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STUDY ON FATIGUE CRACK GROWTH OF A PRESSURE PIPE UNDER FLUCTUATING LOADS

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ABSTRACT

In this paper, the finite element software ABAQUS is used to study the crack propagation rule. In this paper, a theoretical formula for the general process of fatigue crack propagation is derived, and the calculation scheme of simulation programming is determined; The simulation model is validated by the reuse test, and then the fatigue crack propagation rule of the pressure pipe under different parameters is simulated and analyzed by the validated model. The final results show that the fatigue crack in the pipe wall thickness, crack shape factor and stress ratio under the influence of similar, with the parameters of the fatigue life of the cracked pipe are rising gradually decreased, and the decrease rate is gradually reduced.

Key Words: Pressure pipe; X80; Fatigue crack; Finite element; Pressure pipeline

0. Introduction

In the past more than 10 years, the demand for natural gas in the world has increased considerably, and the capacity of pipeline transportation has been greatly improved. The steel for natural gas pipeline has been raised from X60 to X80. X80 steel has the characteristics of high strength, ductility and fracture resistance. It is also the leading steel in the international gas transmission pipeline [1]。 The pressure pipeline will cause fatigue damage because of the pressure fluctuation during the transportation of medium, For the pipeline with cracks on the surface, fatigue damage is more likely. Because of the pressure pipeline in the process of conveying the main pressure for the internal pressure, the circumferential stress is much greater than the axial stress, so axial crack stress is higher, more dangerous, so this paper is mainly on the axial surface crack fatigue growth analysis.

On the basis of the literature [2], according to the standard test data, the predicted fatigue life value is quite different from the full-scale experimental value. Therefore, according to the fatigue calculation theory, the corresponding calculation formula is compiled into ABAQUS to calculate the full size fatigue crack growth, and more accurate evaluation of the pipeline with crack defects can be made.

1. Fatigue crack propagation theory and programming calculation

Generally speaking, the program written in ABAQUS fatigue simulation is based on the fracture criterion of relative energy release rate. Crack fatigue propagation is generally divided into 3 stages, namely, slow crack propagation, stable expansion and rapid expansion. The former two stages are longer, and the stable expansion stage takes the longest time. In the stage of stable crack growth data are calculated, so the results will be smaller, the fatigue life of set aside a certain safety margin.

The circumferential stress of the pipeline[3] is：

$$\sigma = \frac{pD}{2t}$$

Type: P - pipe internal pressure, Pa; D - pipe diameter, m; t - pipe wall thickness, M.

Because:

$$G = \frac{(1-v^2)}{E}K^2,\ \sigma_{min} = R\sigma_{max}$$

Type: *G* - energy release rate, N/m;*v* Poisson's ratio, the dimensionless stress intensity factor; *K*, Pa, m1/2; *E* Pa; - Minimum elastic modulus, circumferential stress, Pa; the maximum circumferential stress, Pa.

Also because:

$$\Delta K = Y\Delta\sigma\sqrt{\pi a} = Y(\sigma_{max} - \sigma_{min})\sqrt{\pi a} = Y(1-R)\sigma_{max}\sqrt{\pi a}$$ Y

Formula: *Y* - crack shape factor; a - crack half length, *M*.

Because:

$$K^2 = Y^2(1-R)^2{\sigma_{max}}^2\pi a$$

The relative energy release rate was:

$$\Delta G = \frac{\sigma_{max}^2 - \sigma_{min}^2}{E}\cdot(1-v^2)\cdot\pi a = \frac{(1-R^2)(1-v^2)\pi a\sigma_{max}^2}{E} = \frac{(1-R^2)(1-v^2)}{Y^2(1-R^2)}\cdot\frac{\Delta K^2}{E}$$

So:

$$da/dN = C[\frac{\Delta K}{(1-R)^n}]^m = C[\frac{\Delta G}{(1-R)^n}]^{m/2}\cdot\frac{Y^m(1-R)^m}{(1-v^2)^{m/2}(1-R^2)^{m/2}}\cdot E^{m/2}$$

Because the test data of small specimens can only be used for the fatigue expansion of pipe surface cracks, the fatigue expansion in the direction of crack thickness can be corrected by Newman[4]:

$$C_{thick} = C_{surf}/0.9^m$$

Type: Paris constant that extends along the thickness of the pipe wall; the Paris constant along which the crack propagates along the pipe surface.

The calculation based on the experimental results of small specimens is dangerous, and the formula of small sample test needs to be converted to full scale pipeline. The fatigue crack growth test of full scale pipeline shows that the transformation formula is[5]:

$$\lg(da/dN)_F = 0.4773 + 1.11721\lg(da/dN)_S$$

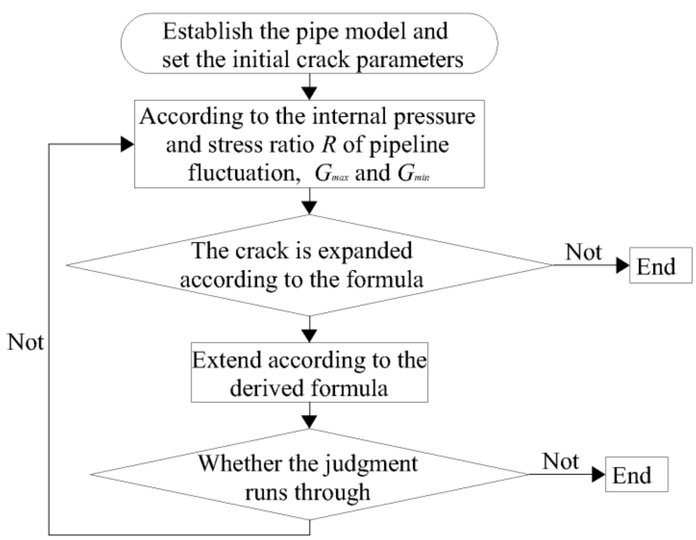
Type: $(da/dN)_F$—full scale pipe crack growth rate, m/cycle ; $(da/dN)_S$—Standard specimen; crack growth rate, m/cycle。

The formula is corrected by combining the experimental results:

$$\frac{da}{dN} = C'_{thick}\left[\frac{\Delta G}{(1-R)^n}\right]^{m'/2} \cdot \frac{f \cdot Y^{m'}(1-R)^{m'}}{(1-v^2)^{m'/2}(1-R^2)^{m'/2}} \cdot E^{m'/2}$$

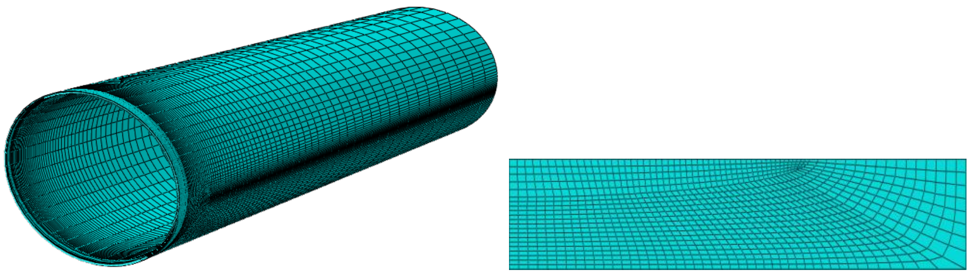
Type: *f*—experimental correction factor; C'_{thick}, *m'*—After conversion of parameters.

In ABAQUS, the calculation program is compiled by using Python language, and the theoretical parameters of fatigue crack propagation rate are programmed into calculation. The damage evolution law based on energy linear softening mixing model is adopted. The calculation flow chart is shown in figure 1.



2. Verification of fatigue crack model for pressure pipe

According to the literature [4], DiaoShun, FengYaorong and others carried out full-scale fatigue test using the homemade X60SSAW pipeline. Pipeline specifications for up to Ø660×8.7mm, the tensile strength is 540MPa。The propagation of surface cracks with depth of 3mm and length of 50mm under fatigue loading is investigated experimentally. The Paris fatigue equation [4]in steady expansion stage of tube is:$da/dN = 2.15 \times 10^{-9} (\Delta K)^{3.1675}$.Now, we do finite element simulations on it.Mesh the pipe model, as shown in figure 2. The boundary condition applies symmetrical load to the crack end surface and is fixed away from one end.



（a）Whole mesh generation（b）Whole mesh generation

Fig2. Mesh generation of surface fatigue crack model

The load stress ratio of the experiment is R=0.1, the maximum load is 7.5MPa, and the minimum load is 0.75MPa. The periodic amplitude curve is expressed in Fourier series. The expression[6] is:

$$\begin{cases} a = A_0 + \sum_{n=1}^{N} [A_n \cos\omega(t - t_0) + B_n \sin n\omega(t - t_0)], & t \geq t_0 \\ a = A_0, & t < t_0 \end{cases}$$

Type:N—number of ourierseries; ω—circular frequency, rad/s；t_0—start time;A_0—initial amplitude;A_n—cos term (n=1,2,3,... (N); B_n—sin term (n=1,2,3,... (N).

The simulation is performed by cyclic loading with a stress ratio of 0.1.The initial internal pressure is calculated to beA_0=4.125,A_n=0,B_n=3.375.Because the calculation mainly aims at the crack propagation under the cyclic number, the loading period has little effect on the calculation. Here,

take the T=1, take theω=2π, t_0=0。The load time amplitude curve is shown in figure 3.

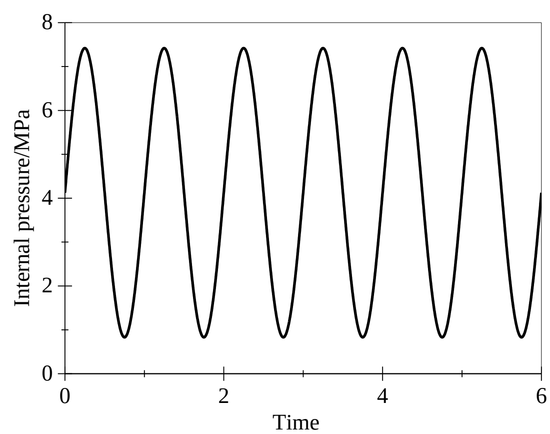


Fig3.Sketch of fluctuating load

Figure 4 is the stress of the fatigue crack propagation through time and the corresponding cycle result diagram. From the simulation results, it can be concluded that after 6223 times of cyclic loading, the cracks run through the pipe wall and leak. Then, the result of the experiment is about 8000 times. This is because in the experiment, the pipe surface crack is cut with a grinding wheel, and then the blade is drawn at the tip of the notch, but in fact it is blunt, so it will pass through the sharpening process at the initial stage of fatigue loading. According to the literature [7] the crack initiation life generally only accounted for the entire life of 10%, so the experimental results in stable propagation order occupy the most part of the life, and in the ABAQUS numerical simulation program is adopted, the fatigue crack propagation period parameters, so the simulation results are smaller than the experimental value, which also have a certain safety margin, reliable calculation.

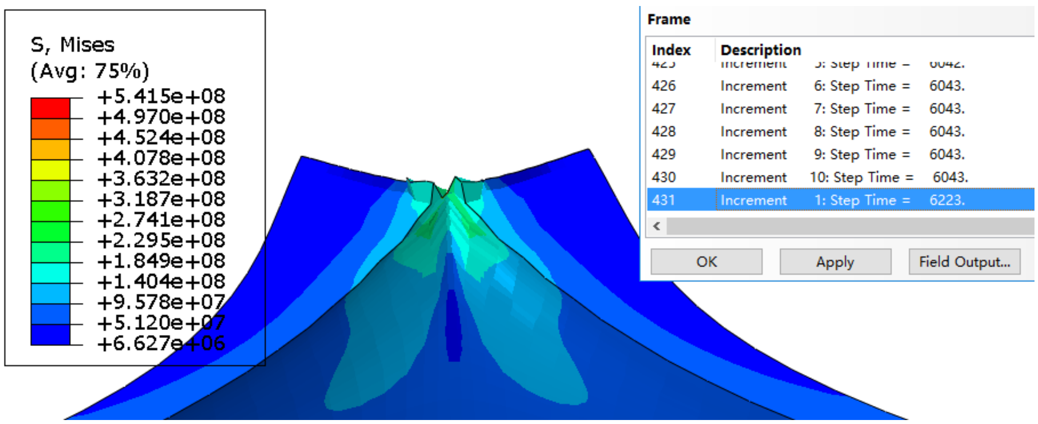


Fig4. Fatigue crack penetration time nephogram

The finite element simulation results are compared with the experimental results, as shown in figure 5.The a-N curve of crack can, in part, before and after the finite element simulation of crack propagation rate along the thickness direction is slightly smaller than the experimental value, this is because the finite element simulation using data from crack stable growth stage.

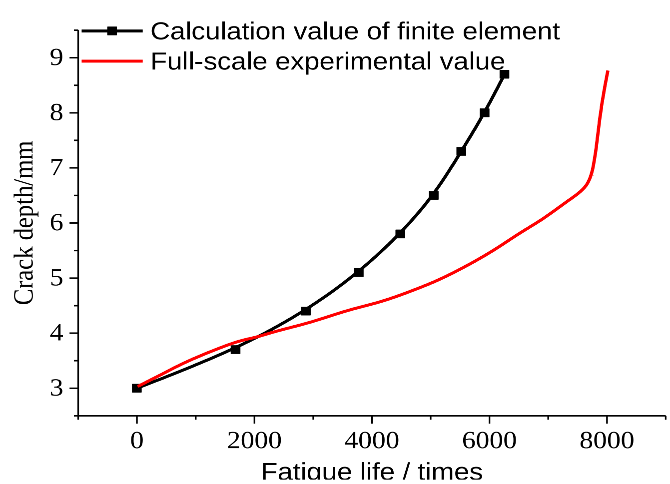


Fig5.Comparison of simulation and test of fatigue crack propagation

When the pipeline is penetrated, if the cyclic load is continued, the crack will enter the stage of rapid plastic instability, and then the model will be torn in a short time.

3. Variation of fatigue life of pipes with different thickness and cracks

When the gas pipeline is running, the gas flow is not stable, there will be some changes, so it will cause certain pressure fluctuations. Under fluctuating pressure, there are many factors that affect pipeline fatigue life, among which the stress ratio, crack initial depth ratio and crack shape factor are the most important factors. Taking the second pipeline of the west to east gas pipeline as an example, the crack propagation of a X80 pipe with 1219mm diameter under fatigue loading is calculated. The design pressure of the pipeline is 12MPa, and the propagation law of the pipe under different wall thickness, different crack length, different crack depth and different stress ratio is simulated.API 579-1/ASME FFS-1gives the values of C and m for ferriticpearlitic steels in neglecting the interaction between corrosion and fatigue, and is known from the literature [8]: ∶ c=6.89×10^{-9}, m=3, n=0.5。

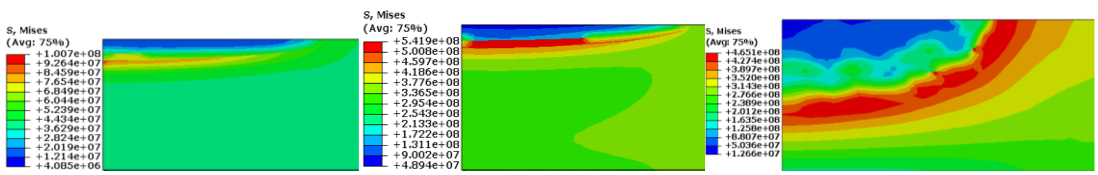


Fig6.Variation of stress in fatigue crack propagation

Figure 6 is the variation of stress during fatigue crack propagation. It can be seen from the diagram that with the fluctuation of the internal pressure in the pipeline, the maximum stress at the crack tip will appear different values, which is related to the internal pressure of the pipeline in the transient state. Similar to the static crack growth, the maximum stress also appears at the crack tip during the fatigue crack growth. The fatigue crack also expands along the radial direction, and then expands to the axial direction when the crack reaches a certain depth. The crack keeps the semi elliptical shape in the process of extending.

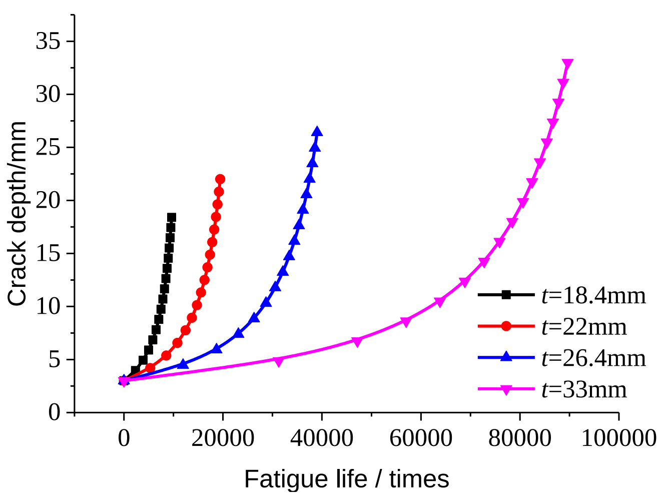


Fig7. Fatigue life of pipeline under different wall thickness

As shown in Fig. 7, the fatigue life of the crack from the initial depth to the through leakage is shown under different wall thickness pipelines. The initial crack depth isa_0=3mm, c_0=25mm, and the stress ratio is R=0.6, The maximum fluctuation is 12MPa。From the figure, with the increase of the thickness of the pipe wall, the fatigue life of the pipe increases, because the pipe wall thickness increases mean initial crack depth ratio decreased, ΔK will be reduced, thus increasing the fatigue life of$N$. The variation of the crack depth with the number of cycles is in the form of power function, and with the increase of cycle times, the crack propagation rate also increases rapidly.

4. Fatigue life variation of cracked pipe with different length

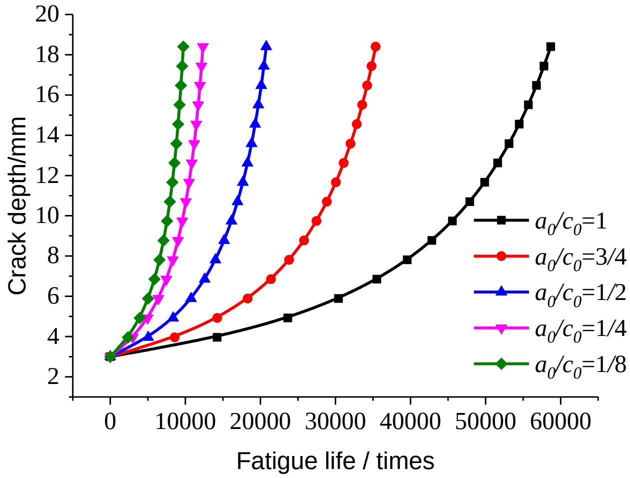


Fig8. Fatigue crack growth life of pipelines with different depth to diameter ratio

As shown in Figure 8 the influence of the different crack shape factors on the life of the pipeline with an outside surface crack is found. The initial crack deptha_0=3mm, the stress ratio$R$=0.6, the wall thickness t=18.4, and the maximum fluctuation is 12MPa.It is shown from the diagram that the fatigue crack propagation life decreases as the depth diameter ratio of the crack decreases. Because when the initial depth Fig. 3-28 fatigue life of pipeline under different crack depths of the crack is constant, the length of the crack increases with the decrease of the depth to diameter ratio of the crack, so that the fatigue life decreases gradually. With the decrease of the depth to diameter ratio of the crack, the fatigue life reduction rate of the pipeline decreases gradually, which shows that the fatigue life of the cracked pipeline decreases with the increase of the crack length.

5. Fatigue life variation of cracked pipes with different depths

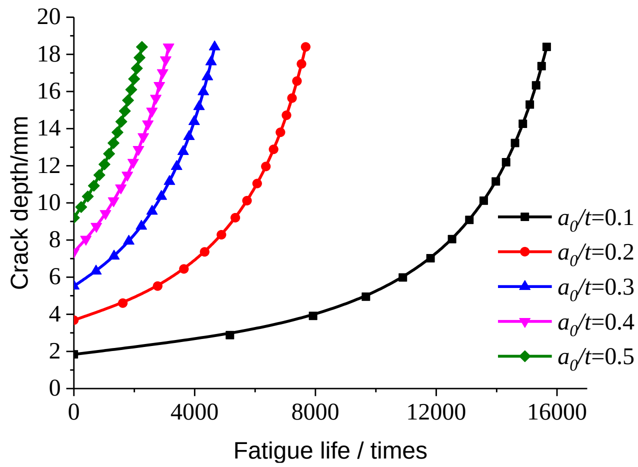
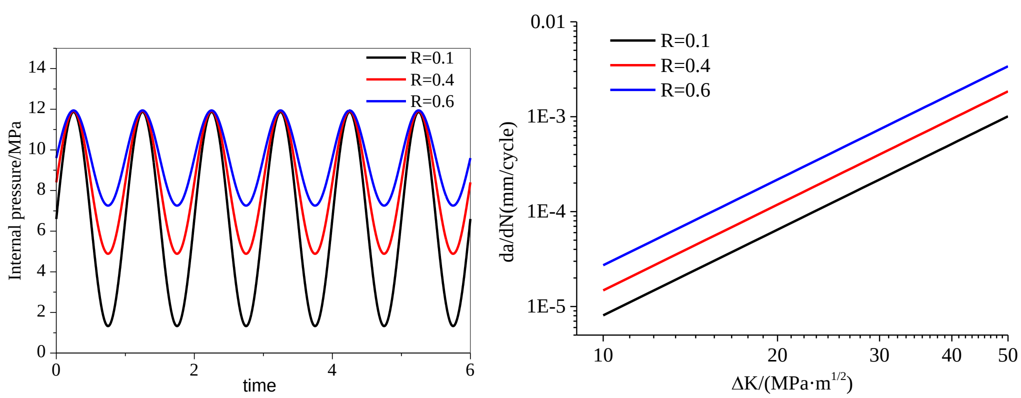


Fig9. Fatigue life of pipeline under different crack depths

Figure 9 shows the influence of initial crack depth on the fatigue life of pipes with surface cracks., The initial crack length c_0=25mm, the stress ratio R=0.6, the wall thickness t=18.4, and the maximum fluctuation is 12MPa.It can be seen that the fatigue life of the pipeline decreases sharply with the increase of the initial crack depth. Because with the increase of the crack depth, ΔK increases, the fatigue life N decreased. With the increase of the crack depth, the fatigue life of the pipeline decreases and the rate decreases gradually.

6. Fatigue life variation of cracked pipe under different stress ratio



(a) Internal pressure fluctuation at different stress ratio (b) Fatigue crack growth rate under different stress ratio

Fig10. Fluctuation of internal pressure and fatigue crack growth rate under different stress ratio

When the constant wall thickness and initial crack shape, the ratio of fatigue life of pipeline with surface crack were calculated and analyzed under different stress, the initial crack deptha_0=3mm, crack half lengthc_0=25mm, wall thickness t=18.4, maximum fluctuation pressure is 12MPa, the internal pressure fluctuation as shown in figure 10(a).Under different stress ratio, the formula of fatigue propagation rate corresponding to fatigue crack growth is different, as shown in Figure 10(B).

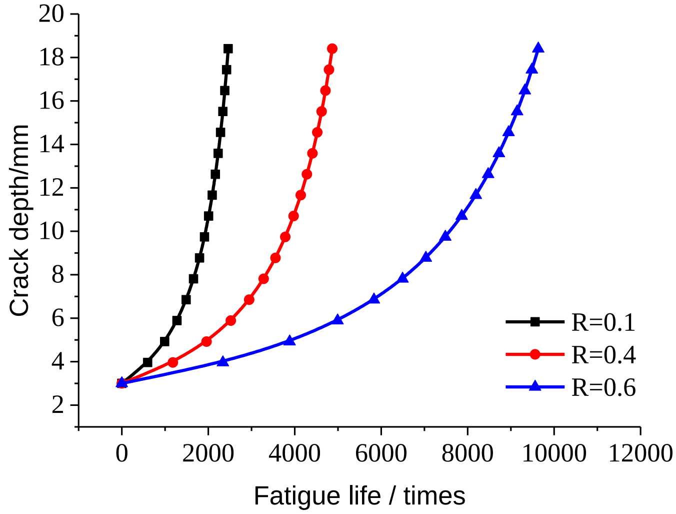


Fig11. Fatigue crack growth life of pipeline under different stress ratio

Figure 11 shows the influence of stress ratio on fatigue life of pipes containing surface cracks. It can be seen from the diagram that the fatigue life of the pipeline increases with the increase of stress ratio. Because the stress ratio is larger, indicates that the pipeline internal pressure fluctuation is smaller, so according to the formula, ΔK with the Δp decreases, so the increase of N. With the decrease of the stress ratio, the fatigue life reduction rate of the cracked pipeline decreases gradually.

7. Conclusion

The fatigue crack growth process of pressure pipe is divided into three stages: slow expansion, stable expansion and rapid expansion. The former two stages are longer, and the stable expansion stage takes the longest time.

The fatigue crack in the pipe wall thickness, crack shape factor and stress ratio under the influence of similar, when the crack is shallow, growth rate is relatively low, with increasing the depth of the crack propagation rate, rapid increase, until through the wall.

With the increase of the wall thickness, the crack depth diameter ratio, the stress ratio and the crack depth, the fatigue life of the pipeline with cracks decreases gradually, and the rate of decrease gradually decreases.

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