ORAL/POSTER REFERENCE: ICF100237

EXPERIMENTAL RESEARCH ON FRACTURE AND FATIGUE OF SCT SPECIMEN SIMULATING HIGH-STRAIN REGION OF PRESSURE VESSEL NOZZLES

Chen Xuedong Yang Tiecheng Cheng Chuanqing
Hefei General Machinery Research Institute
No.888, West Changjiang Road, Hefei 230031, China

Jiang Jialing
Zhejiang University

ABSTRACT

This paper makes an in-depth analysis and research on the shaped compact tensile specimen (SCT), which simulates the high strain zone of pressure vessel nozzle. The elastoplastic FE analysis and test of SCT specimen show that SCT specimen fully possesses the characteristics of stress and strain simulation of high strain zone of pressure vessel nozzle, which is able to realize simulation of high strain zone of engineered structure with small test specimen and can conveniently change stress-strain field of the test specimen through changing the scale of geometric dimension, open size and shape of the test specimen. The rotational factor and crack tip opening displacement of SCT specimen are measured, The influence of local high strain plastic zone and the closing effect of the structure on fatigue crack propagation rate is studied and the engineering calculation method for COD of high strain zone and propagation rate of fatigue crack is proposed through theoretical analysis and calculation of fracture fatigue parameters of SCT specimen and experimental research and analysis of fracture fatigue crack propagation of SCT specimen, which provides a basis for fracture and fatigue assessment of high strain zone of pressure vessel nozzle.

KEYWORDS

pressure vessel, nozzle, high strain zone, SCT specimen, fracture, fatigue crack propagation

1. INTRODUCTION

High-strain zone of pressure vessel nozzle yields higher stress concentration due to continuous destruction of geometric structure, resulting in very high stress-strain level within local region. Meanwhile, complicated structure of nozzle location increases the degree of difficulty of fabrication inspection, therefore, occurrence of welding defects can not be thoroughly avoided. Moreover, the effect of welding residual stress and performance deterioration of material adjacent to welds make this location extremely susceptible to fracture and fatigue damage of pressure vessel[1].

In recent 30 years, many countries launched extensive research on the subject of fracture fatigue in pressure vessel nozzle. Man has been seeking medium and small-sized specimens that can simulate the characteristics of the nozzle location of the real-sized vessels for effective fracture fatigue analysis[2], models such as wide plate, flat-plate nozzle, shaped plate, shaped CT specimen(SCT), bi-directional loading cross shaped plate etc. Research results[3] show that SCT specimen has the advantage of compact structure, small test load etc, which provides a more effective way for fracture and fatigue research of high-strain zone of pressure vessel nozzle.

In this paper the plastic rotational factor and COD of SCT specimen are measured, the effect of local high-strain plastic zone and closing effect of the structure on propagation rate of fatigue cracks is researched and the engineering calculation method for COD and propagation rate of fatigue cracks of high-strain zone is proposed through theoretical analysis and calculation of fracture fatigue parameters of SCT specimen and experimental research and analysis on fracture and fatigue crack propagation of SCT specimen in combination with FE stress-strain analysis and test stress measurement of SCT specimen, thus providing a basis for fracture and fatigue assessment of high-strain zone of pressure vessel nozzle.

2. STRESS-STRAIN ANALYSIS OF SCT SPECIMEN

The characteristics of the stress-strain field of pressure vessel nozzle zone is the local high-strain zone and high-strain gradient zone are restrained by the wide elastic zone. SCT specimen is just proposed based on this feature of high-strain zone of the nozzle. SCT specimen is obtained by opening at the middle of CT specimen and local thinning variation. This variation realizes strong elastic restraint of high-strain zone of the opening periphery and reinforcement at external side of the specimen. The structural diagram and main dimensions can be seen in Fig. 1.

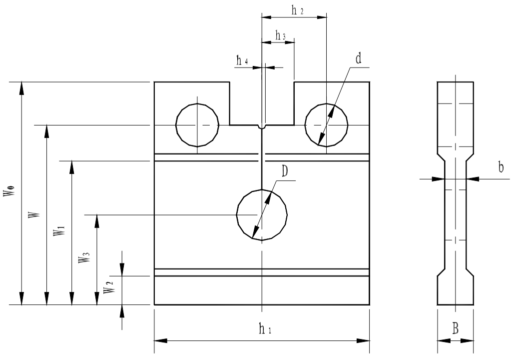
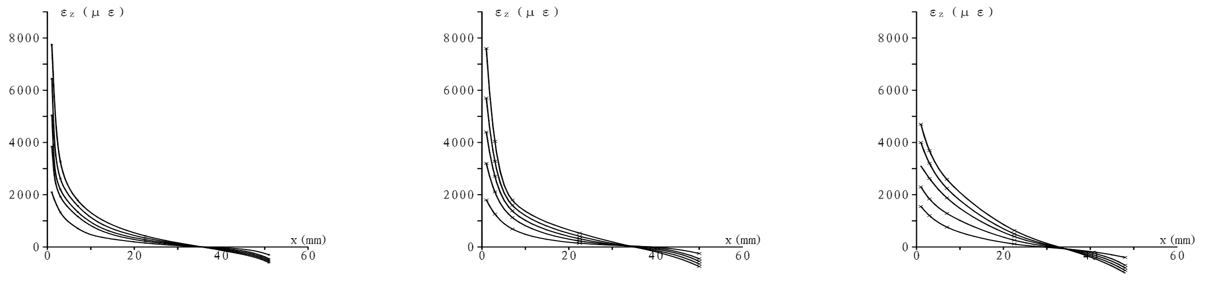


Fig. 1 Structural diagram of SCT specimen
$W=90mm$; $h_1=1.2W$; $h_2=0.375W$; $h_3=0.2W$; $2h_4=2.5mm$; $W_0=1.25W$; $W_1=(5/6)W$; $W_2=(1/5)W$; $W_3=(2/3)W$; $b=(1/15)W$; $B=(1/5)W$; $d=12.5mm$ $D=15,20,25mm$

2.1 Elastoplastic FE analysis

In consideration of stress concentration due to opening on SCT specimen, the opening periphery of the specimen has already entered the state of local yield under the action of a certain load, therefore, the specimen adopts elastoplastic FE calculation method for the specimen.

For the specimens with opening diameter of 15mm, 20mm and 25mm, the strain distributions in Z-direction of the specimen without cracks along cracking line under the action of 10, 15, 17, 19 and 20kN respectively are shown in Fig. 2.

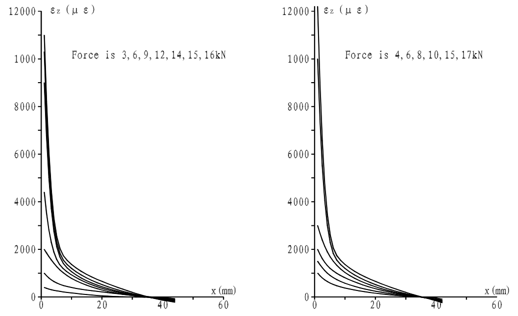


a. Φ15mm specimen b. Φ20mm specimen c. Φ25mm specimen

Fig. 2 Distribution of elastoplastic strain(Z-direction) of SCT specimen

2.2 Test stress-strain analysis of SCT specimen

In order to verify FE calculation results, the test stress-strain analysis is carried out on SCT specimen. Fig. 3 shows the distribution of measured strain e_z of the specimen with opening diameter of 15mm and 20mm respectively.



a. Φ15mm specimen b. Φ20mm specimen

Fig. 3 Distribution of measured strain of SCT specimen (Z-orientation)

It can be seen from measured results of FE calculation and strain that SCT specimen certainly has the three characteristics of high-strain zone of pressure vessel nozzle:

(1) **high-peak strain** when the load reaches P=17kN (equivalent to average cross- section stress $\sigma_m=1700/541=31.4MPa=0.097\sigma_y$), the measured strain at the position 2mm away from the opening periphery has exceeded 10000 με, which is as high as $6e_y$. The peak strain extrapolated from strain distribution curve to the position X=0 of the opening periphery has already reached 13000 με, which is as high as $8.2e_y$.

(2) **high-strain gradient** with the increasing distance from opening periphery, the stress-strain value decreases very quickly. Measured results show that within the range of 8mm, strain value is reduced by about 50%, whereas within the range of 25mm, it is reduced by about 80%.

(3) **high-elasticity restraint** when the distance from opening periphery exceeds 20mm, the loading range for this test has already been under the state of elasticity. Particularly, for the reinforcement rib at right side of the specimen in Fig.1, its elastic restraining capability is stronger.

The above results show that the strain distribution law of SCT specimen is very similar to high-strain zone of engineered construction such as pressure vessel nozzle, etc., thus having a good simulation.

Both the strain peak and the size of yield zone of SCT specimen decrease with the increase of opening diameter, showing that the opening diameter is a more important structural parameter of SCT specimen.

3. FRACTURE RESEARCH OF SCT SPECIMEN

3.1 Calculation of fracture initiating force

Wells induced the empirical formula for COD according to the test results of wide-plate specimen with small crack:

$$\delta = 2\pi e a \tag{1}$$

In early 1980s, we found if the strain reaches several times the material yield strain when we conduct experimental research on fracture and fatigue of the nozzle, Formula (1) is too conservative, so we derived the formula below from Neuber relation[4]:

$$\delta = \pi e a \tag{2}$$

Cai Cigung[5] and Mercle[6] give the J-integral expression for full-yield model:

$$J = 2\pi a \int \sigma de \tag{3}$$

In recent 20 years, various forms of COD expression at high strain were all obtained based on the above expression by adopting an appropriate safety factor.

The COD expression adopted in PD6493－80, 91 for high strain:

$$\delta = 2\pi e_y a(e/e_y - 0.25) \tag{4}$$

Chinese CVDA Code adopts COD expression for high strain:

$$\delta = \pi a(e + e_y) \tag{5}$$

These COD expressions are all basically based on the wide-plate tests that seek full-yield state. Because the stress-strain field of wide plate is uniform, which is very different from high-strain zone of engineered construction such as pressure vessel nozzle etc., application of δ calculation method obtained from wide-plate test results to high-strain zone of practical engineered construction will yield a big deviation.

By deriving from Dugdale's COD expression for strip yield model and Cai Cigung's J-integral expression for full yield model, we get unified expressions for various states of stress within the entire range from low stress to high strain, i.e.:

$$\delta = \frac{\pi a e_y}{m}\left(\frac{\sigma}{\sigma_y}\right)^2 \qquad \left(\frac{\sigma}{\sigma_y} \le \frac{1}{\pi}\right) \tag{6}$$

$$\delta = \frac{1}{m} a e \qquad \left(\frac{\sigma}{\sigma_y} \text{或} \frac{e}{e_y} > \frac{1}{\pi}\right) \tag{7}$$

when $\sigma/\sigma_y = 1/\pi$,

$$\delta_{(6)} = \delta_{(7)} = \frac{a e_y}{\pi m} \tag{8}$$

where m is COD reduction factor. For flat stress, m=1; for flat strain, m=2; for most practical constructions between them, m=1.5.

After considering 2 times safety factor, we get the following expressions:

$$\delta = \frac{2\pi a e_y}{m}\left(\frac{\sigma}{\sigma_y}\right)^2 \qquad \left(\frac{\sigma}{\sigma_y} \le \frac{1}{\pi}\right) \tag{9}$$

$$\delta = \frac{2ae}{m} \qquad \left(\frac{\sigma}{\sigma_y} \text{或} \frac{e}{e_y} > \frac{1}{\pi}\right) \tag{10}$$

3.2 Measured Results Of Rotational Factor Of Crack Mouth Opening Displacement And COD

3.2.1Test contents

(1) Based on strain measurement on SCT specimen without cracks, cut a manual notch at right side of the opening using linear cutting machine. Attach 5 pairs of cutting edge diagonally in front of crack tip, as shown in Fig. 4.

(2) Prefabricate fatigue crack at a load of 0~6kN, stop when we can see 1~2mm fatigue crack on the surface with our eyes.

(3) Take two pieces of specimen with respective Φ15mm and Φ20mm specially for test calibration of rotational factor r. Determine rotational factor r according to position of cutting edge, opening displacement and total length of cracks (calculate from position of loading line).

3.2.2Test results and analysis

(1) Measured results of rotational factor for crack mouth opening displacement and COD

The conversion from crack mouth opening displacement V to COD δ can be carried out with the following formula:

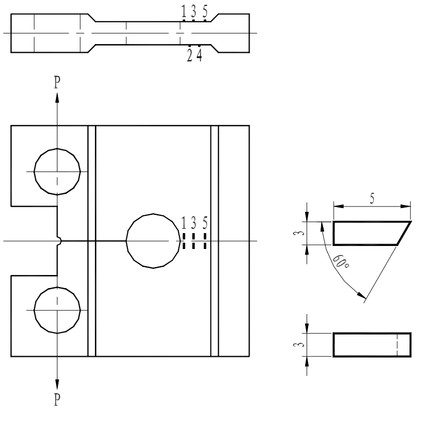


Fig. 4 Arrangement of lateral cutting edge for SCT specimen

$$\delta = \frac{r(W - a_t)V}{a_t + r(W - a_t) + Z} \tag{11}$$

where W——width of test specimen;
a_t——crack length calculated from loading line of the specimen, mm;
V——crack mouth opening displacement, mm;
Z——thickness of cutting edge, for SCT specimen, Z=0;
r——rotational factor, calibrated through test.

By conducting test calibration on SCT specimen with cracks of different length, the measured rotational factor r is about 0.28, yet this value basically does not vary with crack length and load.

With the clamp-type tensiometer fixed on the crack mouth, we measured the crack mouth opening displacement V at each load during loading process, the results are shown in Fig. 5. From the measured V and calibrated r, we can obtain COD δ according to formula (11).

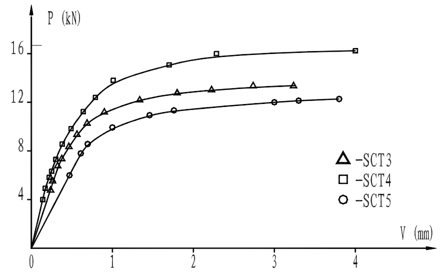


Fig.5 P-V curve of SCT specimen

(2) δ - e curve

Take δ measured on the specimen with cracks and the peak strain e (0.5mm away from opening periphery) measured on the specimen without cracks under the same load as the coordinates of δ - e curve, join the marked points that correspond to each load during the whole test process, they become δ - e curves, as shown in Fig. 6.

Plot expression (5), (9) and (10) onto the diagram at the same time, it can be seen that the test data points basically lie above the curves of expression (9) and (10), indicating that this expression can be taken as the calculation expression for fracture assessment of the cracks in high-strain zone.

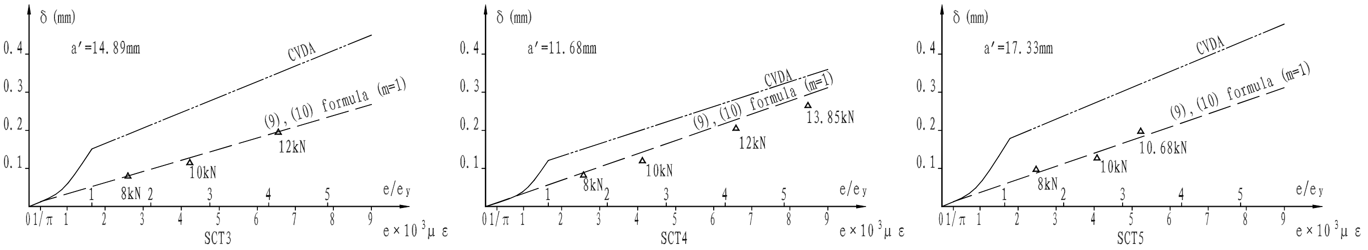


Fig. 6 δ - e curve of SCT specimen

4. EXPERIMENTAL RESEARCH ON FATIGUE CRACK PROPAGATION IN HIGH-STRAIN ZONE OF SCT SPECIMEN

4.1 Test Method And Conditions For Fatigue Of SCT Specimen

The test conditions for the fatigue of SCT specimen are listed in Table 1. The crack length is determined simultaneously by outlining method and unloading flexibility method. Outlining adopts load-reducing outlining method[7], the number of cycles is acquired and recorded automatically by computer.

TABLE 1
TEST CONDITIONS FOR FATIGUE OF SCT SPECIMEN

Specimen No.	Opening diameter mm	Max. load kN	Load ratio R	Loading frequency Hz	Length of prefabricated crack mm	Remarks
SCT6	25	8.0	0.05	8.0	1.31	17kN prestretching
SCT7	25	8.0	0.05	8.0	1.31	

4.2 Measurement Of Closing And Opening Force Of Fatigue Cracks

In the process of fatigue crack propagation, a residual tensile strain zone remains in front of crack tip, this residual deformation reduces crack opening displacement, the external elastic zone compresses the plastic zone of crack tip during unloading, making compression stress occur near crack tip after unloading, even reach reverse yielding. When reloading, load increase eliminates compression stress of crack tip, the crack fully opens. From this time the load indeed contributes to crack propagation. The closing effect of fatigue cracks in plastic zone has a bigger effect on fatigue crack propagation. Therefore, the closing and opening force of fatigue cracks of SCT specimen are measured during the test.

The methods for determining closing and opening force of fatigue cracks are Elber's[8] and Brahmaf's[9]test measurement methods and McCLung's[10] FE calculation method. In this paper the test method is adopted to measure closing and opening force of SCT specimen. In the test we use tensiometer and load sensor to measure P-COD diagram of the specimen, as shown in Fig. 7. It can be seen from Fig. 7 that the slope of P~COD curve between point A and B is bigger than the ones of other section, indicating the rigidity of the specimen is biggest and the crack fully closes; the slope of the curve between point B and C gradually decreases, the crack gradually opens and fully open at point C; after point C, the slope of the curve presents linear feature. Therefore, records below point C of the curve indicate the cracks does not fully open until point C is reached, therefore, the force corresponding to point C is the opening force. Also from Fig. 7 it can be seen that the return process also has the similar case, yet the opening and closing forces are basically equal. The value for opening force, COD δ and crack length corresponding to this value measured in the test are acquired and recorded automatically by computer.

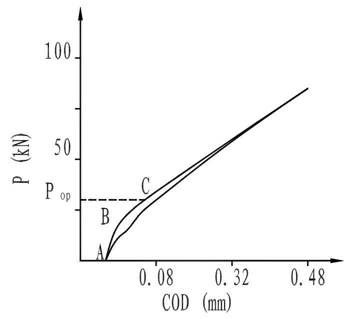


Fig. 7 SCT specimen vs. P-COD curve

The value of effective stress ratio U obtained through calculation is:

$$U = \frac{\sigma_{\max} - \sigma_{op}}{\sigma_{\max} - \sigma_{\min}} = \frac{p_{\max} - p_{op}}{p_{\max} - p_{\min}} \tag{12}$$

U-a relation can be seen in Fig. 8.

It can be seen from Fig. 8 that U values of the two specimens are bigger in the beginning, but they are quickly decreased to a certain value, and slowly increased to a stable value. The U value of prestretched specimen SCT6 is smaller than that of unprestretched specimen SCT7. When the crack propagates to a certain length, the U values of the two specimens gradually approach. At this time, crack has already propagated beyond the plastic zone of SCT specimen, the effect of prestretched plastic zone on crack closing has been eliminated.

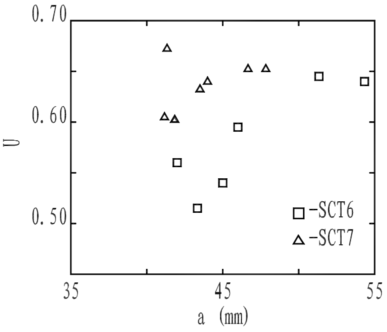


Fig. 8 Effective stress ratio of SCT specimen

4.3 Fatigue crack propagation rate

Within the elastic zone, fatigue crack propagation rate can be calculated by Paris equation:

$$\frac{da}{dN} = A(\Delta K)^m \tag{13}$$

Elastoplastic fracture parameter—COD δ is a simple and practical parameter, suitable for both elastic and elastoplastic conditions. The Paris equation is rewritten as follows after Δ δ is taken as a fatigue parameter in the test:

$$\frac{da}{dN} = B(\Delta\delta)^n \tag{14}$$

Calculate COD as per formula (11).

The da/dN～Δ δ relation measured in the test are shown in Fig. 9, by regression, the Paris equation is obtained:

$$\frac{da}{dN} = 2.683\ (\Delta\delta)^{3.21} \tag{15}$$

It can be seen from Fig. 9 that at the same Δ δ, the fatigue crack propagation rate of prestretched specimen is smaller than that of the unprestretched one. When the crack propagates to a certain length, their propagation rates approach. The data are diversely scattered. For smaller cracks, the phenomenon of short cracks occur although da/dN decreases, Δ δ increases. It can be regarded that this phenomenon is mainly attributable to the influence of crack closing effect.

The presence of structural plastic strain zone makes the closing effect of the cracks more serious, resulting in reduction of $\Delta\delta_{\text{eff}}$ and slowdown of fatigue crack propagation rate. It can be seen from the effective stress ratio U (Fig. 8) that the U value of prestretched specimen SCT6 is lower than that of unprestretched specimen SCT7 due to existence of residual plastic zone. Therefore, production of residual plastic strain at the location of stress concentration such as the nozzle knee in conventional hydraulic test of pressure vessel is very favorable to reduction of fatigue crack propagation rate of these locations and extension of fatigue life.

Make closing effect correction to Δ δ:

$$\Delta\delta_{eff} = \frac{\Delta K_{eff}^2}{2E\sigma_y} \tag{16}$$

$$U = \frac{K_{\max} - K_{open}}{K_{\max} - K_{\min}} = \frac{\Delta K_{eff}}{\Delta K_{\max}} = \sqrt{\frac{2E\sigma_y \Delta\delta_{eff}}{2E\sigma_y \Delta\delta}} = \sqrt{\frac{\Delta\delta_{eff}}{\Delta\delta}} \tag{17}$$

$\Delta\delta_{eff}$～da/dN relation after taking into account the closing effect is shown in Fig.10. It can be seen from Fig. 10 that the two specimens have a good linearity for data and approach very much, which is expressed using unified fatigue crack propagation rate as follows:

$$\frac{da}{dN} = 5.827\ (\Delta\delta_{eff})^{2.56} \tag{18}$$

The crack fatigue propagation rate of standard CT specimen of the same material is:

$$\frac{da}{dN} = 4.905\ (\Delta\delta_{eff})^{2.06} \tag{19}$$

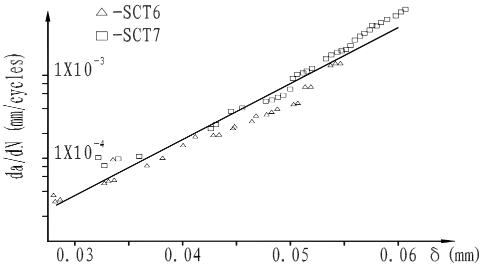


Fig. 9 da/dN-Δδ relation of SCT specimen

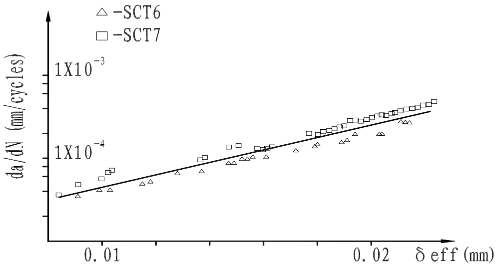


Fig. 10 da/dN-$\Delta\delta_{eff}$ relation of SCT specimen

It can be seen from the above equations that the fatigue crack propagation law of SCT specimen after closing effect correction is basically in agreement with the results of standard CT specimen.

5. CONCLUSION

(1) FE calculation and measured results on test stress of SCT specimen successfully repeat the main characteristics of high strain of engineered construction such as pressure vessel nozzle, the simulation of high-strain zone of engineered construction is realized using small test specimen, and by changing the scale of geometric dimensions, opening diameter and shape of the specimen, it is convenient to change its stress-strain field, thus providing an effective and convenient tool for fracture and fatigue research of pressure vessel with nozzles.

(2) Measured the plastic rotational factor of SCT specimen r=0.28, and measured the δ of COD by r and crack mouth opening displacement;

(3) Measured the opening and closing force of fatigue cracks in high-strain zone of SCT specimen, obtaining the effective stress ratio U;

(4) Proposed the engineering calculation method for COD in high-strain zone of SCT specimen and propagation rate of fatigue cracks corrected through closing effect, thus providing a basis for fracture and fatigue assessment of high-strain zone of pressure vessel nozzle.

REFERENCE

1. Decock, J., *Determination of Stress Concentration Factors and Fatigue Assessment of Flush and Extruded Nozzles in Welded Pressure Vessels, 2nd Int. Conference On Pressure Vessel Tech., Part 2*, pp.821-834(1973)
2. Li Zezhen, Soloms G., Lucia A.C., Volta G., 1988, *A Special Compact Tension Specimen for the Simulation of the Nozzle Corner Strain Field*, Commission of the European Communities, JRC-Ispra establishment, 21020 Ispra, Italy
3. Chen Xuedong, Yang Tiecheng, Li Zezhen, Wang Zhaowei, *Design Curves for Fracture Assessment in High-Strain Region of Pressure Vessel Nozzles, 9th International Conference on Pressure Vessel Technology*, Sydney Australia 9-14 April 2000
4. Zeng Guangxin, Li Zezhen, *The Two Basic Problems for the Defect Assessment Methods, Collection of Pressure Vessel Defect Assessment Materials* (No.5).
5. Cai Cigung, 1979, *Crack Propagation in Plastic Strain Zone*, J. of Mechanics
6. Mercle, 1976, *ASTM STP* 536
7. Gao Zengliang, Li Zezhen, *Research on Fatigue Propagation Law of Shaped Specimen Plate Simulating High-strain Zone of Pressure Vessel Nozzle*, Zhejiang Industrial University Bulletin, No.4, 1985
8. Elber Wolf, *The Signification of Fatigue Crack Closure, Damage Tolerance in Aircraft Structures*. ASTM STP 486, American Society for Testing and Materials, 1971, 230-243
9. Barhma, K. Et al, *Observation of Crack Closure Using a Crack Mouth Opening Displacement Gauge*, Int. J. Fatigue, 1989.11(1); 37-41
10. McClung, R. C. And Sehitoglu, H. *On the Finite Element Analysis of Fatigue Crack Closure -1, Basic Modeling Issues*, -2 Numerical Results, Engineering Fracture Mechanics, 1989, 33, 217-272