Prediction for Crack Propagation and Arrest of Shear Fracture in Ultra-high Pressure Natural Gas Pipelines

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Prevention of shear fracture in the natural gas pipelines is one of the most important problems for the safety of the natural gas transportation. The present paper gives a prediction method for the crack propagation and arrest in the ultra-high pressure pipelines which is the recent trend of the pipeline design and the toughness requirements for the high-grade line pipes to avoid the fracture.

KEY WORDS: propagating shear fracture; natural gas pipeline; ultra-high pressure; high-grade line pipe.

1. Introduction

In recent years, ultra-high pressure pipelines for natural gas pipelines have been in the limelight and the fracture safety of the pipelines is now one of the urgent problems to be solved for the natural gas transmission. Propagating shear fracture is well-known phenomenon, but the earlier studies were limited to the pipelines of lower pressure less than 15 MPa,1–4) which is the lower limit of so-called ultra-high pressure. The design pressure of recent pipelines has tended to exceed this limit and grows higher and higher for economic efficiency. This paper offers the prediction for the propagating shear fracture in ultra-high pressure pipelines for the safety of the latest natural gas transmission.

2. Earlier Work of HLP Committee and Subjects to be Solved

High Strength Line Pipe (HLP) Committee in ISIJ carried out full-scale burst tests seven times in 1978–1983. Four tests were carried out in Kamaishi, Japan, and two tests were in British Gas Company (BGC), UK. All the results are shown in Fig. 1, and the fracture appearance of C1 test is shown in Fig. 2. The pipes tested are X70 in API grade, 48 inches (1219 mm) in diameter and 18.3 mm in wall thickness. In A and B series tests, air was used for pressurizing gas and in C series tests, natural gas was used. In A and B series tests, the pressure was 11.6 MPa corresponding to 80% of the specified minimum yielding strength (SMYS). In C series tests, one test (C1) was carried out at the pressure of 11.6 MPa, but another test (C2) was at the pressure of 10.4 MPa corresponding to 72% of SMYS.

In all the tests, the notch ductility, i.e. the full-size Charpy energies at the test temperatures of the test pipes were intentionally varied and the crack arrestability of the pipes were investigated. The most important was the difference of crack propagation behaviour due to the pressure media between air and the natural gas. In C1 and C2 tests where the natural gas was used, the crack was far difficult to be arrested than in A and B series tests where air was used.

In Table 1, the gas compositions of C1 and C2 tests are shown. The gases are so-called natural gases containing heavier alkanes than methane, which causes “dual-phase decompression”. The gas decompression curves which signifies the velocity of gas escape from the fractured portion in the pipeline are shown in Fig. 3, where the peculiar plateaus featuring dual-phase decompression are observed. These plateaus obstruct the gas escape from the fractured pipes and induce long crack propagation and difficulty of the crack arrest. HLP committee introduced a unique method to predict the crack propagation and arrest to analyze all the results of these tests.1) The method is schematically shown in Fig. 4. It is based on the conflict between the gas decompression curve and the material resistance curve (J-curve) which signifies the relation between the crack velocity and the pressure at the tip of the propagating crack. During the short time differential (for example, 1/10 000 s), the gas pressure...
at the tip of the propagating crack is set constant and the crack propagates at the velocity corresponding to the pressure. The minute crack propagation induces minute decompression corresponding to the time differential, which induces the lower crack velocity and so on. If the two curves, the J-curve and the decompression curve are determined, the crack velocity and the propagation distance can be simulated easily even by a personal computer. Examples of the simulated results are shown in Fig. 5. Experimental results are well consistent with the prediction, i.e. the prediction method of HLP committee can be applicable to the pipelines of X70 in grade, 48 inches in diameter, 18.3 mm in wall thickness and 10.4 MPa or 11.6 MPa in pressure. But for the general expression, especially for the ultra-high pressure more than 15 MPa, the followings should be solved.

1) Problems on J-curve
   · Effect of specimen thickness in notch ductility tests
   · Correlations between notch ductility tests
2) Problems on gas decompression curve
   · Dual-phase decompression under ultra-high pressure

| Test No. | C2 | N2 | N3 | C1 | N2 | N3 |
|----------|----|----|----|----|----|----|
| C1       | 0.54 | 0.57 | 85.57 | 4.38 | 0.22 | 0.57 |
| C2       | 0.50 | 0.72 | 85.57 | 4.71 | 0.23 | 0.56 |
| C3       | 0.55 | 0.70 | 85.57 | 4.72 | 0.24 | 0.56 |
| C4       | 0.56 | 0.71 | 85.57 | 4.73 | 0.25 | 0.56 |
| C5       | 0.57 | 0.72 | 85.57 | 4.74 | 0.26 | 0.56 |
| C6       | 0.58 | 0.73 | 85.57 | 4.75 | 0.27 | 0.56 |

Table 1. Gas compositions of BGC burst tests. (mol%)
3) Simulation of crack propagation
- Crack arrest in ultra-high grade pipelines
- Required toughness practical for industrial application

3. Material Resistance Curve

The toughness of the steel materials is generally estimated from the notch ductility or absorbed energy of Charpy test. But for the line pipes of the oil or gas transmission pipelines, Drop Weight Tear Test (DWTT) is favorably used because the specimen thickness is the same to the wall thickness of the pipes, which diminishes sometimes arbitrary thickness effect on the toughness estimation.

In Fig. 6, the specimens of the three kinds of DWTTs are shown. The standard DWTT is the most popular test method but the pre-cracked DWTT is the most reliable method for the measurement of the crack propagation toughness and the chevron notch DWTT is the modified test method for practical use.5)

The material resistance curve has been with experimental verification of X70 line pipes and the following equations can be adapted for higher or lower grade line pipes.5)

\[
V_c = 0.670 \times \frac{\sigma_{\text{flow}}}{\sqrt{D_p/A_p}} \times \left( \frac{P}{P_a} - 1 \right) \quad \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots 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Fig. 7. Dependence of DWTT energy on specimen thickness.
where $C_v$ is the full-size Charpy absorbed energy (J), $D_p$ the pre-cracked DWTT energy, $D_{cn}$ the Chevron notch DWTT energy (J), $D_{st}$ the standard API DWTT energy (J) and $t$ the specimen thickness or the wall thickness of the pipes (mm). It is notable that all the energies in Eqs. (3), (4) and (5) should be measured in fully ductile mode, because the propagating shear fracture occurs in fully ductile mode.

Figure 8 shows the experimental verification of Eq. (3). Wide scatter of the experimental values to the predicted values is observed, and this tendency is all the same in the chevron notch DWTT and the standard API DWTT. The reason for the scatter in the experimental values is the essential difference between DWTTs and Charpy test. The absorbed energy of Charpy test consists of crack initiation energy and crack propagation energy. In pre-cracked DWTT, initiation energy is almost perfectly removed owing to pre-cracking. The absorbed energy of pre-cracked DWTT consists of crack propagation energy alone, which induces good estimation for propagating shear fracture in pipelines. Chevron notch DWTT is not so desirable in the sense that it contains small amount of initiation energy. Standard API DWTT contains considerable amount of initiation energy. In the correlations between DWTTs and Charpy test, these differences are reflected and scatter cannot be avoided essentially.

Another reason of wide scatter in the correlations is due to the so-called separation observed in the fracture appearance of the specimens. Especially in the TMCP (Thermo-Mechanically Controlled Process) steels, the specimen thickness is divided to multi-layers during the fracture of the specimens which reduces the absorbed energy remarkably. This reduction depends on specimen thickness, and so even in the same test method employed, the scatter in the correlation is inevitable. In Fig. 9, the absorbed energies of full-size Charpy and 2/3-size Charpy are compared. The specimen thickness of full-size Charpy test is 10 mm and test of 2/3-size Charpy test is 6.67 mm. Wide scatter is observed and even in Charpy test, the effect of the specimen thickness is between $t^1$ and $t^2$.

It should be concluded that the scatter in the correlation between DWTTs and Charpy test is inevitable, but from the viewpoint of practical application for industry, the correlations of Eqs. (3), (4) and (5) should be used unavoidably for the estimation of the material resistance curve.

And thus, the material resistance curve in Fig. 4 can be given from the full-size Charpy absorbed energy $C_v$ from the combination of Eqs. (1), (2) and (3). But from the viewpoint of the reliability of the curve, the pre-crack DWTT energy $D_p$ is the most preferable, next the chevron notch DWTT energy $D_{cn}$ and lastly the standard API DWTT energy $D_{st}$, instead of the Charpy absorbed energy $C_v$.

4. Gas Decompression Curve

The compositions of C1 and C2 gas shown in Table 1 are typical for natural gas transmission, but many kinds of gases exist in the world. Equilibrium state is varied for the kinds of gases, as shown in Fig. 10. As the gas goes rich, which means that gas contains heavier alkanes than methane, the dual phase region goes wider from “a” to “e” in Fig. 10. In this figure, “d” corresponds to C2 gas in Table 1. In ultra-high pressure pipelines, the gas starts from the dense phase and as the pressure goes down, the temperature also goes down following to an isentropic line and intrudes in the region of the dual phase.

The gas decompression in response to the crack propagation is shown in Fig. 11 schematically. A rapid gas escape from the fractured portion induces lower temperature and dual-phase decompression, and the conflict between gas de-
The compression velocity and crack propagation velocity occurs.

The decompression curve can be estimated from BWRS equation of state and the British gas model assuming that the gas flow in one-dimensional through “a full-bore opening”. Detailed method can be found in another paper in this volume, and here only the estimated results will be shown. As the initial pressure increases, acoustic velocity increases, and the plateau of the dual phase goes lower, and both effects of increasing pressure suggest that, as the initial pressure, the operating pressure of pipelines increases, the gas escape from the fractured portion is accelerated and the crack can be easily arrested.

The established method to estimate the gas decompression can handle the any kind of gases with various compositions, and in this report, the compositions of C2 gas categorized as a rich gas is used hereinafter. The combination of the decompression curves shown in Fig. 12 and the J-curves in Eqs. (1), (2) and (3) gives the crack propagation and arrest according to the method showed in Fig. 4.

An estimated decompression curve and J-curves of X100 are shown in Fig. 13. As the absorbed energy $C_v$ decreases, the J-curve goes down and the crossing point with the gas decompression curve goes higher which means that the crack propagation at a high velocity.

5. Prediction for Crack Propagation and Arrest

Examples predicted by the computer simulation are shown in Fig. 14. The followings are assumed for the simulation. The pipe grade is X100, and the operating pressures are varied as 15 MPa, 20 MPa and 25 MPa which are so-called ultra-high pressure. The pipe sizes are varied as 48 inches, 42 inches and 36 inches in diameter and wall thickness are estimated so as the design stress corresponds to 72% of the specified minimum yield strength of X100. The gas is C2 gas shown in Table 1 and the ambient temperature is 0°C. Value of $\sigma_{flow}$ is the mean of the specified minimum yield strength and tensile strength.

In the upper figures, J-curves are close to the plateau of the decompression curve and the crack propagates long in low velocity such as 100 m/s. The peculiar change of the crack velocity seen in the figure shows a typical effect from the dual-phase decompression behaviour of the rich gas. The crack arrest is very difficult and even in the line pipe of 500 J $C_v$, the crack propagates 24 m in distance.

In the middle figures, the gas decompression curve shifts to a higher velocity side and the plateau goes down. The change of the crack velocity shows the effect from the dual phase decompression but the crack arrest is far easier than in the case of upper figures. Charpy energy of 130 J can cause the crack arrest less than 20 m in distance.

In the lower figures, the gas decompression curve shifts more and more to higher velocity side and the plateau goes down remarkably. The J-curves come apart from the plateau of the gas decompression curve and the effect of the dual-phase decompression on the change of the crack velocity diminishes. The crack arrest is very easy and 60 J of $C_v$ is enough for 12 m arrest in distance.

Figure 14 reveals that as the operating pressure increases, the propagation distance tends to be shorter for the same $C_v$ values considered. Many cases were simulated and the required values of $C_v$ for a short crack arrest, 12 m in one side or 24 m in both sides, were estimated. Figure 15 indicates the case of X60. The pipe diameter and the wall thickness were varied in wide range, but so far as the design stress is kept constant such as 0.72SMYS, the requirement was almost on a single curved line regardless of the pipe size parameters. It was clarified that the Charpy requirement of a specified design stress depends on only the operating pressure, but little on the sizes of the pipes. As the operating pressure increases, the Charpy requirement decreases rapidly, because the gas decompressing velocity increases and the wall design thickness increases or the design pipe diameter decreases, both of which bring about the easier crack arrest. The effect of the gas decompression velocity is shown in Fig. 12 and that of the wall thickness or
the pipe diameter is expressed in Eqs. (1), (2) and (3). Figures 16 and 17 are the cases of X80 and X100 respectively, and the same tendency can be found. The requirement for $C_v$ under the constant operating pressure goes up as the pipe grade increases from X60 to X80 and to X100, but in all cases, the requirement goes down greatly as the operating pressure of the pipeline increases. It can be concluded that, in the ultra-high pressure pipelines, the propagating shear fracture is difficult to occur and the Charpy requirement to prevent the fracture is reduced considerably.

But it should be noted that as the operating pressure increases, the wall thickness should be increased or the pipe diameter should be decreased sometimes unrealistically. Therefore, the Charpy requirements for varied pipe sizes are shown in Tables 2, 3 and 4 revised from Figs. 15, 16 and 17. In these tables shaded portions indicate that Charpy requirement exceeds 500 J. The Charpy requirements go...
severer as the operating stress increases such as 0.60, 0.72 and 0.80 SMYS and as the diameter of the pipes increases. But the most remarkable change can be found in the wall thickness. As the wall thickness increases, the requirement decreases drastically, because the operating pressure increases and the toughness of the pre-cracked DWTT expressed in Eq. (3) increases remarkably.

In Figs. 15, 16, 17 and Tables 2, 3, 4, complicated features are found for the fracture safety of the ultra-high pressure pipelines. If the increase of the pressure is accepted by pipe sizes, that is the heavier wall thickness or the smaller pipe diameter, the propagating shear fracture is more difficult to propagate an the crack is arrested easier and lower toughness of $C_v$ is required. If the grade of the pipes is changed to higher one such as from X60 to X100, the Charpy requirement goes severer generally. But the requirement is much dependent on the pipe sizes, and if the thicker wall thickness and the smaller diameter are appropriately taken into consideration, the ultra-high pressure pipelines can be practically used for natural gas transmission.

Charpy requirements hitherto described should be altered for the kind of gas, the operating temperature and the expected crack arrest. Actual conditions of the pipeline should be taken into consideration, but the developed method to predict for the crack propagation and arrest enables these conditions to be dealt with.

6. Conclusions

A simulation method is accomplished and the prediction for crack propagation velocity and distance of the propagating shear fracture is enabled for any operating pressure, any grade of line pipes used and any compositions of natural gas for transmission. For the fracture safety of the ultra-high pressure pipelines, the followings are concluded.

(1) The increase of the operating pressure of the pipelines is not necessarily unsafe for the propagating shear fracture. The gas escape from the fractured portion is accelerated even in dual-phase decompression, and the effect of the pipe sizes can act for easy crack arrest in ultra-high pressure pipelines.

(2) Charpy requirements can be given for the grades and the sizes of the line pipes used. High grade pipes such as X100 can be used safely for ultra-high pressure pipelines so far as the appropriate design stress and pipe sizes are selected. The smaller diameter and the thicker wall thickness are preferable for the short crack arrest of the propagating shear fracture.

(3) The positive proof of the prediction is left for future work. Full-scale burst tests are required for the ultra-high pressure pipelines.
pressure pipelines.

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