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STUDIES ON MAXIMUM HYDROSTATIC TESTING PRESSURE FOR NEW PIPELINE

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Abstract. Hydrostatic testing is an important step in pipeline construction. This test ensures the integrity of newly-constructed pipelines. Testing pressures used by Chinese construction contractors are lower than that in foreign countries. Nowadays, higher testing pressure is considered safer for pipeline operation. But what is testing pressure we should apply? Basing on fracture mechanics theory, this paper addresses the effects of testing pressure on pipeline materials, and calculates the maximum safe testing pressure. Also, experiments validate the theoretic conclusions.

Introduction

Pressure Testing, the last procedure in the pipeline construction, is regarded as one of the most important means to ensure safety after pipeline goes into operation. The aims of reliable testing are to eliminate residual defects in pipelines and to demonstrate the fitness of pipelines. After a test, a pipeline can be expected to safely contain its intended operating pressure. The confidence level that a pipeline is fit for safe service increases as the ratio of test pressure to operating pressure increases. In China, the commonly applied gas pipeline pressure testing standard is “code for design for gas transmission pipeline engineering”, in which the minimum and maximum testing pressure are specified and the maximum testing pressure is not allowed to create loop stress greater than 95% of SMYS. This value is much lower than pressure stress applied in other countries for example 100% of SMYS or more in north American. In order to increase the hydrostatic testing level, China University of Petroleum-Beijing and PetroChina Pipeline R&D Center takes great amounts of research work. This paper presents the study on maximum hydrostatic testing pressure and gives the theoretic and experimental results.

Theoretic Studies on Maximum Hydrostatic Pressure

The main effects of hydrostatic testing on pipe material include fatigue growing velocity of residual cracks, pressure reversals of line pipe, work life of cracks and load status of pipelines. The discussions of these four aspects are as follows.

Fatigue Growing Velocity of Residual Cracks. Residual cracks in pipelines in operation extend continually under cycle stress caused by internal pulsing pressure. For surface cracks, their depths get deeper and deeper until they penetrate pipe walls.

Given a elliptical surface crack with depth a0 and length 2b0. After hydrostatic testing, its size becomes depth a1 and length 2b1. Stress intension factor of crack open top can be expressed as follows.

$$K = \frac{1.1M\sigma\sqrt{\pi a_1}}{\sqrt{Q}} \tag{1}$$

Where: $Q = \Phi^2 - 0.212\left(\frac{\sigma}{\sigma_s}\right)^2$, Φ denotes secondly full-ellipse integral related to a_1 / b_1;

$\sigma = \frac{PR}{t}$, P denotes internal pressure, R denotes pipe radius, t denotes thickness of pipe wall;

$M = \left(1 + 1.61\frac{a_1^2}{Rt}\right)^{\frac{1}{2}}$, M denotes expansion factor; σ_s denotes yield stress.

Growing velocity of this crack under inner cycling pressure can be expressed as Paris equation by differential coefficient of crack depth to loading times of inner cycling pressure.

$$da/dN = C(\Delta K)^n \tag{2}$$

Where: $\Delta K = \frac{1.1M\Delta\sigma\sqrt{\pi a_1}}{\sqrt{Q}}$, C and n are material constants which can be measured through experiments.

The life of this crack is

$$N = \int dN = \int_{a_1}^{a_c} \frac{da}{C(\Delta K)^n} \tag{3}$$

Where: a_1 denotes initial crack depth, a_c denotes critical crack depth.

Generally, the change of pipeline operational pressure is regular, while hydrostatic testing pressure is much greater than normal operational load. The ratio of them is 1.25 or more. This high overloading will create a large plastic area around cracks tops which would prevent cracks from getting through it. This greatly reduces the crack growing velocity and the higher the single overloading, the slower the crack propagates.

The theoretic conclusion "high overloading would reduce the crack growing velocity" is validated by FIG. 1 and FIG. 2. Fig. 1 and FIG. 2 present the a-N curve of overloaded tensile specimens for X70 and X80 steel.

So the Paris equation will be

$$da/dN = C_p C\left(\Delta K\right)^n \tag{4}$$

where Cp is less then 1.

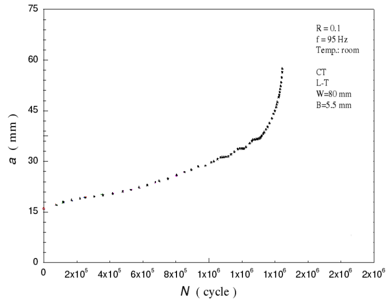

Figure 1: a-N curve of overloaded tensile sample for X70

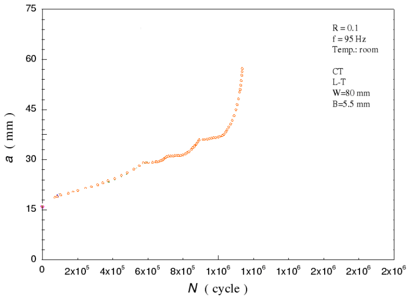

Figure 2: a-N curve of overloaded tensile sample for X80

Pressure Reversals Caused by Hydrostatic Testing. Flaws in pipelines extend inevitably during the testing course， so the depths of cracks increase to a1 from the original a0. The increase depends on the pipe material properties, original severity of the cracks and testing pressure level. The growth of depths of flaws reduces the ability of pipe to bear maximum pressure and this phenomenon is called pressure reversal.

The equivalent penetrative crack length is

$$a_{eg0} = \frac{1.211a_0}{1 + 1.55(a_0/b_0)^{1.7}} \tag{5}$$

When hydrostatic test completes, the equivalent penetrative crack length a_{eg1} can be calculated in according to the COD theory,

$$\int_{aeg_0}^{aeg_1} \frac{da}{C(\Delta K)^n} = 1 \tag{6}$$

Correspondingly, the limit load the pipe can bear is

$$P = \frac{2\bar{\sigma}t}{\pi MR}\arccos\left[\exp\left(-\frac{\delta_c E\pi}{B\bar{\sigma}a_{eg}}\right)\right] \tag{7}$$

Where: $\bar{\sigma} = \sigma_s + (\sigma_b - \sigma_s)/4$;E denotes tensile elastic modulus of pipe material; δ_c denotes critical value of crack top open displacement.

So we can work out P_0 and P_1, which respectively represent the maximum pressure the pipe can bear before and after hydrostatic test. So the pressure reversal is

$$\Delta P = P_0 - P_1 \tag{8}$$

Table 1: Pressure reversals caused by testing for pipes with different sizes of cracks

b_0/a_0	a_0	b_0	a_{eq0}	a_{eq1}	P_0(MPa)	P_1(MPa)	%
8	0.1	0.4	0.0	0.0	14.12	14.12	0.00
	1.0	8.4	0.7	0.7	14.12	14.12	0.00
	2.0	16.3	2.6	2.6	14.07	14.07	0.00
	3.0	24.3	5.8	5.8	13.37	13.36	0.02
	4.0	32.2	10.2	10.2	11.78	11.77	0.06
	5.0	40.2	15.9	15.9	9.97	9.96	0.13
	6.0	48.2	22.8	22.8	8.25	8.23	0.26
	7.0	56.1	30.9	30.9	6.71	6.68	0.50
	8.0	64.1	40.3	40.3	5.40	5.34	0.96
	9.0	72.0	50.9	50.9	4.31	4.23	1.81
	10.0	80.0	62.8	62.8	3.43	3.32	3.34
16	0.1	0.8	0.0	0.0	14.12	14.12	0.00
	1.0	16.7	1.4	1.4	14.11	14.11	0.00
	2.0	32.6	5.2	5.2	13.51	13.51	0.02
	3.0	48.6	11.6	11.6	11.31	11.30	0.08
	4.0	64.5	20.4	20.5	8.79	8.77	0.21
	5.0	80.4	31.7	31.9	6.58	6.55	0.53
	6.0	96.3	45.5	46.1	4.82	4.75	1.32
	7.0	112.2	61.8	63.6	3.50	3.38	3.19
	8.0	128.2	80.6	85.5	2.55	2.37	7.17
	9.0	144.1	101.8	114.7	1.80	1.61	14.66
	10.0	160.0	125.6	157.0	1.42	1.04	26.71

Table 1 shows pressure reversals of 27-inch OD X60 pipe after hydrostatic testing to 90 percent of SMYS. We can see that the smaller cracks lead to very “light” pressure reversals, while large cracks sizes, especially large surface size will cause more severe pressure reversals. However, for new pipeline materials made to adequate specifications with adequate inspection and pipe-mill testing, it contains almost no large cracks. We can say pressure reversals are not serious problems and it’s no need to take much consideration to this problem.

The Effects of Testing Pressure on Cracks Life. According to above analysis, pressure testing reduces the extension velocity, but at the same time it make cracks sizes increase and resultantly lead to pressure reversals. So the cracks life is made up of two parts, one is the life cracks getting through large plastic area, the other is the life from getting through the large plastic area to penetrating pipe wall.

$$N=\int_{a_1}^{a_c}\frac{da}{C(\Delta K)^n}$$
$$=\int_{a_1}^{a_1+a^*}\frac{da}{C_pC\left[\frac{1.1M\sigma_{\max}\sqrt{\pi a}}{\sqrt{Q}}\right]^n}+\int_{a_1+a^*}^{a_c}\frac{da}{C\left[\frac{1.1M\sigma_{\max}\sqrt{\pi a}}{\sqrt{Q}}\right]^n} \quad (9)$$

Fig. 3 and Fig. 4 present the fatigue life of pipes with smaller cracks and larger cracks respectively after pressure testing. Steel pipes used in the experiments are 40-inch OD by 0.69inch w.t. X70 pipes.

As shown in Fig. 3 and Fig. 4, the deeper the defects, the shorter the fatigue life of pipes. If the cracks are not very severe(a/t≤1/5), fatigue life of pipe depends on the crack depth , wall thickness of pipe and fatigue load level $\Delta\sigma$. However, the remaining work life of pipes will always increase with the boost of stress level of pressure testing. When cracks get deeper (a/t≥1/5), at certain testing pressure level, crack life will reduce as the impact of pressure reversal is greater than the impact of large plastic area on crack extension velocity.

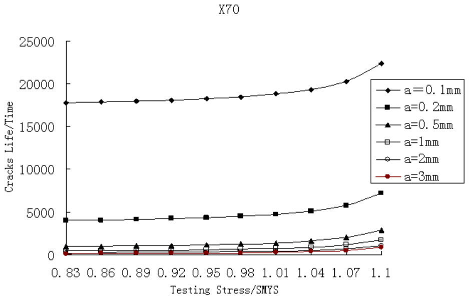

Figure 3 : Impact of test pressure level on cracks life for smaller cracks

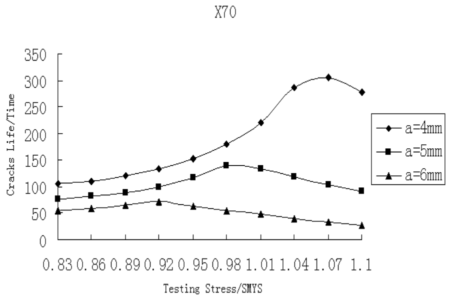

Figure 4: Impact of test pressure level on cracks life for larger cracks

Impact of Loading Status on Testing Pressure. Loading status of buried pipeline, of which we simply consider circumferential stress and longitudinal stress, can be regarded as two dimensional planar stress. Mises yielding equation is usually be used to calculate the value of yield stress. In accordance with Mises yielding condition, parts of an object yield when yielding energy corresponding to stress status of that part is up to a certain value.

The Mises yielding equation for two dimensional stress status is as follows.

$$\sigma_1^2-\sigma_1\sigma_2+\sigma_2^2=\sigma_s^2 \quad (10)$$

Plotted in X-Y coordinates, this equation exhibits a ellipse as shown in figure 5. In which, $\sigma_L=\sigma_1$, $\sigma_c=\sigma_2$, $\sigma_0=\sigma_s$.

Stress points inside the ellipse means materials keeping elastic status. If stress points are on or outside the ellipse, materials become plastic. As shown in this figure, longitudinal tensile stress can on a certain extent enhance the yield strength. For buried pipeline, $\sigma_L=0.3\sigma_C$, the ratio of the yield strength of pipeline to the yield strength of pipe material is 1.11.

According to these analysis, when circumferential stress is up to 110% of SMYS, pipeline starts to yield with loop deformation of 0.5%. That means high pressure testing can not lead to large deformations.

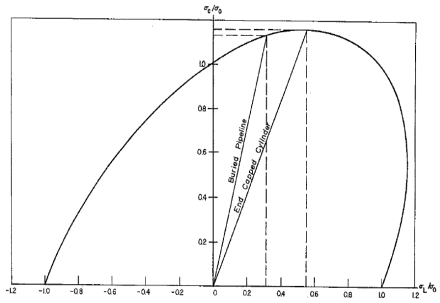

Figure 5: Explanation for higher yield strength with biaxial tensile stress

Experimental Validation

In order to validate theoretic results, we select X60, X70 and X80 pipe to perform hydrostatic testing. The procedure of testing is: ①fill the pipe with water; ② pressurize to 95% of SMYS； ③keep this pressure for 24 hours;④measure the strains of the selected locations; ⑤ depressurize and drain; ⑥ measure the strains of the selected locations;⑦ fill the pipe, pressure to 100% of SMYS, and repeat the same procedure;⑧fill the pipe, pressure to 110% of SMYS, and repeat the same procedure.⑨fill the pipe with water and keep pressurizing until pipes burst.

Through experiments we found that the diameters and wall thicknesses of steel pipe have no changes after the testing. Results show no plastic deformation. Pipes likely yield until testing pressure gets up to 120% of SMYS.

Conclusions

As mentioned above, the higher the ratio of test pressure to operating pressure, the more confidence one can have in the serviceability of a pipeline. Therefore, there is no reason not to test a pipeline to appropriate higher levels. But it is controversial about what is the highest possible level that can be feasibly be done without creating harmful yielding of pipe materials. This paper shows the results of theoretic analysis we made using rupture mechanics theories. These results are validated by experiments we have done.

Following is main conclusions of the paper:

- High testing pressure creates a plastic area around cracks top. This plastic area would prevent the cracks from growing. So high testing pressure reduces the growing velocity of cracks.
- Pressure reversals caused by high pressure testing is very “light” for small defects. It is reasonable to neglect the effects of pressure reversals when determining the maximum testing pressure for well-inspected new pipelines.
- The remaining work life of new pipeline containing cracks not deeper than 20 percent of wall thickness is longer with the boost of testing pressure.
- For buried pipelines, testing to 110 percent of SMYS will not cause serious plastic deformation.
- Experiments found pipes keep elastic when tested to 110 percent of SMYS and may yield until testing stress gets to 120 percent of SMYS.

In summary, for new pipeline materials made to adequate specifications with adequate inspection and pipe-mill testing, one does not expect test failures even at pressure levels corresponding to 110 percent or more of SMYS. Test stress level of 110 percent of SMYS is safe for new-constructed pipeline.

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