failure assessment, a titanium pressure vessel with an axially extended internal surface crack was adopted. Based on the stress-strain relationships of as-received material and pre-strain treated materials, FE analyses were performed on the titanium pressure vessel with crack. The FE results of strain field of titanium pressure vessel with crack are shown in Fig.9. The area of plastic zone decreases with increasing the pre-strain, and the J-integral value depends on the pre-strain value. Based on the values of J-integral, the FACs of as-received and pre-strain treated materials are established based on Option 3 of BS 7910:2013, as shown in Fig.10. The FAC of titanium pressure vessel with crack is pre-strain dependent, and the dependence is more significant at low pre-strain value than at high pre-strain value.

Besides the pre-strain dependence of FAC, the pre-strain dependence of the assessment point also needs to be discussed. Based on the mechanical properties of as-received material and pre-strain treated materials, the co-ordinates of assessment points can be calculated. According to BS 7910:2013, the fracture ratio K_r is determined by:

$$K_r = \frac{K_I^p + K_I^s}{K_{mat}} + \rho \tag{14}$$

where K_I^p is the stress intensity factor caused by the primary loads, K_I^s is the stress intensity factor caused by the secondary loads, ρ is a function due to plasticity interaction

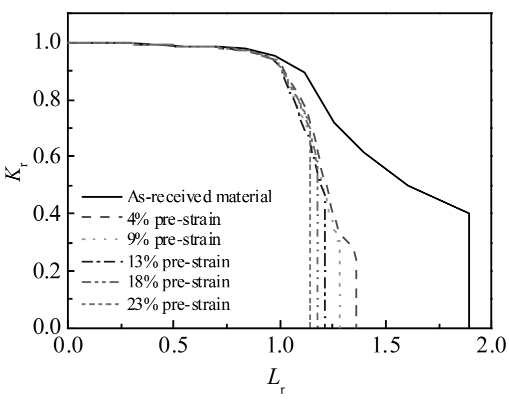

Fig.8 Effect of pre-strain on FAC established by Option 3 of BS 7910:2013

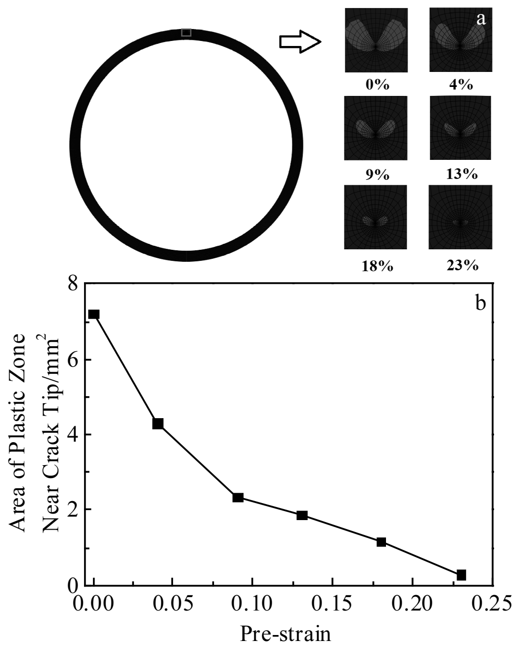

Fig.9 Effect of pre-strain on the strain field near crack tip for titanium pressure vessel with crack (a) and variation of plastic zone area near crack tip with pre-strain (b)

effects. The fracture toughness K_{mat} can be determined by J_{IC}, elasticity modulus E and Poisson's ratio ν

$$K_{mat} = \sqrt{\frac{EJ_{IC}}{1-\nu^2}} \tag{15}$$

J_{IC} is pre-strain dependent, and based on the theory derived model in Eq.(11) by Cosham[17]. The variation of J_{IC} with pre-strain can be obtained from Fig.4. Therefore, during the integrity assessment, the pre-strain dependent fracture toughness is considered in the assessment point.

The load ratio L_r is determined by:

$$L_r = \frac{P}{P_L} = \frac{\sigma_{ref}}{\sigma_Y} \tag{16}$$

where σ_{ref} is the reference stress, which is related to the geometry, crack size and load condition. For the titanium pressure vessel with crack, the positions of the assessment point under different pre-strain values are determined in Fig.10. During the FE analyses, a series of loads are considered to establish FAC, while the assessment point corresponds to a certain load. Considering both the dimensions of titanium pressure vessel and the crack depth in this study, the inner pressure of 2 MPa is selected after several trail calculations. The object of this work is to analyze the influence of pre-strain on the position of assessment point, and similar results can also be obtained at lower pressure loads. As shown in Fig.10, the position of the assessment point is correlated with pre-strain value, which moves to upper left with increasing the pre-strain.

The material properties used in the analysis are usually

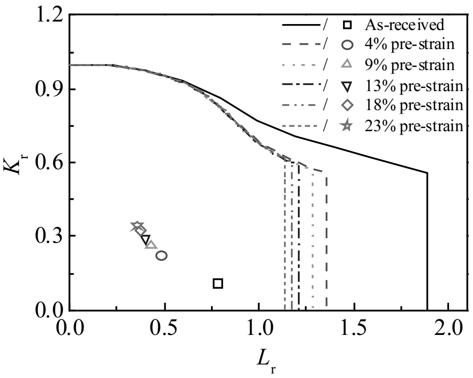

Fig.10 Effect of pre-strain on failure assessment for titanium vessel with crack

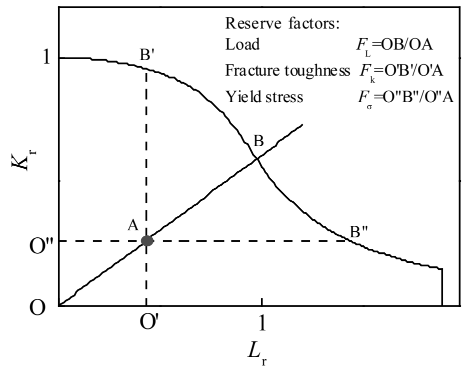

Fig.11 Calculation methods of reserve factors of load, fracture toughness and yield stress

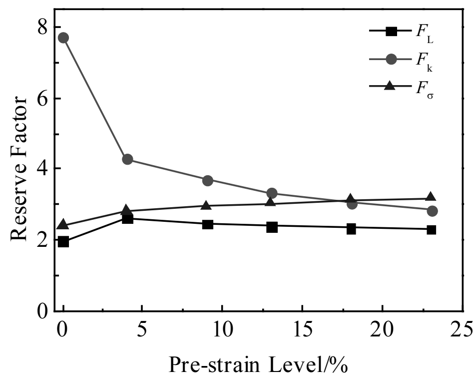

Fig.12 Effects of pre-strain on reserve factors of load, fracture toughness and yield stress

obtained from a finite number of tests, which are treated as a set of fixed quantities. While the input data in engineering are affected by some uncertainties, such as different batches of materials, materials discontinuity, limited measurement accuracy, so it is necessary to use the reserve factor to analyze the reliabilities of different variables. The lager the reserve factor, the safer the assessment result. Therefore, to better understand the effect of pre-strain on the assessment result, reserve factors need to be applied. Reserve factors can be expressed with respect to any parameter. The reserve factors of applied load, fracture toughness and yield stress are considered, and they are defined as[24]:

$$F_L = \frac{\text{Load which would produce a limiting condition}}{\text{Applied load in assessed condition}} \quad (17)$$

$$F_k = \frac{\text{Fracture toughness which produces a limiting condition}}{\text{Fracture toughness of material being assessed}} \quad (18)$$

$$F_\sigma = \frac{\text{Yield stress which produces a limiting condition}}{\text{Yield stress of material being assessed}} \quad (19)$$

After FAD is established, the reserve factors of load, fracture toughness and yield stress can be determined by the position of the assessment point, as depicted in Fig.11: $F_L = \text{OB/OA}$, $F_k = \text{O'B'/O'A}$, $F_\sigma = \text{O''B''/O''A}$.

From the assessment points in Fig.10, the reserve factors under different pre-strain values can be calculated, and the relationships between the reserve factors and pre-strain value are shown in Fig.12. Due to the effects of pre-strain on the assessment point and FAC, the reserve factors are pre-strain dependent and different reserve factors have different variation laws. The reserve factor of yield stress increases with pre-strain value. However, the reserve factor of fracture toughness significantly decreases with the pre-strain, especially at low pre-strain value. And the reserve factor of load is almost independent on pre-strain value. Therefore, the pre-strain increases the yield stress and suppresses the deformation at crack tip, but the fracture toughness and the reserve factor of fracture toughness decrease.

4 Conclusions

1) Tensile tests of pre-strain treated CP-Ti reveal that the yield stress and yield-ultimate strength ratio increase, but the ductility decreases with the increase in pre-strain value. Based on the theory derived model of pre-strained fracture toughness, the fracture toughness decreases with increasing the pre-strain.

2) The FE analysis results of CT specimens and titanium pressure vessel with crack illustrate that the pre-strain can greatly affect the strain field near the crack tip, and the area of plastic zone near crack tip decreases with the increase in pre-strain. Therefore, the *J*-integral value decreases with increasing the pre-strain value.

3) The FACs of Options 1 and 3 of BS 7910:2013 vary with pre-strain value, and the acceptable area decreases. Meanwhile, the assessment point is also dependent on the pre-strain value. The reserve factor of yield stress increases, but the reserve factor of fracture toughness significantly decreases with the increase of pre-strain value. Therefore, the pre-strain needs to be considered in the integrity assessment of CP-Ti structures.

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预应变对含裂纹钛制压力容器失效评定的影响

代　巧[1,2]，王　飞[1]，张　健[1]，陈晓阳[1]，周金宇[1]，周昌玉[3]

(1. 江苏理工学院，江苏 常州 213001)

(2. 江苏省绿色过程装备重点实验室，江苏 常州 213164)

(3. 南京工业大学，江苏 南京 211816)

摘　要：为了分析预应变对含裂纹钛制结构完整性的影响，研究了预应变对工业纯钛拉伸力学性能、断裂韧性及失效评定图的影响。拉伸试验结果表明：工业纯钛的屈服应力和屈强比均随预应变增大而增大，而塑性变形能力随预应变增大而减小，同时断裂韧性随预应变增大而降低。对紧凑拉伸（CT）试样和含裂纹钛制压力容器进行断裂有限元分析，结果表明：裂纹尖端的塑性区随预应变增大而减小，从而导致 *J* 积分值随预应变增大而减小。基于 BS 7910:2013 的失效评定曲线分析发现：选择 1 曲线和选择 3 曲线会随着材料预应变而变化，安全区域逐渐减小。因此，随着预应变的增加，失效评定图中屈服应力的储备系数增加，而断裂韧性的储备系数降低。由本研究可知：预应变会对失效评定产生显著影响，需要将其考虑到含裂纹钛压力容器的完整性评定中。

关键词：预应变；失效评定曲线；裂纹；工业纯钛；压力容器

作者简介：代　巧，女，1986 年生，博士，讲师，江苏理工学院机械工程学院，江苏 常州 213001，电话：0519-86953210，E-mail: daiqiao@126.com