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# Failure Pressure Analysis of Corroded Pipelines with Spherical Corrosion Pit

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**Abstract**

In this paper, failure pressures of corroded pipeline with single-point and double-point spherical corrosion pits were investigated by finite element method. Effects of internal pressure, radius, depth and spacing of corrosion pits on failure pressure of corroded pipeline were discussed. The results show that failure pressure of corroded pipeline with spherical corrosion pit obtained by FEM is bigger than by ASME B31G. The maximum von Mises stress appears on the bottom of the single-point corrosion pit along pipeline axis direction. While the maximum stress appears on the inside of the double-point corrosion pit first. The minimum stress appears on the ends along ring direction of the pipeline. Failure pressure of corroded pipeline with double-point corrosion pit is smaller than the single-point. Failure pressure of the corroded pipeline decreases with corrosion pit depth increases, but increases with the increasing of the spacing and wall thickness. With the increasing of the radius of corrosion pit, failure pressure of corroded pipeline with single-point corrosion pit decreases, while it increases for double-point corrosion pit.

**Keywords** corroded pipeline, failure pressure, spherical corrosion pit, numerical simulation, von Mises stress

## 1. Introduction

Pipelines have been widely concerned as the main transportation of water, oil and gas. Corrosion is one of the most important failure modes of buried pipelines [1], because they have to cross the complex topography and transport a variety of medias. Electrochemical corrosion is the main reason for pipeline corrosion. Under the action of geological, soil and high pressure medium, corrosion pits appear on both inner and outer walls of the pipeline. With the perforation of these corrosion pits or crack propagation, rupture accidents may occur. Leak accidents of oil and gas not only cause a large number of casualties accidents, but also result in economic loss and environmental pollution [1]. Global or local thinning of the wall thickness would reduce the static and dynamic strength of pipeline after pipeline corrosion. In July 2011, crude oil pipeline explosion of Dalian international transportation corporation caused widespread fire and a large number of oil spill, meanwhile a lot

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of pipeline equipment was damaged and the sea was polluted [2]. In November 2013, rupture accident of Huang-Wei pipeline happened, which caused a large number of oil leakage, and the oil spilled into the rainwater pipeline. And roads and motor vehicles were dynamited in this accident. Therefore, it is very important to study the residual strength of pipeline for its safety evaluation and operation.

ASME-B31G was used to calculate the failure pressure of corroded pipeline by American society of mechanical engineers in the 1970s [3]. DNV RP-F101 was put forward to assess corroded pipeline by DNY and BG based on full-scale experiment and finite element analysis at the beginning of the 21st century [4]. According to the blasting experiment and numerical simulation, a computational formula of failure pressure was proposed by Choi. This computational formula is suitable for X65 pipeline [5]. Based on MB13G method, EPA method was proposed by Freire according to blasting limit experiment [6]. Recent years, Chen studied the interaction relationship for submarine pipeline with axial corrosion defects [7]. Shuai predicted failure pressure of corroded pipeline by finite element method, and fitted a prediction formula [8]. But the discussion of effects of multi-point corrosion pits on failure pressure is very little.

In this paper, von Mises stress and plastic strain of corroded pipelines with a single and double-point spherical corrosion pits were investigated based on FEM, and effects of the internal pressure, depth, radius and spacing of corrosion pits on failure pressure were discussed. These results can be used for the pipeline safety evaluation, residual lifetime prediction and residual strength analysis.

## 2. Failure criteria of pipeline

Material hardening has a great effect on the blasting failure of the pipeline. So, in order to reflect the hardening properties after material yield, Ramberg-Osgood stress-strain rule was used in this model [8].

$$\frac{\varepsilon}{\varepsilon_0} = \frac{\sigma}{\sigma_s} + \alpha\left(\frac{\sigma}{\sigma_s}\right)^n \tag{1}$$

Where, $\varepsilon_0$ is initial strain, $\varepsilon_0 = \sigma_s / E$ . $\sigma_s$ is yield stress, MPa. $E$ is elasticity modulus, MPa. $\alpha$ is the hardening coefficient. $n$ is power hardening exponent.

There are three kinds of failure criteria for the numerical simulation of corroded pipeline. The first one is the elastic limit criterion [9]. The pipeline is prone to failure if von Mises stress of corrosion area is bigger than the yield stress of the material. The second one is the failure criterion based on plastic limit state [10]. Failure of corroded pipeline can be determined by hoop stress of corrosion area. When the hoop stress reaches the tensile strength, pipeline failure occurs. The third one is plastic failure criterion [11]. When the minimum equivalent stress is bigger than the ensile strength, failure occurs. In this paper, the reason why the elastic limit criterion is replaced by plastic failure criterion is its conservative, and von Mises stress is regarded as the minimum equivalent stress [12].

$$\sigma_v = \left\{ \frac{1}{2}\left[ (\sigma_1 - \sigma_2)^2 + (\sigma_1 - \sigma_2)^2 + (\sigma_1 - \sigma_2)^2 \right] \right\}^{\frac{1}{2}} < [\sigma] \tag{2}$$

Where, $\sigma_v$ is von Mises stress, MPa. $[\sigma]$ is the allowable stress, MPa.

According to ASME B31G-2009 [13], the failure pressure is:

$$P_f = \frac{2t}{D}\bar{\sigma}\left( \frac{1 - 0.85\frac{d}{t}}{1 - 0.85\frac{d}{t}\cdot\frac{1}{M}} \right) \tag{3}$$

Where, $P_f$ is failure pressure of the pipeline, MPa. $D$ is outer diameter of the pipeline, mm. $t$ is wall thickness of the pipeline, mm. $d$ is the depth of the corrosion pit, mm. $M$ is Folias expansion coefficient. $\bar{\sigma}$ is the flow stress, MPa.

$$\bar{\sigma} = \sigma_s + 68.95 \tag{4}$$

$$M = \sqrt{1 + 0.6275\left(\frac{l}{\sqrt{Dt}}\right)^2 - 0.00337\left(\frac{l}{\sqrt{Dt}}\right)^4}, \frac{l^2}{Dt} \le 50 \tag{5}$$

$$M = 0.032\frac{l^2}{Dt} + 3.3, \frac{l^2}{Dt} > 50 \tag{6}$$

Where, $\sigma_s$ is yield strength of the pipeline, MPa. $l$ is the length of the corrosion pit, mm.

## 3. Numerical simulation model

An advanced general purpose finite element program ABAQUS is employed to simulate the mechanical behavior of buried pipeline under internal pressure. In this paper, spherical corrosion pits are considered. Finite element model of 1/4 pipeline was established for the symmetry of structure and load. As shown in Fig.1, eight-node solid elements are employed to model the pipeline. High-density meshes were used near the corrosion pits. Diameter of the pipeline is 324 mm, wall thickness of the pipeline is 10.6 mm. In order to eliminate the edge effect, length of the pipeline is 3 times the diameter.

A linear isotropic strain hardening model has been considered in the plasticity model of the steel pipeline material. This model has been used with a von Mises yield surface criterion [14]. Numerical results are obtained for X65 steel pipeline. Yield stress is 448.5MPa, tensile strength is 531 MPa, Young's modulus is 206 GPa, Poisson's ratio is 0.3, density is 7800kg/m$^3$ [14]. The end of the pipeline was fixed along z direction. The two symmetry planes were imposed symmetry constraints along x, z directions respectively. Internal pressure was applied on the internal wall of the pipeline.

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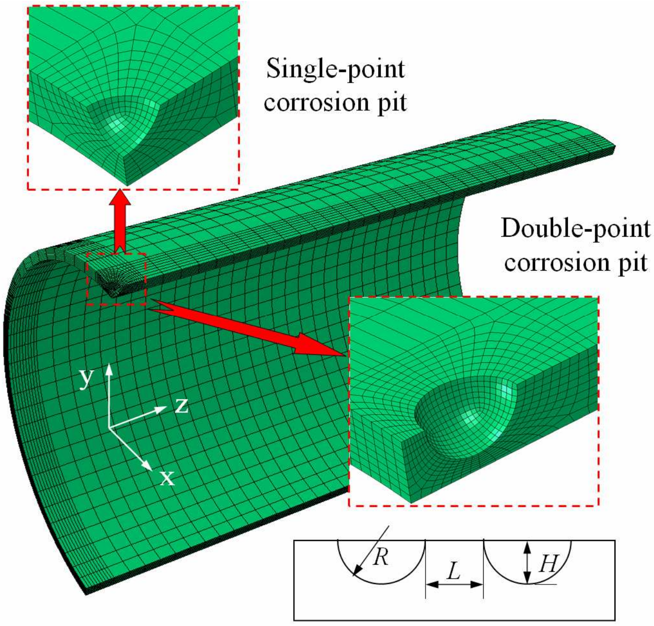


**Figure 1.** Finite element model of spherical corrosion pit

## 4. Results and discussions

### 4.1 Model validation

In order to verify the reliability of the established finite element model for corroded pipeline, the failure pressure of corroded pipeline was calculated by numerical simulation and ASME B31G. Table 1 shows the failure pressures of the pipeline with a single-point corrosion pit by the two methods. When the diameter of corrosion pit is 16mm, depth is 8mm, the failure pressures of corroded pipeline with spherical corrosion pit obtained by FEM and ASME B31G are 33.95 MPa and 32.5 MPa, the error is only 4.33%. When the radius of the corrosion pit is 10 mm and 12 mm, the errors are only 1.79% and 0.38%. It means that the finite element method in this paper is reliable, and it can be used to predict the failure pressure of corroded pipeline. The failure pressure of corroded pipeline with spherical corrosion pit obtained by FEM is bigger than by ASME B31G.

**Table 1.** Failure pressures of pipeline by FEM and ASME B31G (Unit, MPa)

| Wall thickness(mm) | Radius(mm) | Depth(mm) | FEM | ASME31G | Error (%) |
|---|---|---|---|---|---|
| 10.6 | 8 | 8 | 33.95 | 32.54 | 4.33 |
| 12.2 | 8 | 8 | 43.40 | 38.02 | 14.15 |
| 8.5 | 8 | 8 | 21.89 | 24.42 | -10.36 |
| 10.6 | 8 | 6 | 39.76 | 33.16 | 19.90 |
| 10.6 | 8 | 7 | 36.88 | 32.91 | 12.06 |
| 10.6 | 10 | 8 | 32.45 | 31.88 | 1.79 |
| 10.6 | 12 | 8 | 31.26 | 31.14 | 0.38 |

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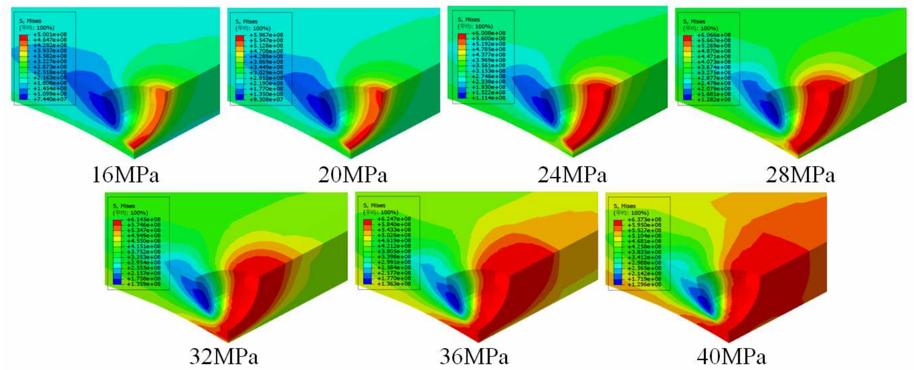
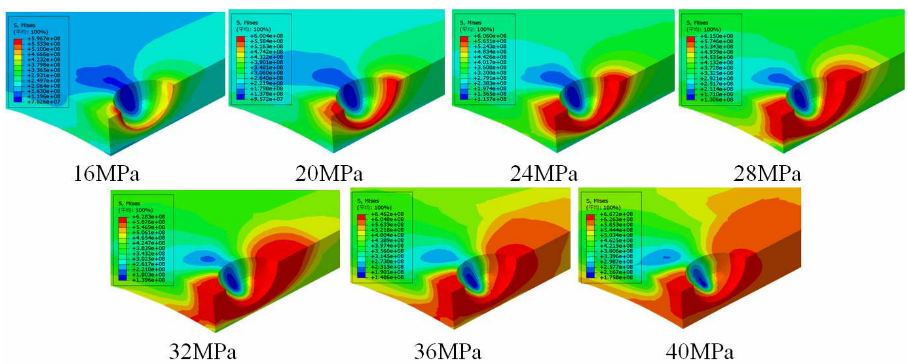
However, ASME B31G can only be used to predict the failure pressure of corroded pipeline with some kinds of corrosion pits, but not suitable for all spherical corrosion pits. For example, When the radius of the corrosion pit is 8 mm, depth is 6mm, the failure pressures of corroded pipeline with spherical corrosion pit obtained by FEM and ASME B31G are 39.76 MPa and 33.16 MPa, the error is 19.9%. And when the wall thickness of the corrosion pit is 12.2 mm, the error is 14.15%. So, ASME B31G can't be used in all conditions of spherical corrosion pit. In Table 1, wall thickness, diameter and depth of corrosion pit have a great effect on the failure pressure of corroded pipeline.

### 4.2 Stress and strain

When the radius of the corrosion pit is 8 mm, depth is 8 mm, von Mises stress distributions around the pit under different internal pressure are shown in Fig.2. The maximum stress appears on the bottom of the single-point corrosion pit along pipeline axis direction. While the maximum stress appears on the inside of the double-point corrosion pit first. The minimum stress appears on the ends along pipeline ring direction. Von Mises stress increases with the increasing of internal pressure. When the stress is bigger than the yield limit, stress of the whole pipeline increases rapidly. Then pipeline explosion occurs when the internal pressure is bigger than failure pressure. Under the same internal pressure, the maximum von Mises stress and high stress area of corroded pipeline with double-point corrosion pit are bigger than single-point corrosion pit. Therefore, corroded pipeline with double-point corrosion pit is prone to failure than single-point corrosion pit.




(a) Single-point corrosion pit



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(b) Double-point corrosion pit

**Figure 2** Von Mises stress distribution around the pit under different pressures

Plastic strain distributions around the pit under different pressures are shown in Fig.3. When the internal pressure is 16 MPa, there is on plastic strain for single-point corrosion pit. The maximum plastic strain of single-point corrosion pit appears on the bottom of the pit, while the maximum plastic strain of double-point corrosion pit appears on the inside of the pit. Under the same pressure, the maximum plastic strain of single-point corrosion pit is smaller than the double-point corrosion pit. Plastic area increases with the increasing of internal pressure.

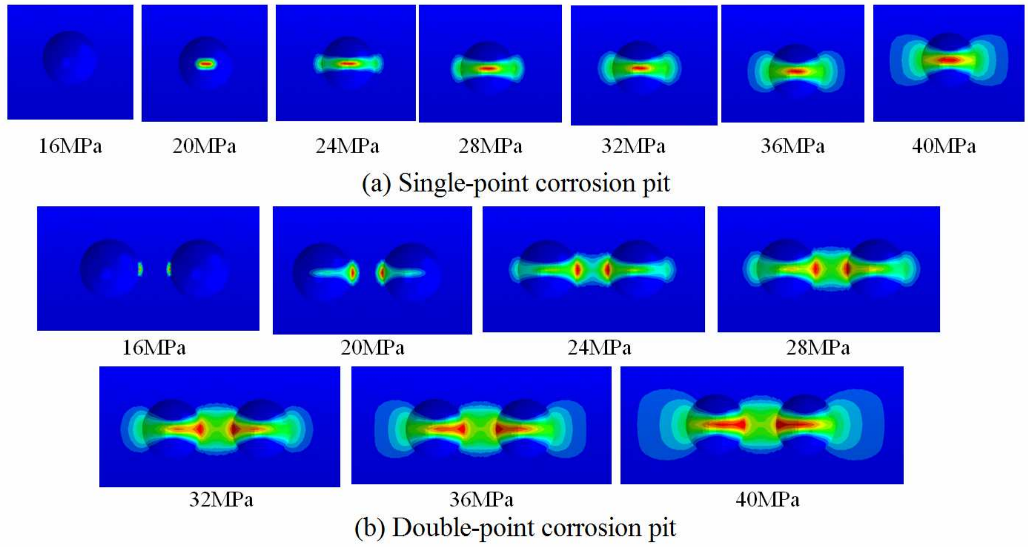


**Figure 3** Plastic strain distribution around the pit under different pressures

### 4.3 Depth of the corrosion pit

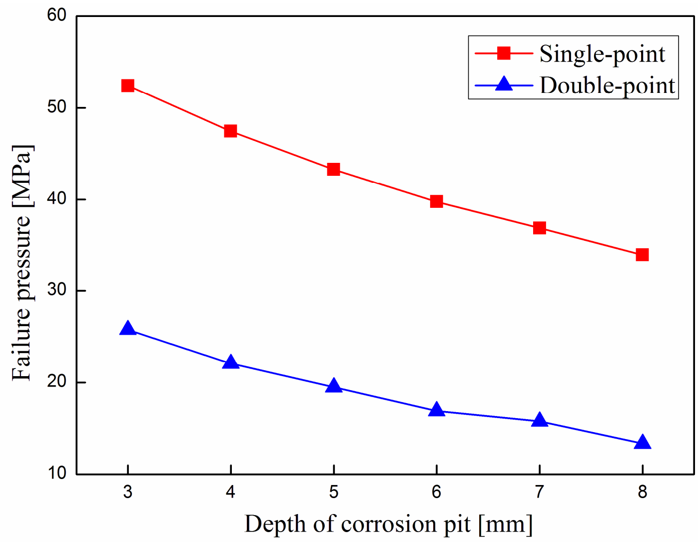


**Figure 4** Failure pressure of corroded pipeline under different corrosion pit depths

When the radius of the corrosion pit is 8 mm, Fig.5 shows failure pressures of corroded pipeline with single-point and double-point corrosion pits under different pit depths. Failure pressure of corroded pipeline decreases with the increasing of corrosion pit depth with nonlinear rule. When the corrosion pit depth is smaller, the failure pressure difference between single-point corrosion pit and double-point corrosion pit is bigger. But it decreases with the increasing of corrosion pit depth. For the same pit depth, failure pressure of single-point corrosion pit is over twice as double-point corrosion pit. Therefore, calculation model of single-point corrosion pit is not suitable for the actual conditions.

### 4.4 Radius of the corrosion pit

When depth of corrosion pit is 6mm, failure pressures of corroded pipeline under different pit radiuses are shown in Fig.5. With the increasing of radius of the corrosion pit, failure pressure of the corroded pipeline with single-point corrosion pit decreases, while it increases for the corroded pipeline with double-point corrosion pit. The failure pressure difference between single-point corrosion pit and double-point corrosion pit decreases with pit radius increases. When the radius of the corrosion pit is more than 14 mm, the change rates of the two curves is small. It means that failure pressure of corroded pipeline will not change when the radius of spherical corrosion pit exceeds the critical value.

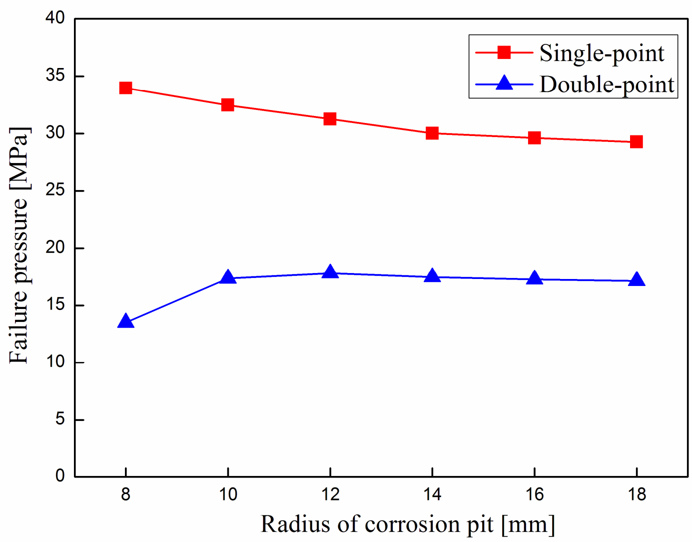


**Figure 5** Failure pressure of corroded pipeline under different pit radiuses

### 4.5 Wall thickness of the pipeline

Wall thickness of the pipeline has a great effect on its failure pressure. If the depth of corrosion pit is bigger than the wall thickness, pipeline leak occurs. When radius of the corrosion pit is 8 mm, depth is 8 mm, failure pressures of corroded pipeline under different wall thicknesses are shown in Fig.6. With the increasing of wall thickness, failure pressure of corroded pipeline increases. The failure pressure difference between single-point corrosion pit and double-point corrosion pit increases with wall thickness increases. The change rate of failure pressure of single-point corrosion pit is bigger than the double-point corrosion pit. Therefore, thick wall pipeline should be used in severely corrosive environment.

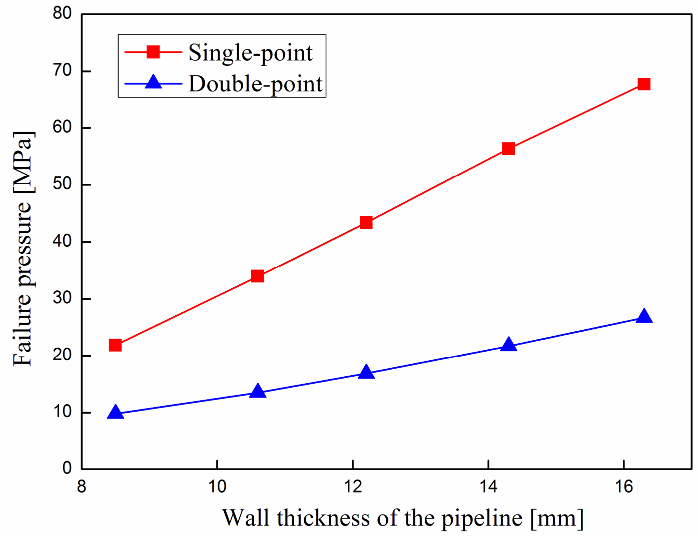


**Figure 6** Failure pressure of corroded pipeline under different wall thicknesses

### 4.6 Spacing of corrosion pits

Failure pressures of corroded pipeline with double-point corrosion pit under different spacing are shown in Fig.8. With the increasing of the spacing, failure pressure of corroded pipeline increases gradually, but the change rate decreases. Failure pressure of the corroded pipeline changes small when the spacing is more than 20 mm. So, effect of the interaction between corrosion pits on failure pressure decreases with the spacing increases. Intensive corrosion pit distribution could increase the pipeline failure probability.

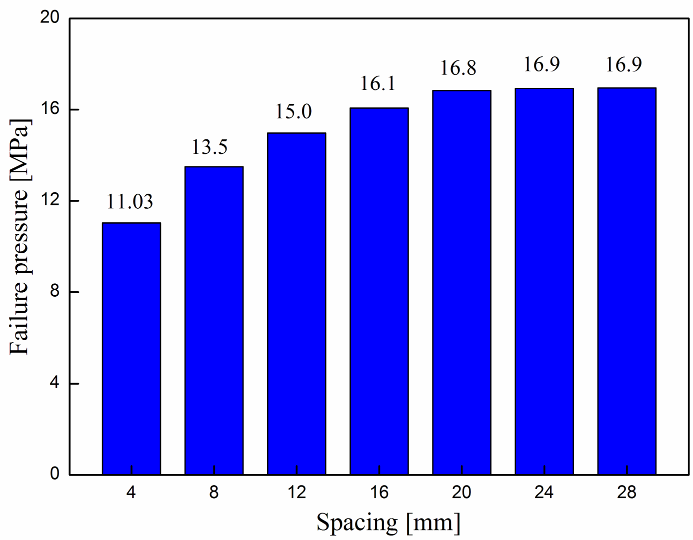


**Figure 7** Failure pressure of corroded pipeline with double corrosion pit under different spacing

## 5. Conclusions

(1) Failure pressure of the corroded pipeline with spherical corrosion pit obtained by FEM is bigger than by ASME B31G. The maximum stress appears on the bottom of the single-point corrosion pit along pipeline axis direction. While the maximum stress appears on the inside of the double-point corrosion pit first. The minimum stress appears on the ends along ring direction of the pipeline. Von Mises stress and plastic strain increase with the increasing of internal pressure. Under the same pressure, the maximum plastic strain and von Mises stress of single-point corrosion pit are smaller than the double-point corrosion pit.

(2) Failure pressure of corroded pipeline with double-point corrosion pit is smaller than the single-point. Failure pressure of corroded pipeline with spherical corrosion pit decreases with the corrosion pit depth increases, but is increases with the wall thickness increases. With the increasing of radius of the corrosion pit, failure pressure of the corroded pipeline with single-point corrosion pit decreases, while it increases for double-point corrosion pit. Failure pressure of corroded pipeline increases gradually with the increasing of the spacing, but it changes small when the spacing is more than 20 mm.

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