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The Influence of Internal Pressure on Ductile Fracture Behavior from a Surface Defect on a Pipe

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ABSTRACT

This paper presents the influence of internal pressure on ductile fracture behavior conducting three pressurized and un-pressurized pipe tension tests with machined surface notches. Especially, it is focused on investigation of the ductile crack initiation from the aspects on effective opening displacement at a notch tip. The influence of internal pressure was negligible on ductile crack initiation from a surface notch. On the other hand, the crack driving force became higher as internal pressure increased. Ductile tearing resistance curves (R-curves) obtained from pressurized pipe tests and Single Edge Notched Tension (SENT) tests are also investigated. A R-curve from SENT tests shows good agreement with that from pipe tests. Therefore, it is possible to use the R-curve of a SENT specimen as that of a pressurized pipe specimen. According to these results, the critical strain on ductile crack initiation and leakage of the pressurized pipe was predicted, and it is verified that predicted critical strain was well in agreement with an experimental result.

KEY WORDS: ductile crack initiation; tearing resistance; SENT test; internal pressure; crack propagation;

INTRODUCTION

In recent years, construction of natural gas pipelines is expanding to severe environmental area such as seismic or permafrost region (Glover, 2003). In these regions, it can be expected that pipelines will be subjected to large deformation due to large ground movement associated with liquefaction in seismic region or frost heave in permafrost. It is not possible to apply conventional stress-based design or integrity assessment methods in cases where a pipeline is subjected to large plastic strain that greatly exceeds the yield stress of the pipe material. A number of studies have been carried out on strain-based design and integrity assessment methods. Tensile strain limit of a pipeline is usually characterized using uni-axial tests such as the curved wide plate (CWP) test (Denys, 2004). Accordingly, the most critical fracture mode in pipelines is considered to ductile fracture originating from defects in girth welds, and prediction of ductile crack initiation of CWP test has been proposed using critical equivalent plastic strain at notch tip obtained from SENT tests (Sadasue, 2004). The tensile strain capacity of ductile crack initiation decreases as Y/T ratio of the base metal increases (Igi, 2007).

On the other hand, there is an increasing demand of high-pressure operation due to high efficiency of natural gas transportation. However, CWP tests could not take into account the effect of internal pressure. Therefore it is important to investigate the effect of internal pressure on ductile fracture behavior. Pressurized and un-pressurized pipe tensile tests have been conducted to investigate the influence of internal pressure on the tensile strain capacity of a pipeline (Gioielli, 2007, Minnaar, 2007). These tests indicated that internal pressure does not seem to affect R-curves. However it is not mentioned the influence of internal pressure on ductile crack initiation. Furthermore, with respect to the influence of internal pressure on the ductile crack initiation and growth, only a few data are available because of the difficulty of pressurized pipe tension test.

From these backgrounds, the influence of internal pressure on the ductile crack initiation and ductile tearing behaviors are investigated by conducting pressurized and un-pressurized tension tests using pipe specimens with machined surface notches. R-curves obtained from pipe and SENT tests are also investigated. According to these results, the critical strain on ductile crack initiation and leakage of the pressurized pipe was tried to predict using SENT and FEA results.

EXPERIMENTAL PROCEDURE

Tested Material

The test specimens were taken from JIS STPG 370 seamless pipes with 216.3mm of outside diameter (OD) and 10.3mm of wall thickness (WT). Typical tensile properties of the material and nominal stress-nominal strain (S-S) curve are shown in Table 1 and Fig. 1, respectively.

Table 1 Tensile properties in L-direction

YS [MPa]	TS [MPa]	uEL [%]
261	449	19.5

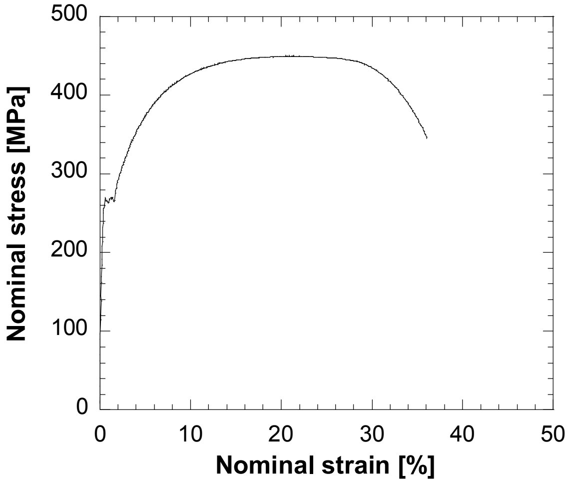

Fig. 1 Nominal stress vs. nominal strain curve

Tension tests

SENT specimens were taken from the pipe as illustrated in Fig. 2. An edge notch was introduced by electrical discharge machining (EDM). The notch was machined with 2.1mm in depth and the radius at the notch tip was 0.1mm. SENT tests were performed by applying uniaxial tensile loading at ambient temperature. During the test, load and notch opening displacement were recorded using a load cell and a clip gauge, respectively. The SENT tests were unloaded at the specific notch opening displacement to investigate ductile crack initiation and propagation behaviors.

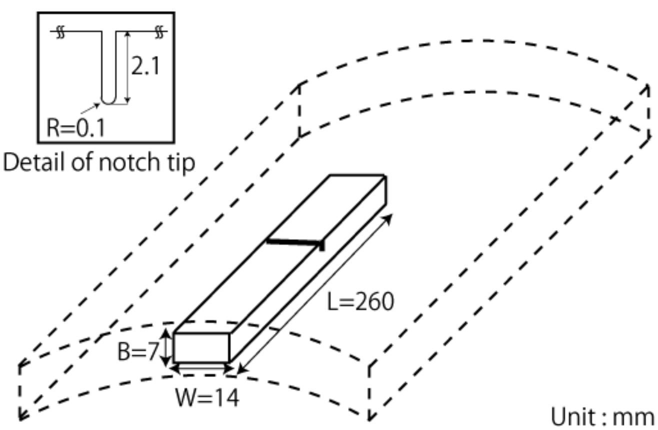

Fig. 2 Geometry and size of SENT specimen

As for pipe test specimens, EDM notches with30mm in surface length were introduced on the outer surface of the pipe body. The notch tip radius was 0.1mm. Table 2 presents the test conditions of pipe tests. P-1 specimen had 2 EDM notches (3.0 and 4.0mm in depth). The EDM notches were machined at the center of the pipe specimen and 2 notches placed at 180 degrees apart from each other. P-2 and P-3 specimen had 4 notches (2.5, 3.0, 3.5 and 4.0mm in depth). The EDM notches were machined at the center of the pipe specimens and 4 notches placed at 90 degrees apart from each other. Figure 3 shows the EDM notch profile and the notch locations. P-2 and P-3 tests were conducted under the condition of the constant internal pressure of 14.7 MPa, corresponding hoop stresses were equivalent to 72% of specified minimum yield strength (fd=0.72). Internal pressure was applied using water as a medium.

During the test, load, the notch opening displacement, and axial GL (gauge length=450mm) displacement were recorded using a load cell, clip gauges, π gauges, respectively. P-1 and P-2 were tested until ductile cracking point and P-3 was tested until the leakage under displacement control conditions. After the tests, each specimen was sectioned and observed microscopically to measure the propagating ductile crack length and the amount of deformation at notch tip as illustrated in Fig. 4. The amount of deformation at notch tip is defined as effective opening displacement, δ_{eff} in Fig. 5. The effective opening displacement was determined by using displacement at positions subtending 90 degrees from the initial notch tip.

Table 2 Test conditions of pipe tests

Test No.	Internal pressure	Unloading condition
P-1	0MPa (fd=0)	Ductile crack initiation
P-2	14.7MPa (fd=0.72)	Ductile crack initiation
P-3	14.7MPa (fd=0.72)	Leakage

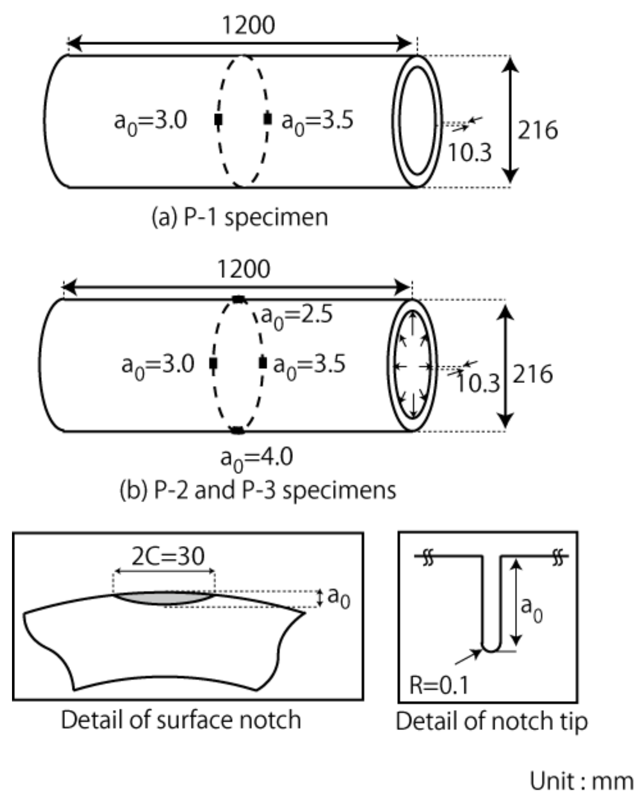

Fig. 3 Pipe specimens with external surface notches

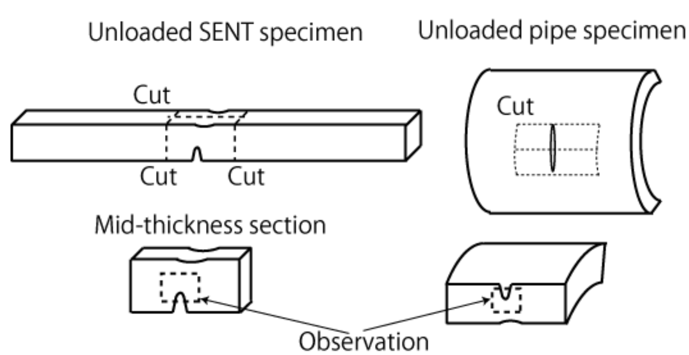

Fig. 4 Procedure for measuring ductile cracking

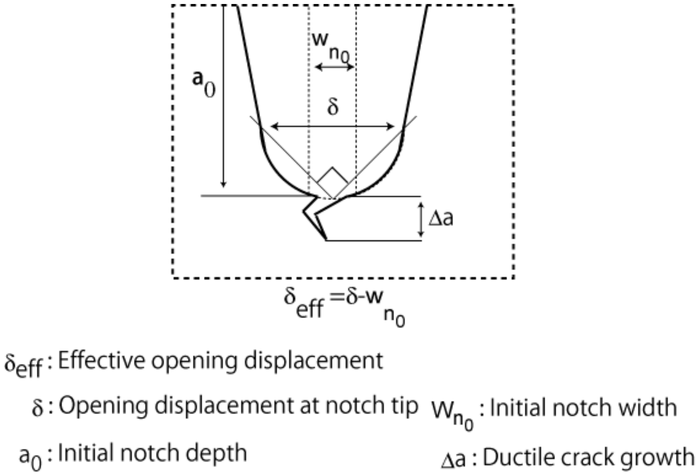

Fig. 5 Definition of effective opening displacement for experiment

FINITE ELEMENT ANALYSIS PROCEDURE

In order to investigate the local deformation behavior around the notch tip in the pipe tests, FEA were performed using 3-dimensional 1/4 symmetrical models. Figure 6 shows the FE models of the pipe specimens. The initial notch geometry included in the tests was reproduced exactly in the models. The minimum element size at the notch tip was 0.025mm x 0.025mm x 0.5mm. A series of models with increasing notch depth were used to clarify the ductile tearing behavior. The analysis code was ABAQUS Ver.6.7. The effective opening displacement of the FEA was defined as shown in Fig. 7 according to experimental measuring procedure. In the FEA models, the relationship between effective opening displacement and overall strain is obtained. The overall strain is used to express the critical strain on ductile crack initiation or leakage from a surface notch of a pressurizes pipe.

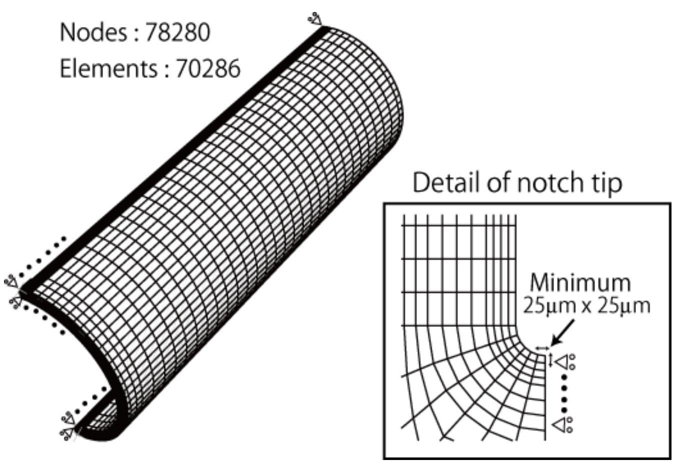

Fig. 6 FEA models for a pipe specimen

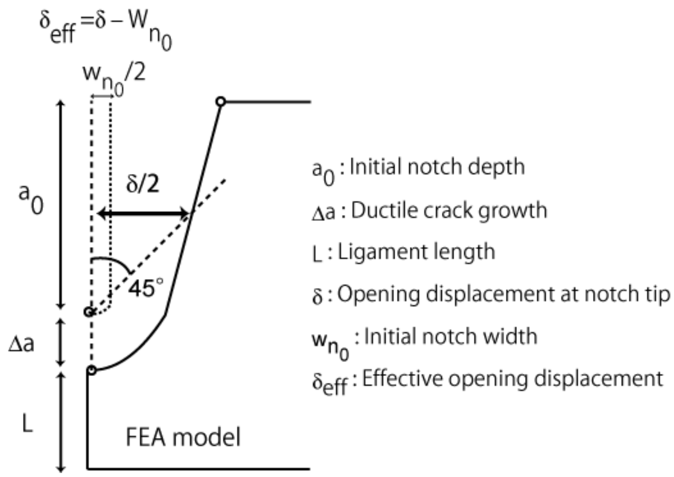

Fig. 7 Definition of effective opening displacement for FEA

EXPERIMENTAL RESULT

As an example of the experimental results, Fig. 8 shows the sectional observations of ductile initiation and growth from the notch tip obtained in the SENT tests. It can be confirmed that a ductile crack has occurred with a length of approximately 50μm from the deepest point of the notch tip. Figure 9 shows the load vs. clip gauge displacement curves obtained from SENT tests together with the locus of ductile crack initiation. The ductile crack initiation from the surface notch is detected at clip gauge displacement = 1.1 mm. Figure 10 shows the condition of ductile initiation and growth from the notch tip observed in the pipe test. It can be confirmed that a ductile crack has occurred from the deepest point of the notch tip just as SENT tests. Figures 11 and 12 show the comparison of load vs. axial displacement curves from the pipe test and the FEA result. It can be recognized that load vs. axial displacement curves obtained from experiment and FEA result show good agreement until unloading.

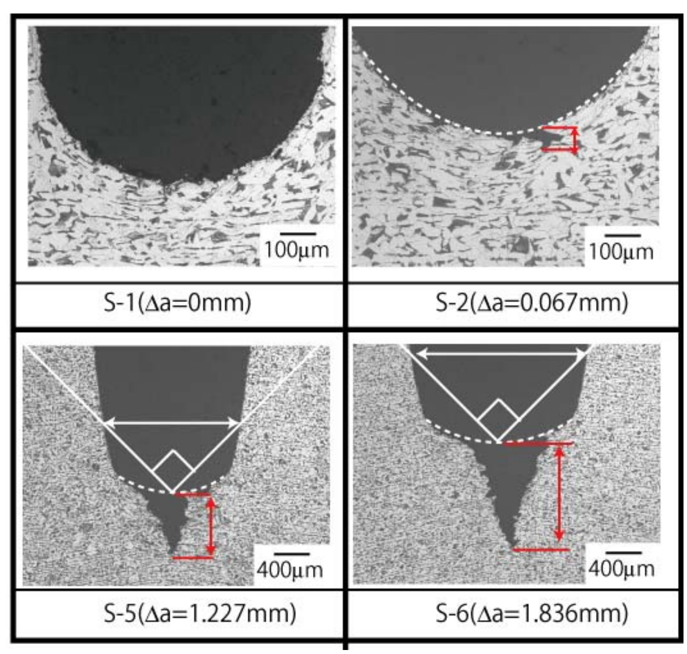

Fig. 8 Sectional observations of measuring ductile cracking in SENT tests

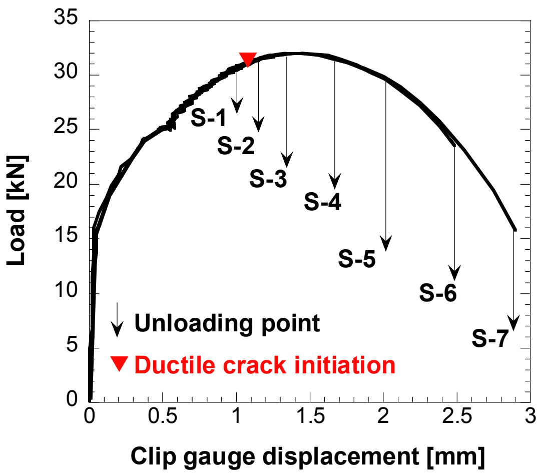

Fig. 9 Load vs. clip gauge displacement curves from SENT tests

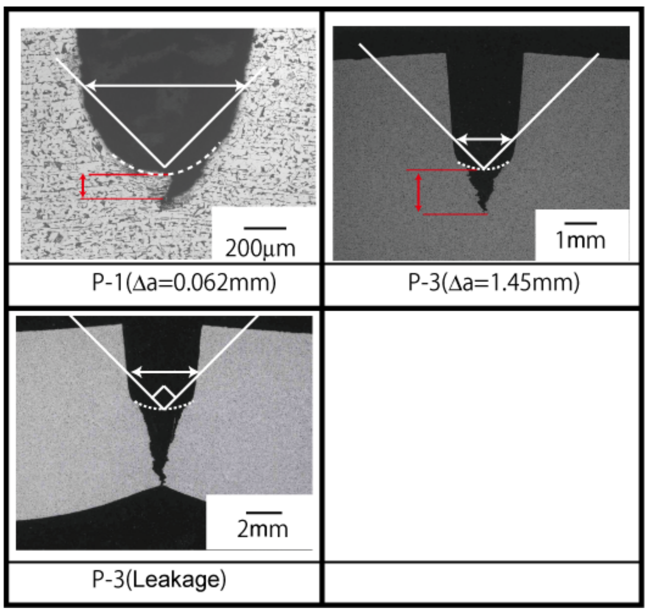

Fig. 10 Examples of measuring ductile cracking in pipe tests

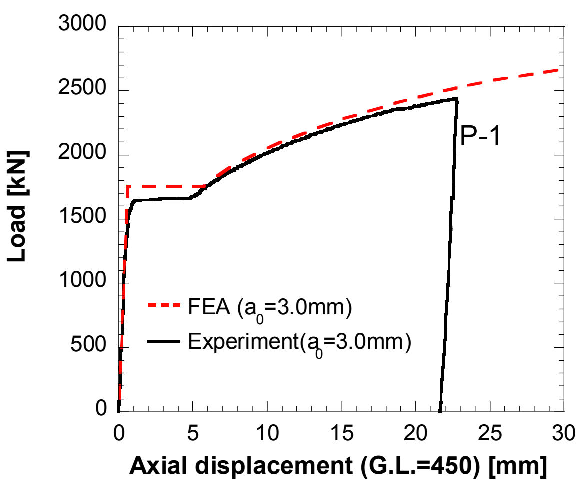

Fig. 11 Comparison of load vs. axial displacement curves between experiment and FEA results under un-pressurized condition

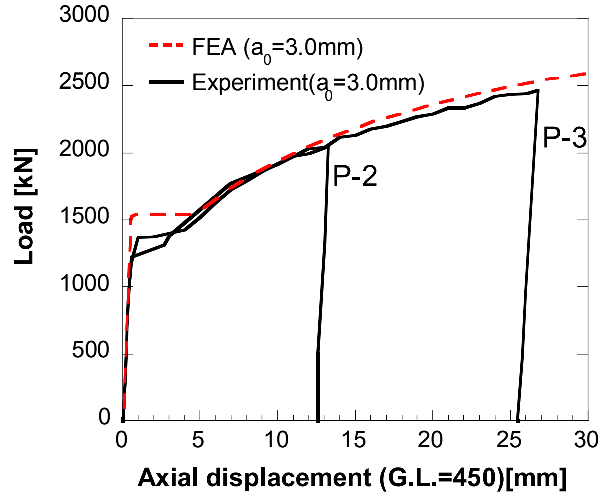

Fig. 12 Comparison of load vs. axial displacement curves between experiment and FEA results under pressurized condition

DISCUSSION

The influence of internal pressure on ductile crack initiation

Generally the ductile crack initiates from the crack tip after blunting of the crack. In this case, the ductile crack initiation from crack tip is controlled by equivalent plastic strain (An, 2003, Ohata, 2004). The estimation of the ductile crack initiation from notch tip using effective opening displacement is also useful. Effective opening displacement can evaluate ductile cracking directly from the experiment. Therefore, effective opening displacement will be a more convenient parameter for assessment of ductile cracking from notch tip, as compared with equivalent plastic strain (Sadasue, 2004). In this study, effective opening displacement is used estimating ductile cracking.

Figure 13 shows R-curves represented by the effective opening displacement of un-pressurized and pressurized specimens. R-curves from each condition show good agreement. The ductile crack initiation point (Δa_i=0.05mm) was obtained by extrapolation using the experimental data of ductile crack growth less than 1mm. The effective opening displacement on ductile crack initiation $\delta_{eff}^{\ i\text{-}cr}$ from each condition is approximately the same values. This result indicates that the influence of internal pressure is negligible on ductile crack initiation. Figure 14 shows the relationships between effective opening displacement and axial displacement (G.L.=450mm) for un-pressurized and pressurized pipe specimens obtained from FEA together with the point of ductile crack initiation. The critical strain on ductile crack initiation becomes lower as the internal pressure increases.

These results indicate that the influence of internal pressure is negligible on the effective opening displacement on ductile crack initiation and R-curve. On the other hand, internal pressure increases the effective opening displacement at equal levels of applied strain. Namely, internal pressure affects the critical strain on ductile crack initiation and leakage because it increases crack driving force.

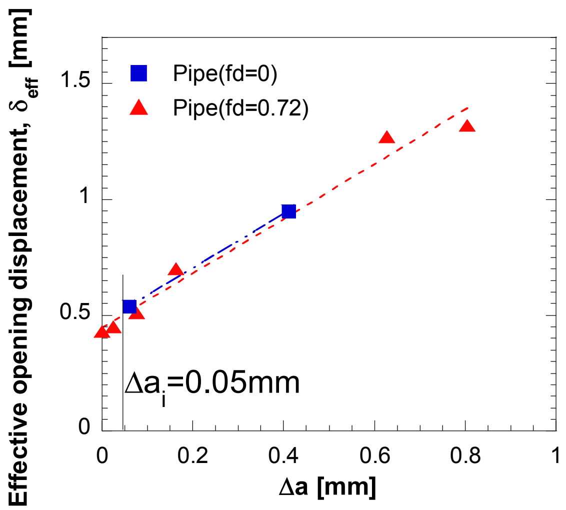

Fig. 13 Comparison of R-curves obtained from pipe tests

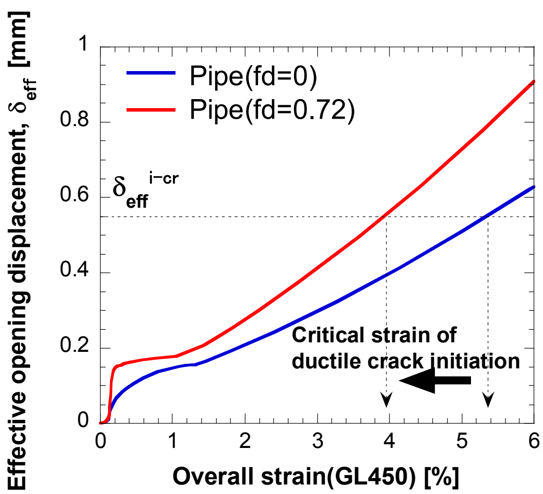

Fig. 14 Influence of internal pressure on the critical strain on ductile crack initiation

Ductile tearing resistance curves from pipe and SENT tests

Figure 13 suggests that the effective opening displacement on ductile crack initiation and R-curve are insensitive to internal pressure. It is expected that the effective opening displacement on ductile crack initiation and R-curve from a uni-axial test such as SENT test is useful to obtain those of a pressurized pipe. Therefore, comparison of R-curves between pipe and SENT tests was carried out in detail.

Figure 15 shows the R-curves obtained from pipe and SENT tests. The ductile crack initiation point (Δa_i=0.05mm) was obtained by extrapolation using the experimental data of ductile crack growth less than 1mm as shown in Fig. 16. The R-curves of pipe and SENT tests were able to be expressed on one curve. The effective opening displacement on ductile crack initiation from pipe and SENT tests also are approximately the same values. The difference between the experimentally obtained R-curves is very small, hence a size effect is not observed. These results indicate that SENT specimen is useful in predicting the R-curve of a pipe.

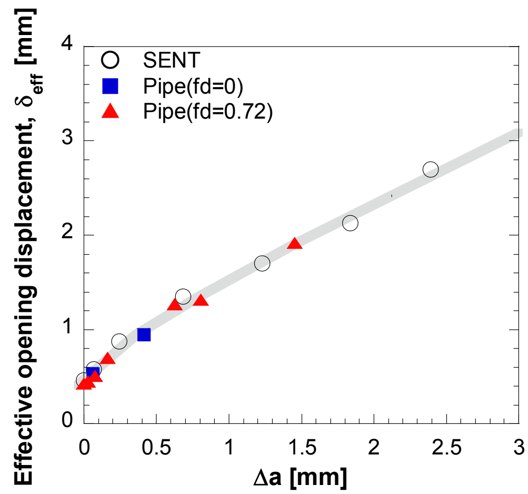

Fig. 15 Comparison of R-curves between SENT and pipe tests

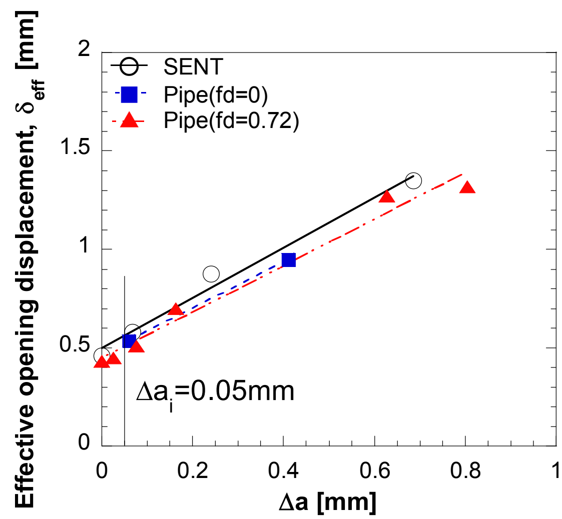

Fig. 16 Comparison of the effective opening displacement on ductile crack initiation between SENT and pipe tests

Prediction of the critical strain on ductile crack initiation and leakage by using R-curve and FEA

The R-curve from SENT tests can be applicable as of pressurized pipe tests because the R-curves from pipe and SENT tests shows good agreement as shown Fig. 15. This result indicates that the ductile tearing behavior of a pressurized pipe can be predicted from the R-curve of SENT tests and supplementary FEA. Therefore the critical strain on ductile crack initiation and leakage of the pressurized pipe was tried to predicted using these results.

The prediction procedure is summarized in five steps as shown in Fig. 17. In the first step, SENT tests conduct to obtain ductile tearing behavior before break. The relationship between the effective opening displacement and effective ductile crack growth parameter $\Delta a/\ t_{eff}$ is obtained experimentally using SENT tests. In the second step, a series of FEA conducts to obtain the local deformation behavior around the notch tip and axial deformation of a pressurized pipe using FE models with various notch depths. The relationship between the effective opening displacement and overall strain of a pressurized pipe is calculated. In the third step, the crack driving force of a pressurized pipe is obtained from R-curve of SENT tests and FEA results through the same level of effective opening displacement. In the forth step, the critical strain on ductile crack initiation of a pressurized pipe is predicted as the point where the crack driving force reaches the same effective opening displacement on ductile crack initiation of SENT tests. In the last step, the critical strain on leakage of a pressurized pipe is predicted as the point where the crack driving force increases drastically. In this procedure, the effective thickness t_{eff} was defined as Eq. 1 to take the local necking at the ligament into consideration.

$$t_{eff}=(a_0 + \Delta a + L)/t_0 \quad (1)$$

Here, a_0 was initial notch depth, Δa was ductile crack growth, L was ligament length and t_0 was initial wall thickness.

Predicted critical strain on ductile crack initiation and leakage of pressurized pipe tests is compared with the experimental results of P-2 and P-3 specimens, respectively. Figure 18 shows the relationships between effective opening displacement and effective ductile crack growth parameter $\Delta a/t_{eff}$ from SENT tests on the left figure and effective opening displacement and overall strain from the FEA on the right figure. The predicted critical strain on ductile crack initiation shows fairly good agreement with the pressurized pipe test result of P-2 specimen.

Figure 19 shows the predicted crack driving force curve and the critical strain on leakage obtained from the pressurized pipe test of P-3 specimen and the prediction. Though the predicted critical strain on leakage is slightly lower than the pressurized test result, the test result is plotted within 95% confidence limit of the prediction. These results indicate that the critical strain on ductile crack initiation and leakage of a pressurized pipe can be predicted by using SENT tests and FEA results.

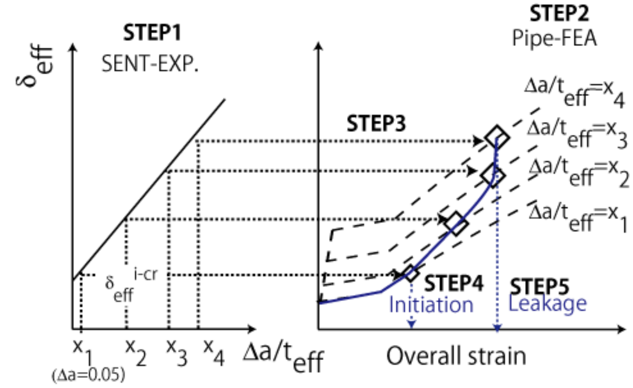

Fig. 17 Prediction procedure of the critical strain on initiation and leakage of a pressurized pipe test using SENT tests and FEA results

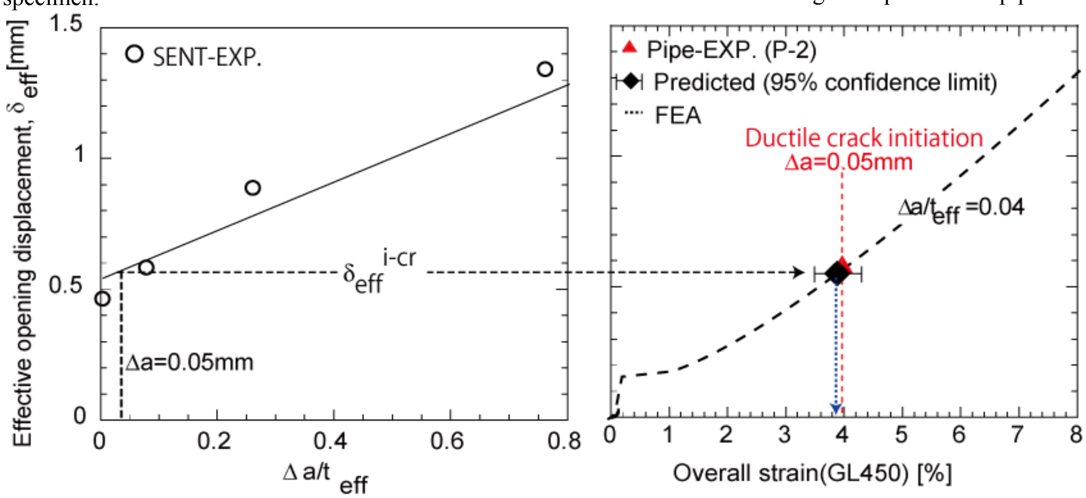

Fig. 18 Prediction of critical strain on ductile crack initiation using SENT tests and FEA results

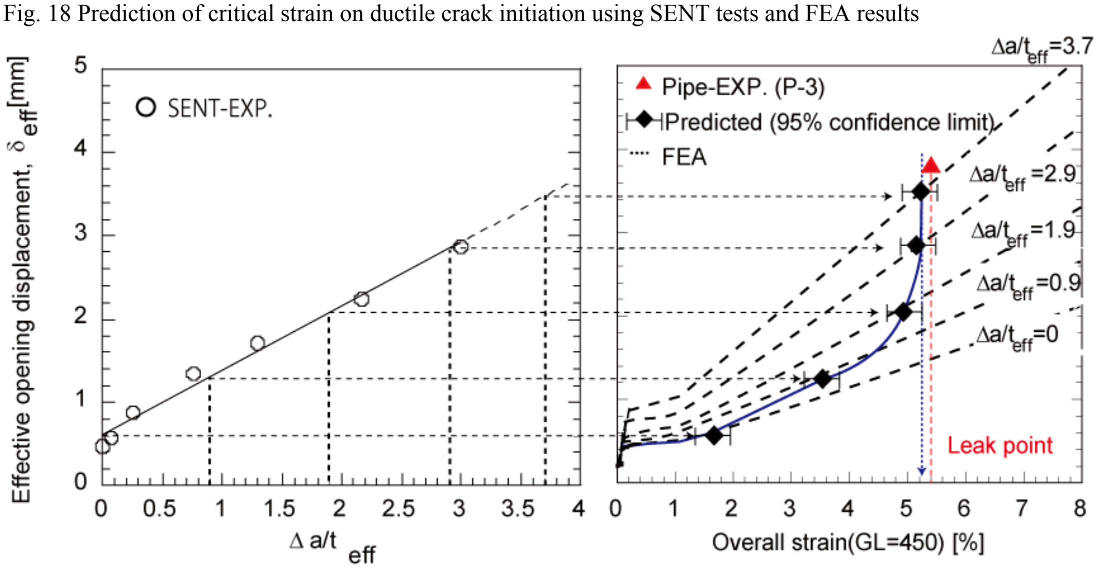

Fig. 19 Prediction of critical strain on leakage using SENT tests and FEA results

CONCLUSIONS

The influence of internal pressure on ductile fracture behavior was investigated conducting pressurized and un-pressurized pipe tests. The critical strain on ductile crack initiation and leakage of a pressurized pipe were predicted by using SENT tests and FEA results.
The following main conclusions were obtained.

1. The influence of internal pressure is negligible on effective opening displacement on ductile crack initiation and R-curve. On the other hand, internal pressure increases crack driving force. Namely, internal pressure affects the critical strain on ductile crack initiation and leakage.
2. The effective opening displacement on ductile crack initiation and R-curve between pipe and SENT tests show fairly good agreement. The R-curve from SENT tests can be applicable as that of a pressurized pipe.
3. The critical strain on ductile crack initiation and leakage of a pressurized pipe can be predicted by using SENT tests and FEA results accurately.

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