Proceedings of IPC2008
7th International Pipeline Conference
September 29-October 3, 2008, Calgary, Alberta, Canada

IPC2008-64059

PRELIMINARY FAILURE ASSESSMENT FOR SPIRAL WELDED DEFECTS OF PIPELINE

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ABSTRACT

The spiral welded defect of steel oil transmission pipeline is one of the main causes resulting in pipeline leakage accident. Hence the failure assessment for known-size spiral welded defects is an important step to ensure the safety of defected pipeline. Lack of suitable criterion for assessing the spiral welded manufacture defects of pipeline network in China, is a difficult technology problem to be solved desirably. This paper first summarized the basic idea of preliminary failure assessment (Grade 1A of code BS 7910:2005) with some insight of our own understanding, and then applied the preliminary failure assessment to the spiral welded defects of oil pipeline, with the use of ultrasonic inspection data of Daqing-Tieling old pipeline from LingYuan to XinMiao, Northeastern China. The calculation of both fracture and plastic collapse failure for spiral welded defects indicates some detected flaws of pipeline are not safe as the internal pressure is greater than 4.5 MPa. A leakage accident of spiral welded pipeline in Western China is also assessed through fractography analyses and failure calculations. This paper concludes that the preliminary failure assessment provides useful outcome for reference in making decision of inspection, integrity assessment and repair of spiral welded pipeline, and hence is a step of fundamental importance and practical significance before more accurate data becomes available for higher grade assessment.

KEY WORDS

pipeline, integrity, spiral weld, defect, fracture, failure assessment

INTRODUCTION

There exist a large number of manufacture defects in the oil pipeline of Northeastern China due to technology limitation at the time of being built in 1970s. The statistics of pipeline leakage accidents has shown that the spiral and girth welded flaws in steel pipelines are the main causes of pipeline failure [1,2]. The most serious weld flaws are found to be lack of penetration and lack of fusion, which resulted in crack initiation after about 30 years operation. Ensuring the fitness for purpose of the pipelines with defects of lack of penetration or fusion is an urgent technical problem to be solved by suitable methods of engineering critical assessment.

This paper first introduced the basic idea of preliminary engineering critical assessment with some insight of our own understanding, and then conducted the assessment to the spiral welded defects of steel pipeline, applying the relevant regulations described in British standard *BS 7910* :2005 [3,4] to the ultrasonic inspection data of Daqing-Tieling old pipeline from LingYuan to XinMiao, Northeastern China. A leakage accident of spiral welded pipeline in Western China is also assessed through fractography analyses and failure calculations.

PRINCIPLE AND METHOD FOR ENGINEERING CRITICAL ASSESSMENT

1. Defect classification and assessment grade

The mechanical descriptions of pipeline welded defects may be divided into three types：geometry imperfection resulting in stress concentration, planar defect resulting in fracture failure of crack, and non-planar defect resulting in plastic collapse of ligament. The defects found in the spiral welds of China pipelines are mostly of combined types and thus need to be identified and considered respectively. However, it is conservative to assess the fracture behavior of volume defect like pore or inclusion as a planar defect.

BS 7910: 2005 code divides the defect fracture assessment into three grades (levels). Grade 1 is a simplified route assessment with two sub-grades of 1A and 1B. The conservative estimation is generally applied to material behavior, residual stress and applied stress, etc.. Grade 2 is a generally applied normal assessing route with two sub-grades of 2A and 2B. Grade 2A and Grade 2B have their FAD independent and dependent of the specific stress-strain relation of assessed material respectively. The more accurate grade 3 assessment is composed of three sub-grades of 3A, 3B and 3C, and generally involves effective numerical computation applying to ductile material with stable tearing behavior.

Grade 1 assessment is generally the first step to assess a defect and the assessment may be considered complete if the safety of a defect under operation pressure or design pressure can be concluded by using conservatively estimated data. More advanced assessment is not only a method improvement, but also an increase of accuracy in all aspects, including stress calculation, residual stress estimation and material property measurement, etc., which means a large amount of additional work and time delay. Consequently, a preliminary assessment of defect is believed to be significant. A preliminary assessment needs no multiple partial safety factors and may make reference to relevant cases if no specific data available, for example, fracture toughness data may be deduced from Charpy V-notch impact energy, etc..

2. Failure assessment diagram (FAD) based on fracture mechanics

Grade 1A assessment concerns with two failure modes of pipeline defects: the plastic collapse failure of remaining ligament and the fracture failure of crack, which are quantified by σ_{ref} , the reference (local) stress applied on the ligament of assessed defect, and K_I , the stress intensity factor of mode-I for defect opening fracture. The FAD of Grade 1A assessment as shown in Figs.3-5 has two non-dimensional variables

$$S_r = \sigma_{ref} / \sigma_f \, , K_r = K_I / K_{mat} \, , \qquad \text{(1a,b)}$$

as horizontal and vertical coordinates respectively, where the material flow strength σ_f is taken to be the average of yield strength and ultimate strength for considering the material work hardening effect, and it should not be greater than the value of yield strength multiplied by *1.2.* Material fracture toughness K_{mat} may take the effectively measured value of linear elastic plane strain fracture toughness, K_{IC} , if available. It is allowed for Grade 1A assessment to derive K_{mat} from Charpy V-notch impact energy on the lower shelf and in the transition region, C_V (in Joules), by the lower bound correlation given in BS7910: $K_{Ic} = (820 \cdot \sqrt{C_V} - 1420) / B^{1/4} + 630 \ (N / mm^{3/2})$ with thickness *B* in *mm*. An empirical formula $K_{Ic} = 8.47 \cdot C_V^{\ 0.63} \quad (MPa\sqrt{m})$ may be found in API 579 code, and K_{mat} may also be obtained from the critical J integral, J_{mat} via $K_{mat}^2 = EJ_{mat}/(1-\nu^2)$.

The Grade 1A assessment lines of $S_r = 0.8$ and $K_r = 1/\sqrt{2} \approx 0.707$ define for all materials an acceptable region, indicating a defect with its assessing point (S_r, K_r) inside is safe. The FAD has included an inherent safety factor, which approximately doubles the crack length resulting in a factor of $\sqrt{2}$ owing to the linear relation between K_I and the square root of crack length.

FAILURE ASSESSMENT FOR SPIRAL WELDED DEFECTS

For a pipeline subject to internal pressure only, the maximum principle stress $\sigma_{\max}$ is the circumferential tension stress σ_θ, which is a membrane stress of thin pipeline given by

$$\sigma_{\max} = \sigma_\theta = P \cdot D/(2B), \tag{2a}$$

where P is internal pressure ($MPa = N/mm^2$), D pipeline diameter (mm), B pipeline thickness (mm). The bending stress, for example caused by geometry imperfections of welded joints, the other secondary stresses and the influence of possible stress concentration are neglected in this preliminary assessment.

A spiral welded defect has its plane generally not parallel to the principle planes, which are the planes normal to pipeline axial, circumferential and radial directions respectively. The preliminary assessing method suggested by BS7910 code is to project a spiral defect in length of $2c'$ onto the principle plane of maximum (circumferential) stress, being an axial defect in length of $2c$ given by

$$2c = 2c' \cdot \cos\alpha, \tag{2b}$$

where α is the angle between spiral and axial directions of pipelines. However, the spiral welded defects studied in this paper do not satisfy rigorously one of the conditions imposed by the code of BS7910 for the projecting method to be applicable, i.e., the angle α should not be grater than about 20°, however, in our applications, α is equal to 45° or 60°. A more conservative alternative is to rotate the spiral defect to axial direction of pipeline.

The failure mode of plastic collapse of defects is to assess the stress rise or magnification in the remaining ligament of pipeline section weakened by axial surface defects and embedded defects as shown in Figs.1 and 2. The bulge effect due to the existence of an axial defect of pipeline also causes additional deformation and stress magnification. The maximum sum of all stresses possibly causing plastic collapse of pipeline is the reference stress σ_{ref} for defect assessment. Refer to Annex P of BS7910: 2005 for reference stress formulas of various axial defects.

The fracture failure mode of defects needs to calculate the stress intensity factor of mode-I, K_I, by

$$K_I = (Y\sigma)\sqrt{(\pi a)}, \tag{3a}$$

where for Grade 1 assessment,

$$Y\sigma = M \cdot f_w \cdot M_m \cdot \sigma_{\max}. \tag{3b}$$

in which $\sigma_{\max}$ is the maximum tension stress loading a crack, and M, f_w and M_m are the correction factors. (3a,b) with $M = f_w = M_m = 1$ is the formula for an infinite plate containing a central crack of length $2a$ with the acting remote field stress $\sigma_{\max}$ being normal to the crack.

The correction factor of bulge effect M is to consider the local convex deformation of shell surface with a long crack under internal pressure. For an axial surface crack of pipeline under internal pressure (depth a, length $2c$, in Fig.1), M is written as

$$M = \frac{1-(a/B)/M_T}{1-(a/B)}, \tag{4a}$$

where Folias factor is defined by

$$M_T = \sqrt{1+1.6c^2/(rB)}, \tag{4b}$$

with r and B being average radius and thickness of pipe respectively. The stress magnification correction factor of type (4a,b) is similar to the counterpart of corrosion defects in ASME B31G code. For embedded defects and circumferential defects of pipeline, the bulge effect is generally not considered, hence,

$$M = 1 \qquad (4c)$$

for embedded and circumferential defects.

The correction factor of finite width f_w is to count for the influence of free surfaces of pipeline, if a defect area is greater than *10%* of the loading section of pipeline. Refer to Annex *M* of *BS 7910* code or the manuals of stress intensity factor for f_w of defects with determined configuration. The formula for defects with undetermined configuration is:

$$f_w = \sqrt{\sec(\frac{\pi A_1}{2A_2})}, \qquad (4d)$$

with $A_2 = BW$ being section area and A_1 the approximate rectangular area of defect. $A_1 = 2ac$ (height a, length $2c$) for surface defects and $A_1 = 4ac$ (height $2a$, length $2c$) for embedded defects. The section width W is not clearly defined in the code, and the minimum distance between neighboring defects might be taken. A large value of W may result in a small correction ($f_w \approx 1$). A maximum W for calculating reference stress (as seen in (5b)) is taken to be $2c + 2B$.

The stress intensity magnification factor M_m is determined by the extent of crack type and configuration deviated from that of infinite plate with central crack, and reference can be made to annex *M* of *BS 7910* code and the manuals of stress intensity factor.

STRESS INTENSITY FACTOR AND REFERENCE STRESS OF AXIAL DEFECTS

With $\sigma_{\max}$ calculated by (2a) and the axial length of projected defect by (2b), K_I is determined from (3a,b) with properly chosen correction factors. Then the following calculation of σ_{ref} for various axial defects yields the coordinate point of (S_r, K_r) in *FAD* from (1a,b) to assess defect safety.

1. Axial surface defect of pipeline

Fig.1 shows an axial defect on internal surface of pipeline, and the corresponding figure of external surface defect may be obtained by moving and rotating the defect so that the flat edge of semi-ellipse is on the external surface. The reference stress for both surface defects is

$$\sigma_{ref} = 1.2 M_s P_m + \frac{2P_b}{3(1-a'')^2}. \qquad (5a)$$

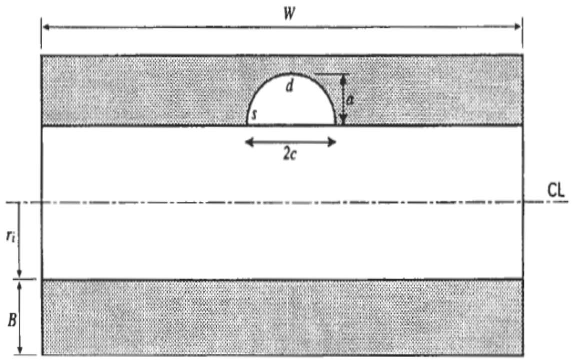

Fig.1 Axial defect on internal surface

The first term on the right side of (5a) is due to the membrane stress P_m and the factor of 1.2 is to bring the level of conservatism of pipeline equal to flat plate. The stress magnification factor M_s is calculated by a formula identical to (4a,b) for the correction factor of bulge effect M. The second term on the right side of (5a) is due to the bending stress P_b, where the parameter a'' is given by

$$a'' = \begin{cases} \frac{a}{B}/[1+(\frac{B}{c})] & as \quad W \geq 2(c+B) \\ 2(\frac{a}{B})(\frac{c}{W}) & as \quad W < 2(c+B) \end{cases}, \qquad (5b)$$

where a'' stands for the ratio of approximate rectangle area of defect $2ac$ to section area BW. If the section width W exceeds $2c + 2B$, a'' takes the value for $W = 2c + 2B$ (be conservative). The average bending stress shown as the second term of the right side of (5a) may be derived by applying the beam theory to a section free of defect with thickness $B(1-a'')$. This paper takes for preliminary assessment $P_m = \sigma_\theta$, $P_b = 0$.

The formula for calculating the stress intensity factor, (3a,b), may be applied to the axial internal or external surface defects of pipeline . The correction factors of M and f_w for calculating K_I may be determined by using the general rule of Eqs.(4) or approximated by a plate model taking

$$M = 1, \quad f_w = \sqrt{\sec[\pi \frac{c}{W}\sqrt{\frac{a}{B}}]} \qquad (5c)$$

The maximum M_m taken at the deepest point d of defect is

$$M_m = 1.12 / \Phi(k), \qquad (5d)$$

for a half ellipse defect on the surface of semi-infinite body with $\Phi(k)$ being the complete elliptical integral of the second kind:

$$\Phi(k) = \int_0^{\pi/2} \sqrt{1-k^2 \sin^2 \theta} d\theta \text{ , } k^2 = 1-(a/c)^2 \text{ .}$$

$$\Phi(k) \approx \sqrt{1+1.464(a/c)^{1.65}} \text{ if } a/2c \le 0.5 .$$

The counterpart for plate model approximation is (for $a/2c \le 0.5$)

$$M_m = [M_1 + M_2(a/B)^2 + M_3(a/B)^4]/\Phi(k), \qquad (5e)$$

where the coefficients of M_1, M_2, M_3 may be found in annex M of BS7910 code.

2. Axial embedded defect of pipeline

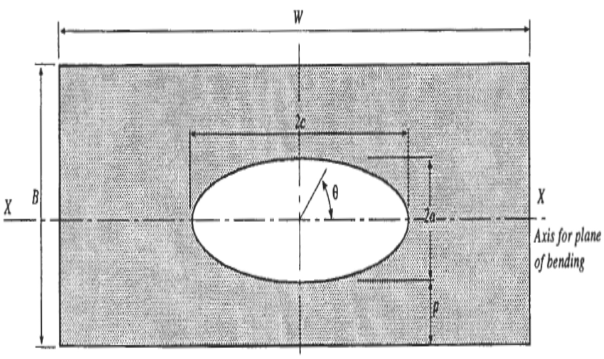

Fig.2 Axial embedded defect

The reference stress for embedded defect shown in Fig.2 is given by

$$\sigma_{ref} = \frac{P_b + 3P_m a'' + \sqrt{(P_b + 3P_m a'')^2 + 9P_m^2 (1-a'')^2 + 4pa''/B}}{3[(1-a'')^2 + 4pa''/B]} \qquad (6a)$$

where p is the minimum distance of defect surface to plate surface, or the minimum thickness of remaining ligament. The value of a'' may be obtained from (5b) with a replaced by $2a$. In the case of $p = 0$ (surface defect) and $P_m = 0$ (nil membrane stress), (6a) is reduced to the second term on the right side of (5a) with the bending stress P_b being the only acting stress. For the case of $p = 0$, $P_b = 0$ and $P_m \cdot a'' \approx 0$ (small defect compared to section area), (6a) is reduced to $P_m / (1-a'')$, reflecting the magnification of membrane stress due to thickness reduction.

The correction factors of M and f_w for calculating K_I may be determined by Eqs.(4), or approximated by (5c) for plate model, with thickness *B* replaced by the effective thickness $B' = 2a + 2p$. The counterparts of (5d,e) for embedded defects are

$$M_m = 1/\Phi(k), \qquad (6b)$$

$$M_m = [M_1 + M_2(2a/B')^2 + M_3(2a/B')^4]/\Phi(k) \qquad (6c)$$

where the coefficients of M_1, M_2, M_3 for embedded defects of plate in annex *M* of *BS7910* code should be used.

PRELIMINARY ASSESSMENT FOR SPIRAL WELDED DEFECTS OF PIPELINE

Failure analysis of Case 1: Spiral weld failure of Qing-Tie old pipeline, Northeastern China.

The parameters for Qing-Tie old pipeline of China are: outer diameter 720mm, thickness 8~10mm, the angle between pipeline axis and spiral weld 60°, the yield strength and ultimate strength for weld metal 381.0 MPa and 556.7 MPa respectively. Charpy V-notch impact energy for weld metal is C_V =11.2 *J*, which gives K_{IC} = 1227.1 $N/mm^{3/2}$ by formula in API 579 code and K_{IC} =1401.1, 1434.3, 1410.2, 1422.4 and 1415.0 $N/mm^{3/2}$ by formula in BS7910 code for the defects listed in Table 1. The above thickness dependent K_{IC} by BS7910 code is used in the following assessment calculation.

The five spiral welded defects have ultrasonic inspection data shown in Table 1, and are assessed as surface defects of finite length using the method given in Eqs.(5). The detailed formulas in BS7910:2005 were programmed by Matlab to produce FADs as shown in Figs. 3, 4 and 5 for the cases of acting internal pressure p=3, 4, 5 respectively.

Table 1 Data for spiral welded defects

Defect No.	Thickness (mm)	Defect length (mm)	defect height (mm)	Symbol in FAD
1#	8.7	60	1.8	o
2#	7.35	400	2.0	x
3#	8.3	115	2.1	+
4#	7.8	480	1.5	*
5#	8.1	230	2.2	•

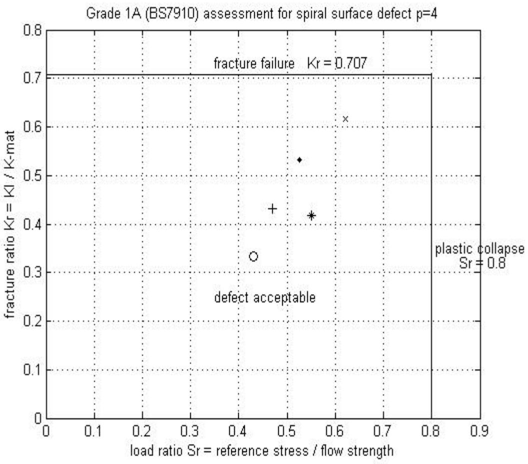

Fig.3 FAD at p=4 MPa

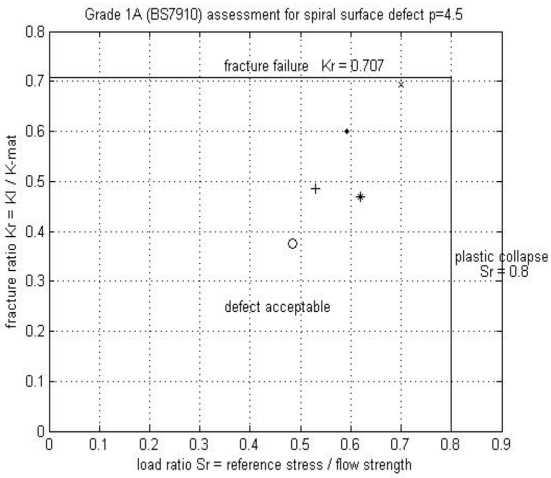

Fig.4 FAD at p=4.5 MPa

It is concluded that the pipeline is safe to operate under internal pressure 4.5 MPa as shown in Fig.4, and it can still work normally up to 5.0 MPa with insufficient safety, as shown in Fig.5 the non-dimensional stress intensity factor is not greater than 0.8. This observation is coincident with the burst accident of Qing-Tie old pipeline of Northeastern China, which was taken place on Nov.1, 2006 under the operation pressure around 5.1 MPa, and the accident spiral welded defect is found to be about 1414.8 mm long after breakage by the in-line inspection. If the length of the spiral defect is estimated to be about 150 mm long before breakage, then the defect depth before breakage has exceeded 2.70 mm by this calculation.

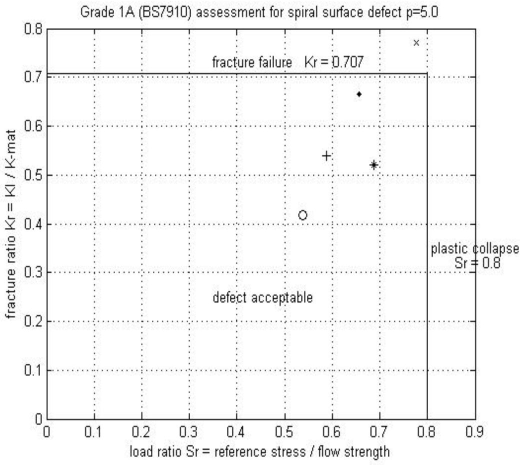

Fig.5 FAD at p=5.0 MPa

Failure analysis of Case 2: Spiral weld failure of Qing-Tie old pipeline at Changchun section of Northeastern China.

The burst accident of Qing-Tie old pipeline at Changchun section of China [2], which was taken place on July12, 1994 under pressure of 3.9 MPa, interrupted the oil transportation for 27 hours until the broken pipe segment was replaced. The pipe was cracked along a spiral weld of 1480 mm long , producing an open mouth with the two sides separated by 18 mm in width and 10 mm in high-low depth. The pipeline was made of X52 steel and was spiral double submerged arc welded. The geometry of pipeline is 720 mm of outer diameter and 8 mm of thickness. The chemical composition, metallography structure and mechanical property of the broken pipe segment were tested and proved to be normal. However, the X-ray detection revealed the existence of spiral welded defects on the inside surface of pipeline, the most of which were lack of fusion. The chemical composition of spiral weld is close to that of base metal, whereas the tensile strength of spiral weld is lower than that of base metal, though the impact toughness of spiral weld is higher than that of base metal.

The fractography analysis of fractured surface indicated that the crack was initialized from an welded defect of lack of fusion on inside surface of pipeline, which has the dimension of 159 mm in length and 2.8 mm in depth. Both the hydraulic test before pipeline service and the assessment calculation by this paper confirmed that the defect was safe at the initiation stage of service under the action of maximum allowable pressure 4.02MPa. According to our calculation, the maximum depth of safe defect under pressure of 3.9MPa is 3.05mm. However, the fractography analysis of fractured surface indicated that defect depth was increased by 4mm after 20 years operation, which is far beyond the safety size limit of defect 3.05mm predicted by this paper. Note the failure mode predicted by this paper is fracture failure, which was not discussed by [2].

Failure analysis of Case 3: Spiral weld failure of Hui-Ning oil pipeline, Western China

The leakage accident of Hui-Ning oil pipeline, which was on service since June of 1978, was taken place on Sep.5, 2006. The spiral welded crack of 760 mm in length and 3.5 mm in depth was on 12 to 3 o’clock circumferential location of pipe as shown in Fig.6. The geometry of pipeline is: outer diameter 377mm, thickness 7-8mm, and spiral angle 45 degree. The tensile strength of pipeline base metal L290 (or X42) is 290MPa, whereas the test data of tensile strength for spiral weld specimen is 242 MPa. The accident was taken place on a swamp with lots water deposited in heavy rain, under the action of pressure between 2.1MPa and 2.91 MPa, which is less than the maximum possible applied pressure 3.5 MPa.

No significant plastic deformation was developed around the crack and no severe corrosion defects seen on both surfaces of pipe.

Fig.6 cracked pipeline

A stepwise cracking line about 3~4mm away from the internal surface of pipe was seen in Fig. 7, indicating that the fracture was not formed for once and the cracking initiated from internal surface towards external surface.

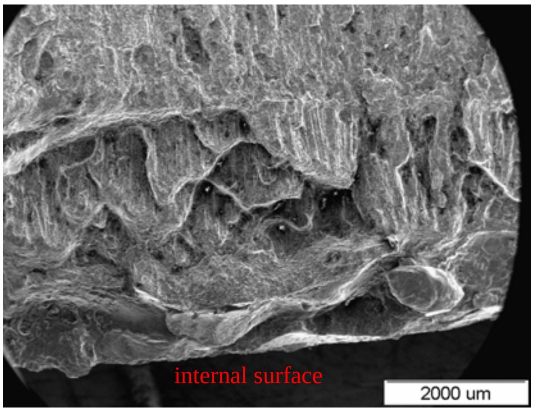

Fig.7 morphology of fractured surface

The microscopic morphology of fractured surface near the internal surface beneath the stepwise cracking line is shown in Fig.8, where the microstructure of metal is found to be not dense.

The microscopic morphology of fractured surface near the external surface of pipe has the characteristic of cleavage fracture with a few dimples, as shown in Fig.9.

An uncracked weld sample cut across spiral weld was tested with the tensile fractograph shown in Fig.10. Two different zones existed on the fractured surface, and the zone near internal surface existed before tensile test is due to lack of fusion.

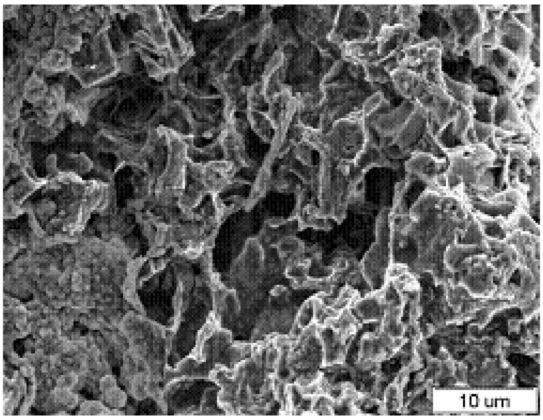

Fig.8 fractograph near internal surface

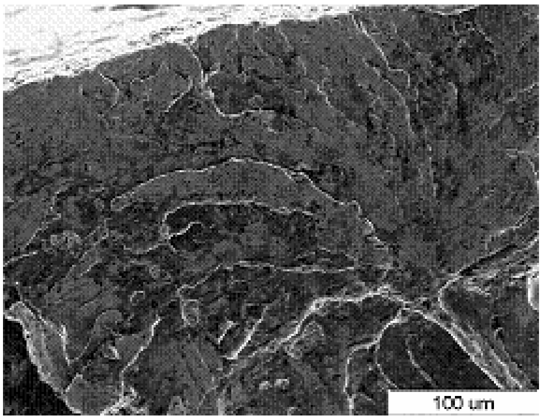

Fig. 9 morphology of cleavage fracture

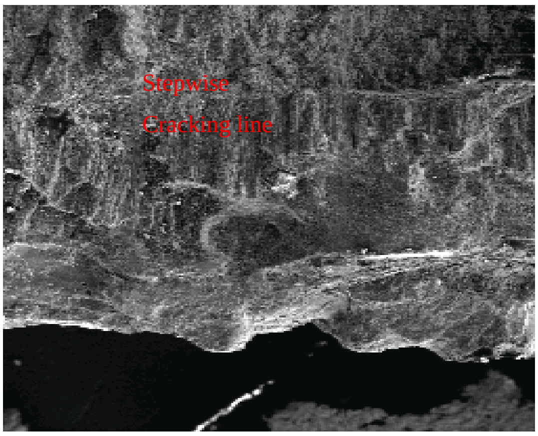

Fig. 10 morphology of tensile fractured surface

The 760 mm long and 3.5 mm deep spiral welded defect is assessed using the static strength data of yield strength 290MPa and ultimate strength 415MPa for weld metal of L290 or X42 pipeline steel. The Charpy V-notch impact energy 11.2 J (a measured value of weld metal for X52 pipeline steel adopted in case 1 study) is used, which yields the fracture toughness value K_{IC} = 1227.1 $N/mm^{3/2}$ by formula in API 579 code.

The calculations show that under the action of internal pressure of 2.91MPa, the defect was loaded by S_r =0.3829<0.8, indicating the safety of pipeline for plastic collapse of ligament, and by K_r =0.7318>0.707, predicting the fracture failure of spiral welded defect. The leakage accident of spiral welded failure of Hui-Ning oil pipeline, Western China, under the pressure of 2.91 MPa is thus confirmed.

CONCLUSIONS

A preliminary failure assessing process for spiral welded defects of pipeline, referring to the defect projecting method and the fracture assessing regulation of Grade 1A of BS7910: 2005, is applied to the ultrasonic inspection data of Qing-Tie old pipeline in the section of LingYuan to XinMiao, Northeastern China. It is observed that some defects have their assessing points close to the safety boundary of $K_r = 0.707$ under pressure 4.5 MPa and some outside the safety boundary under 5.0 MPa but still inside the region of $K_r < 0.8$, coinciding with the data of the burst accident taken place under pressure 5.1MPa. Also, Grade1A assessment applied to the leakage accident of a Western China pipeline confirmed that the spiral welded defect has K_r =0.7318>0.707 under the burst pressure of 2.91MPa, which explained the leakage accident of spiral welded failure of Hui-Ning oil pipeline, Western China.

It is concluded that the application of the preliminary failure assessing process studied in this paper is of fundamental importance and practical significance in making decision of inspection, integrity assessment and repair period for spiral welded pipelines, before more accurate data becomes available for higher grade assessment.

Moreover, a preliminary assessment is also valuable for directing higher grade assessments.

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