Study on the Propagating Shear Fracture in High Strength Line Pipes by Partial-gas Burst Test

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In this paper, for the purpose of investigation on quantitative correlation between the partial-gas burst tests and the full-scale burst tests as a first step of establishing the evaluating method of crack arrestability in pipelines from partial-gas burst test results, the effects of the differences in test conditions on crack propagation behavior between both tests were evaluated. The partial-gas burst tests using high strength X80 pipes were carried out six times with varied gas ratio and failure pressure. The test results indicated that the crack propagation is much influenced by not only the failure pressure but also the gas ratio. After evaluation of the differences between the partial-gas burst tests and the full-scale burst tests, the simulating method of the propagating shear fracture in partial-gas burst tests were proposed. The crack propagation of the partial-gas burst tests was well simulated by this method and good agreement between the experimental data and the simulated results was obtained.

KEY WORDS: full-scale burst tests; partial-gas burst tests; propagating shear fracture; gas ratio.
tests were evaluated. The propagating shear fracture in partial-gas burst tests using high strength X80 pipes was analyzed.

2. Experimentation and Results of the Partial-gas Burst Tests

The partial-gas burst tests using high strength X80 pipes with varied pipe diameter and wall thickness were carried out six times from 1995 to 1999 at Hasaki, Japan.

2.1. Tests on 18 Inches X80 Pipes

The partial gas burst tests on X80 pipes with 18 inches in the diameter and 8.6 mm in the wall thickness were carried out two times. The specimen configuration is shown in Fig. 1. Two pipes for the test were jointed in the center by a girth welds. The seam welds of the two pipes were placed 180 degrees apart and a surface notch was machined across the girth welds by electric discharge between both seam welds so that the initiated crack runs in the base metal, i.e., in the portion 90 degrees apart from the both seam welds. The failure pressure was controlled by the notch depth. The notch depth was 4.8 mm for No. 1 and 3.3 mm for No. 2 test.

The specimen was filled with water except the upper part of the cross section of the pipe, which controlled the “gas ratio”, i.e., the gas volume ratio to the inner volume of the test pipe. Only the portion of the pipe wall around the expected crack path was enclosed in the cooler box made of foam polystyrene and cooled down from the surface by the spray of the liquefied nitrogen. The inner water was not frozen even the case that the test temperature was controlled at −10°C because of the separation by the gap of the upper part. The pressurized nitrogen gas was sent to the upper part until the fracture initiated from the machined surface notch.

The mechanical properties of the pipes tested are shown in Table 1. The pipes on the east side of both tests were manufactured from the same charge, so the properties are the same. The results of the partial-gas burst tests are shown in Table 2. The test temperature of both tests was controlled at 0°C. The gas ratio was 38.2 % for No. 1 test and 26.7 % for No. 2 test.

The fracture paths are shown in Fig. 2. On the west side of No. 1 test, the crack propagated longer than on the east side of No. 1 test as expected because of the lower notch ductility of the pipe. In No. 2 test, the failure pressure was much higher than in No. 1 test but the test resulted in short-
er crack length than expected from the higher test pressure, probably because of the smaller gas ratio than in No. 1 test.

2.2. Test on 24 Inches X80 Pipe

The partial gas burst test on X80 pipe with 24 inches in the diameter and 11.5 mm in the wall thickness was carried out once. The mechanical properties of the pipe used for the test are shown in Table 3. Surface notch was machined in the center of the pipe and the crack propagated in both sides in the base metal of the same pipe after pressurization.

Table 4 shows the test condition and the test result. The test temperature was controlled at $-5^\circ$C and the gas ratio was 18.0%. Fracture path of the test is shown in Fig. 3. In the No. 3 test, the failure pressure was extremely high but the test resulted in shorter crack length than expected because of the very low gas ratio.

2.3. Tests on 36 Inches X80 Pipes

The partial gas burst tests on X80 pipes with 36 inches in the diameter and 20.0 mm in the wall thickness were carried out three times. Three pipes 12 m in length were used for No. 4, No. 5 and No. 6 tests. Their mechanical properties are shown in Table 5. The specimen configuration is shown in Fig. 4.

The results of the partial-gas burst tests are shown in Table 6. The test temperature was controlled at $-10^\circ$C. The gas ratio was 43.6% for No. 4 test, 50.0% for No. 5 test and 38.0% for No. 6 test. In No. 4 and No. 5 tests, the cracks propagated longer than expected because of the high gas ratio and the cracks traveled all through the test specimen. The fracture paths of the partial gas burst tests are shown in Fig. 5. The fracture appearance of the test in No. 4 is shown in Fig. 6 as an example.

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Table 3. Mechanical properties of 24 inches X80 pipe.

| No. | YS(MPa) | TS(MPa) | Full-size Charpy energy (J) |
|-----|---------|---------|-----------------------------|
| 3   | 574     | 730     | 174                         |

Table 4. Result of the partial gas burst test on 24 inches X80 pipe.

| No. | Side | Temp. (C) | Gas ratio (%) | Failure pressure (MPa) | Fracture length (m) | Fracture appearance |
|-----|------|-----------|---------------|------------------------|---------------------|---------------------|
| 3   | East | -5        | 18.0          | 22.4                   | 2.32                | Ductile             |
|     | West |          |               |                        |                     |                     |

Table 5. Mechanical properties of 36 inches X80 pipes.

| No. | YS(MPa) | TS(MPa) | Full-size Charpy energy (J) |
|-----|---------|---------|-----------------------------|
| 4   | 628     | 708     | 225                         |
| 5   | 561     | 712     | 195                         |
| 6   | 555     | 694     | 202                         |

Table 6. Results of the partial gas burst tests on 36 inches X80 pipes.

| No. | Side | Temp. (C) | Gas ratio (%) | Failure pressure (MPa) | Fracture length (m) | Fracture appearance |
|-----|------|-----------|---------------|------------------------|---------------------|---------------------|
| 4   | East | -10       | 43.6          | 25.8                   | >6.00               | Ductile             |
|     | West | -10       |               |                        |                     |                     |
| 5   | East | -10       | 50.0          | 19.4                   | >6.00               | Ductile             |
|     | West | -10       |               |                        |                     |                     |
| 6   | East | -10       | 38.0          | 18.3                   | 3.56                | Ductile             |
|     | West | -10       |               |                        |                     |                     |

Fig. 3. Fracture path of 24 inches X80 pipe.

Fig. 4. Specimen configuration of the partial gas burst tests of 36 inches X80 pipe.

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3. Model for the Propagating Shear Fracture in the Partial-gas Burst Tests

3.1. Subject to be Evaluated for the Quantitative Correlation of the Partial-gas Burst Tests with Full Scale Burst Tests

High-strength Line Pipe (HLP) Committee in The ISIJ carried out several times full-scale burst tests from 1978 to 1983 and the crack arrestability of the linepipes was investigated. From the investigation, HLP Committee established the predicting method for the crack velocity and the distance in the propagating shear fracture of pipelines.1–4) Figure 7 shows schematic illustration of propagating shear fracture in pipelines. When a pipeline ruptures, gas can escape from the full area of the pipe in a process, which is essentially isentropic. Both the propagating shear fracture and the decompression wave can travel in the same direction. The crack speed decelerates when the local speed of the decompression wave at the crack tip is greater than the speed of the propagating shear fracture at a moment. The crack speed accelerates when the speed of the propagating shear fracture at a moment is greater than the local speed of the decompression wave at the crack tip.

HLP Committee's simulating method is schematically shown in Fig. 8. The “J-curve” represents the relationship between the pressure at the crack tip and the crack velocity. The “Gas decompression curve” represents the relationship between the pressure and the gas decompression velocity.

Using the above mentioned two curves, HLP Committee’s method simulates the propagating shear fracture in pipelines by calculating the following loop procedure.

1) Estimate the gas pressure at the crack tip.
2) Calculate the crack velocity corresponding to the pressure at the crack tip.
3) Simulate the crack propagation in a short time differential (for example, 1/10 000 s).
4) Calculate the decompression of the gas corresponding to the time differential and renew the gas pressure at the crack tip.
5) Back to 2).

It is reported that HLP Committee's simulating method can simulate the results of the full-scale burst tests well and can predicts the required notch ductility of the linepipes to prevent the propagating shear fracture. However, the full-scale burst test data used for establishing this method were limited. So it is true that to predict the crack arrestability of...
3.2. The Effect of No Backfill

The fracture appearance of one of the full-scale burst tests carried out by HLP Committee is shown in Fig. 9 as an example. The fracture appearance of the partial-gas burst test in Fig. 6(b) is apparently different from the fracture appearance of the full-scale burst test in Fig. 9 because of the effect of no backfill. This effect had been investigated by Battelle’s Columbus Laboratories and it is reported\(^7\) that the crack velocity in the case of no backfill increases 1.38 times the crack velocity in the case of backfill conditions. This “1.38” is only the mean value for the pipe having 30 inches of soil or sand cover and this value may vary with the pipe size, the operating pressure, and the backfill depth. However, there is no other reliable research result for the effect of no backfill to the crack propagation. So, in this study this “1.38” was used as a mean value for the effect of no backfill on the assumption that this value is applicable to the ultra-high pressure pipelines as same as the ordinary pressure pipelines.

The material resistance curve for the full-scale burst tests of HLP Committee in Eq. (1) can be changed to Eq. (2) for the partial-gas burst tests after consideration of the effect of no backfill.

\[
V_c = 0.670 \times \frac{\sigma_{flow}}{\sqrt{D_t / A_p}} \left( \frac{P}{P_a} \right)^{0.393} \\
(1)
\]

\[
P_a = 0.382 \times \frac{f}{D} \times \sigma_{flow} \\
\times \cos^{-1} \exp \left( -3.81 \times 10^7 \times \frac{D_p / A_p}{\sigma_{flow}} \right) \\
(1a)
\]

\[
D_p = 3.29 \times 1.5 \times C_v^{0.544} \\
(1b)
\]

\[
V_c = 1.38 \times 0.670 \times \frac{\sigma_{flow}}{\sqrt{D_t / A_p}} \times \left( \frac{P}{P_a} \right)^{0.393} \\
(2)
\]

where “\(V_c\)” is the crack velocity (m/sec), “\(\sigma_{flow}\)” the mean value of the yield strength and the tensile strength of the pipe (MPa), “\(P\)” the propagating crack tip pressure (MPa), “\(P_a\)” the arrest pressure under which the crack cannot propagate (MPa), “\(f\)” the wall thickness of the pipe (mm), “\(D\)” the diameter of the pipe (mm), “\(D_p\)” the pre-cracked DWTT specimen (mm\(^2\)) and “\(C_{\gamma}\)” the full-size Charpy absorbed energy (J).

3.3. The Effect of the Difference in Gases

The decompression curve of the ideal gas can be given as Eq. (3).

\[
P = \\
\frac{P}{P_0} = \left( \frac{2 + (\gamma - 1) \times V_c}{\gamma + 1} \right)^{\frac{2\gamma}{\gamma - 1}} \\
(3)
\]

where “\(P_0\)” is the initial pressure, “\(V_c\)” the acoustic velocity of the gas and “\(\gamma\)” the specific heat ratio of the gas.

However, the gas decompression curve calculated by Eq. (3) is different from the decompression curve of the real gas especially in the case of that the ultra-high pressure pipelines and the gases containing larger quantities of heavier hydrocarbons, i.e. the rich gases. This difference is caused from the reason that Eq. (3) cannot evaluate the change of the acoustic velocity, the change of the specific heat ratio and the phase change during the fracture process.

The decompression curve of the real gas can be estimated from the BWRS equation of state\(^{2,3}\) and the British gas model\(^9\) assuming that the gas flow in one-dimensional through a “full-bore opening”. Detailed method can be found in another paper in this volume,\(^10\) and here only the calculated results will be shown. The comparison between the calculated decompression curve of the “Typical Natural Gas” and the calculated decompression curve of the “Nitrogen Gas” is shown in Fig. 10. The composition of the “Typical Natural Gas” used for the calculation is shown in Table 7.

It was said that there is not so much difference between the decompression curve of the “Natural Gas” and the “Air (or Nitrogen Gas)” judging from the past experimental data. This insistence is roughly right in the conventional pressure conditions.
pipelines as seen in Fig. 10(a), but this situation is utterly changed in the ultra-high pressure pipelines as seen as Figs. 10(b), 10(c) and 10(d).

3.4. The Effect of the Gas Ratio

Most simple way to evaluate the effect of the gas ratio to the crack propagation is to use Eq. (4) instead of Eq. (2).

\[ V_c = h(\gamma_G) \times 1.38 \times 0.670 \times \sigma_{flow} \times \left( \frac{P}{P_a} - 1 \right)^{0.393} \]

In this equation, the effect of the partiality of the gas is assumed to be analogically same as the effect of backfill because both cause the decrease in the driving force to the pipe wall.

The results of the partial-gas burst tests No. 1, No. 2, No. 3, and No. 6 were used for determination of the concrete form of this function “\( h(\gamma_G) \)”, which represents the effect of gas ratio to the crack propagation. The results of tests No. 4 and No. 5 were not used because the cracks in these tests traveled long and did not arrest within the length of the test pipe. It is also ascertained that in all tests except No. 4 and No. 5, the reflecting decompression wave from the end caps could not reach to the arrested crack front from the measurement of pressure and crack velocity, which means that “\( h(\gamma_G) \)” does not include the effect of the specimen shortage.

For actual calculation, the initial condition for the crack is needed. From the analyzed result of the full-scale burst tests, HLP Committee adopts the diameter of the pipe “\( D \)” equal to the assumptive initial half crack length “\( l_0 \)” for the crack propagating simulation. This assumptive initial crack length represents “the assumptive non-decompression distance” caused from the fracture initiation process, during which the inner gas can’t escape effectively because of the narrow opening of the crack and the assumption of the “full-bore opening”\(^{10}\) does not hold. Therefore, this assumptive initial crack length apparently affected by the degree of the crack opening during the fracture initiation process, so it seems to be affected mainly by the failure pressure level.

Final form of the best fitting curve after trial and error calculations are shown in Eqs. (5) and (6).

\[ l_0 = D \times \left( \frac{P_{0.72}}{P_f} \right)^2 \]  \( \text{(5)} \)

\[ P_{0.72} = \frac{2t}{D} \sigma_y \times 0.72 \]  \( \text{(5a)} \)

\[ h(\gamma_G) = 0.79 \gamma_G^3 - 2.58 \gamma_G^2 + 2.79 \gamma_G \]  \( \text{(6)} \)

where, “\( l_0 \)” is the assumptive initial half crack length, “\( D \)” the diameter of the pipe, “\( \sigma_y \)” the wall thickness of the pipe, “\( P_f \)” the failure pressure, “\( P_{0.72} \)” the pressure corresponding to 72% YS of the pipe, “\( \gamma_G \)” the yield strength (YS) of the pipe, and “\( \gamma_G \)” the gas ratio of the partial-gas burst test.

4. Simulation for the Crack Propagation of the Partial-gas Burst Tests

The simulated results for the crack propagation of the partial-gas burst tests by the model described in the previous section are shown in Figs. 11 and 12. As shown in Figs. 11 and 12, good agreement between the experimental data and the simulated results are obtained.

It should be noted that there is also good agreement between the experimental data and the simulated results in the case of No. 4 and No. 5 tests as shown in Figs. 12(a) and 12(b) in spite of the test results not used for the determination of the function “\( h(\gamma_G) \)”. It indicates that the effect of the specimen shortage, i.e. the effect of the reflecting decompression wave from the end caps, is small and limited.

Judging from Figs. 11 and 12, it is concluded that HLP Committee’s simulating method for the propagating shear fracture in pipelines can be applied to the partial-gas burst tests after evaluating the effects of the differences in test conditions on crack propagation behavior between the full-scale burst tests and the partial-gas burst tests, that is, no backfill, difference in gases and the effect of gas ratio.
5. Conclusions

For the purpose of investigation on quantitative correlation between the partial-gas burst tests and the full-scale burst tests as a first step of establishing the evaluating method of crack arrestability in pipelines from partial-gas burst test results, the effects of the differences in test conditions on crack propagation behavior between both tests were evaluated. The propagating shear fracture in partial-gas burst tests using high strength X80 pipes was analyzed. The followings are conclusions.

(1) HLP Committee’s simulating method for the propagating shear fracture in pipelines can be applied to the partial-gas burst tests after evaluating the effects of the differences in test conditions on crack propagation behavior between the full-scale burst tests and the partial-gas burst tests, that is, no backfill, difference in gases and the effect of gas ratio. The crack propagation of the partial-gas burst tests was simulated well by this improved HLP Committee’s simulating method and good agreement between the experimental data and the simulated results are obtained.

(2) The partial-gas burst tests should be a link between the full-scale burst tests and the Charpy tests. The partial-gas burst tests are less expensive than the full-scale burst tests and more reliable than the Charpy tests. It is our future work to study more experimental verification for the method developed in this study.

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