Evaluation of Pre-strain Effect on Abnormal Fracture Occurrence in Drop-Weight Tear Test for Linepipe Steel with High Charpy Energy

Toshihiko Amanoa, Taishi Fujishirob, Yasuhiro Shinoharac, Takehiro Inoued *

aMaterials Reliability Research Lab., Research & Development, Nippon Steel & Sumitomo Metal Corporation (NSSMC), Hyogo 660-0891, Japan
bPipe & Tube Research Lab., Research & Development, NSSMC, Hyogo 660-0891, Japan
cKimitsu R & D Lab., NSSMC, Kimitsu Chiba 299-1141, Japan
dPlate & Shape Research Lab., Research & Development, NSSMC, Fujtsu Chiba 293-8511, Japan

Abstract

Brittle fracture control is one of the most important subjects in natural gas transmission pipeline in order to maintain structural integrity over several decades. The Drop Weight Tear Test (DWTT) is widely used as the test method to evaluate the resistance against the brittle fracture for linepipe steels. However, an abnormal fracture frequently occurs during the DWTT in recent high toughness line pipe steels. The abnormal fracture is also known as inverse fracture. The abnormal fracture is defined as the cleavage fracture is observed at the hammer side in DWTT specimen although the ductile fracture firstly initiates from the notch tip side. Many studies for abnormal fracture appearance/behavior have been carried out in order to clarify the mechanism of the abnormal fracture occurrence and to ensure the prevention of long brittle fracture propagation for pipelines.

In this study, a compressive pre-straining at the impact hammer side in the DWTT specimen was evaluated under quasi-static load conditions. The specimen’s surfaces were electrolytically-etched to print circle patterns with 5 mm in diameter in order to measure plastic strain. Charpy impact specimens were taken from the quasi-static loaded and unloaded DWTT specimen to measure the possible influence of pre-straining on toughness. The impact test results show that more than 2 % of the compressive pre-strain gave 7 to 10 % decrease of the Charpy upper-shelf energy. The effect of pre-straining on tensile property was also evaluated. These present experiments indicate that the occurrence of abnormal fracture near the hammer side can be attributed to the compressive pre-straining. Furthermore, the chevron-notched and the pre-cracked DWTTs and the partial gas burst test were conducted in order to compare the brittle-to-ductile transition temperature. Based on these experiments, the effect of notch configuration on the brittle-to-ductile transition temperature and the correlation between DWTTs and pipe test were discussed. In addition, the relationship between the pre-straining and the abnormal fracture appearance was considered.

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Keywords: DWTT; Linepipe steel; Brittle fracture; Abnormal fracture appearance; Pre-strain; Partial gas burst test

* Corresponding author. Tel.: +81-6-7670-5875; fax: +81-6-6489-5794.
E-mail address: amano.4bf.toshihiko@jp.nssmc.com

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1. Introduction

Brittle fracture control is one of the most important subjects in natural gas transmission pipeline in order to maintain structural integrity over several decades. The Drop Weight Tear Test (DWTT) is widely used as test method to evaluate the resistance against brittle fracture for linepipe steels. However, abnormal fracture which is also known as inverse fracture frequently occurs during DWTT in recent high toughness line pipe steels. The abnormal fracture is defined as the cleavage fracture is observed at the hammer side in DWTT specimen although the ductile fracture firstly initiates from the notch tip side. Many studies for the abnormal fracture appearance/behavior have been carried out in order to clarify the mechanism of abnormal fracture occurrence and to ensure the prevention of long brittle fracture propagation for pipelines. Progress for measuring technique and analysis technique during DWTT such as continuous shoot using high-speed camera contribute to the understanding abnormal fracture occurrence. The mechanism of abnormal fracture occurrence has been steadily become clear such studies.

In this study, compressive pre-straining at the impact hammer side in DWTT specimen was evaluated under quasi-static load conditions. The specimen’s surfaces were electrolytically-etched to print circle patterns with 5 mm in diameter in order to measure plastic strain. Charpy impact specimens were taken from the quasi-static loaded and unloaded DWTT specimen to measure the possible influence of pre-straining on toughness. Furthermore, the DWTTs with several types of notch such as chevron notch, pre-cracked notch and the partial gas burst test were conducted in order to compare the brittle-to-ductile transition temperature. Based on these experiments, the effect of notch configuration on the brittle-to-ductile transition temperature and the correlation between DWTTs and pipe test were discussed. In addition, the relationship between the pre-straining and the abnormal fracture appearance was considered.

Nomenclature

| AFA | Abnormal Fracture Appearance | PN | Pressed Notch |
|-----|------------------------------|----|---------------|
| API | American Petroleum Institute | SA | Shear Area    |
| CN  | Chevron Notch               | SATT | Shear Area Transition Temperature |
| DNV | Det Norsk Veritas           | SMYS | Specified Minimum Yield Stress |
| DWTT| Drop Weight Tear Test       | SPC | Static pre-cracked |

2. Material and test procedures

2.1. Material

Table 1 shows material used in this study. API 5L X65 Grade UO linepipe steel manufactured by thermo-mechanical control process (TMCP) is prepared. The dimensions of the pipe are 609.6 mm (24in.) in outer diameter (OD), 19.1 mm in wall thickness (WT) and 9000 mm in Longitudinal length. Table 1 also summarizes the material properties of the base metal with respect to the tensile property and the Charpy absorbed energy. The yield strength (YS) and the tensile strength (TS) in Table 1 were obtained from \( \phi 8.9 \text{ mm} \) round-bar tensile specimens in the transverse direction. The yield stress is defined at the 0.5 % total strain. Fig. 1 shows the Charpy test results. Charpy upper shelf absorbed energies of the pipe tested at + 0 °C was 382 J.

| Pipe ID | Grade | Pipe size | Tensile properties | Charpy upper shelf energy |
|---------|-------|-----------|--------------------|--------------------------|
|         |       | WT (mm)   | OD (mm) | YS (MPa) | TS (MPa) | tEL (%) | Cv (J)   |
| KP251   | X65   | 19.1      | 610    | 532      | 590      | 28.2    | 382      |
Fig. 1. Charpy test results for base metal of the pipe; (a) absorbed energy and (b) shear area fraction

2.2. Drop-weight tear test (DWTT)

In order to investigate the effect of notch configurations on DWTT results with respect to the brittle-to-ductile transition curves, the shear area and the abnormal fracture appearances, three kinds of DWTT specimens were prepared. Fig. 2 shows the specimen configurations and notch types. The pressed notch DWTT (PN-DWTT) specimen is a standard specimen in API 5L/DNV standard. The chevron notch DWTT (CN-DWTT) is also standardized in API. The static pre-cracked DWTT (SPC-DWTT) is prepared using PN-DWTT specimen by conducting static three-point bending test. The details for static pre-cracking method are shown in following section. All DWTT specimens have initially same notch depth. All specimens were flattened and taken from transverse direction of pipe. Fracture surfaces were observed to evaluate shear area fraction and abnormal fracture appearances.

2.3. Static three-point bending test

The static three-point bending tests were conducted at room temperature in order to prepare the SPC-DWTT and the pre-strained materials. Fig. 3 shows a method of statically pre-cracking and measuring degrees of pre-straining. Static pre-crack was induced in the standard DWTT specimens with pressed notch (PN-DWTT) which had dimensions of 76.2 x 305 x 19.1 mm in transverse direction (Fig. 2 (a)). As shown in Fig. 3 (b), the load was applied until a drop in maximum load of approximately 1.25 % (Wilkowski et al., 2012). The surface of the PN-DWTT specimens was electrolytically-etched to print circle patterns with 5 mm in diameter in order to measure the plastic strain (Fig. 3 (c)). Fig. 4 shows an example of the strain distribution after the static three-point bend test in terms of (a) the plastic strain in the traverse direction, (b) the plastic strain in the propagation direction and (c) the equivalent plastic strain. The equivalent plastic strain $\varepsilon_{eq}$ was evaluated from the strain components by Eq. (1);
\[
\varepsilon_{eq} = \frac{1}{3} \sqrt{\varepsilon_x^2 + \varepsilon_y^2 + \varepsilon_z^2}
\]

\[
\varepsilon_z = \frac{1}{(\varepsilon_x + 1)(\varepsilon_y + 1) - 1}
\]

Where, \( \varepsilon_x \) is the strain in the traverse direction, \( \varepsilon_y \) is the strain in the propagation direction (see Fig. 3(c)) and \( \varepsilon_z \) is the strain in the through-thickness direction. \( \varepsilon_z \) was obtained considering the volume constancy condition in Eq. (2).

The Charpy V-notch impact specimens were taken from quasi-static loaded and unloaded DWTT specimens to evaluate the effect of pre-straining on the absorbed energy. The round-bar type tensile specimens whose diameter was 8.9 mm were also taken from loaded and unloaded DWTT specimens. These pre-strained specimens were taken from several locations whose degrees of pre-straining were -4.5 to 4.6 % for the Charpy specimens and were -6 to 12.0 % for the tensile specimens. The Charpy impact tests were conducted at room temperature which is approximately 23 °C because there are not enough specimens to evaluate effect of pre-straining on transition curve. Tensile tests were also conducted at room temperature.

Fig. 3. Method of preparing pre-strained materials; (a) Static three-point bending test, (b) Load vs. displacement curve and (c) circle patterns on specimen surface to measure the plastic strain

Fig. 4. Strain distribution after static three-point bending test; (a) traverse direction (b) propagation direction and (c) equivalent plastic strain

2.4. Partial gas burst test

A partial gas burst test was conducted at low temperature in order to investigate fracture behavior of pipe material and to evaluate a local strain during the crack propagation. Fig. 5 shows illustrations of the partial gas burst test. In this test, the pipe body at upper geometrics was cooled by using liquid nitrogen because a surface notch was machined at upper geometrics of the pipe as fracture origin. The configuration of surface notch is shown in Fig. 5. The stepped notch is adopted in this test. The length and depth of deep notch section are 500 mm and 10 mm, respectively. The depth of deep notch section was determined so that fracture occurs at the pressure correspond to 0.80 SMYS using the Charpy energy-based equation for axial part-through-wall crack in pipe (Kiefner et al., 1973).
The cooling baths were set up on the test vessel. In order to control the pipe surface temperature uniformly, the solenoid valves were used. In this test, it was possible to obtain fracture behaviors under two different test temperatures in one burst test because temperatures in the cooling baths were separately controlled between the west side and the east side. The pipe wall temperatures were measured at 5 mm under the pipe surface in the drilled holes because the pipe surface was affected fluid injections. The test vessel contained 85 % cooled water (not frozen) and 15 % air gap. After keeping the target temperature, the temperatures were held over 20 minutes, and then the test pipe was pressurized until fracture occurs. The nitrogen gas was used as the pressurized medium. Numerous thermocouples, timing wires, pressure transducer, strain gauge and scribed grid were setup to measure the pipe wall temperature, fracture speed, burst pressure, local strain during crack propagation and plastic strain. The test was conducted at our original burst test facility in Japan.

3. Experimental results and Discussions

3.1. Comparison of brittle-to-ductile behavior between DWTTs and partial gas burst test

Table 2 summarizes the main results of the partial gas burst test. Fig. 6 shows the setup of the test pipe before the test and the fracture appearances after the test. The burst pressure was 23.9 MPa which corresponds 84 % SMYS (381 MPa of hoop stress). The burst pressure was a little higher than target pressure. In this test, both brittle crack and ductile crack appeared at the ligament of the initial stepped notch depending on pipe wall temperatures. In the west side, whose temperatures were controlled at between -11 to -21 °C, the ductile fracture was initiated and propagated into the pipe body in fully ductile mode. On the other hand, in the east side, whose temperatures were controlled at between -17 to -38 °C, the single brittle fracture was initiated in the thicker ligament of the initial steeped notch and propagated into the pipe body. Then the single brittle fracture was quickly arrested and change to a shear ductile fracture. The maximum fracture speeds were 290 m/s in the west side and 390 m/s in the east side, respectively. The maximum compressive strain in the west side before reaching the propagating crack which was measured at 40mm away from crack front was approximately 1.3 %. This was lower than that observed in PN-DWTT using the high speed camera (Fujishiro et al., 2012; Sakimoto et al., 2013). It seems that a large compressive strain was induced by bending deformation in PN-DWTT specimens.

| Grade | Pressure (MPa) | Hoop stress (MPa) | side | Fracture appearance | Temperature where SA% measured (°C) | Shear lip area fraction (%) |
|-------|----------------|------------------|------|---------------------|-------------------------------------|---------------------------|
| X65   | 23.9           | 381              | West side | Fully Ductile      | -11                                 | 100                       |
|       |                 |                  | East side | Brittle fracture quickly change to ductile fracture | -18 | 65-100 |
The DWTT results are shown in Fig. 7. The 85% shear area transition temperature (SATT) using DNV SA% rating method which includes ductile fracture from notch due to abnormal fracture appearance (AFA) behavior in rating for the PN-DWTT, the CN-DWTT and the SPC-DWTT were -30 °C, -25 °C and -13 °C, respectively. The brittle-to-ductile transition curves in the CN-DWTT and the SPC-DWTT shifted toward a higher temperature side compare to that in the PN-DWTT due to reducing the crack initiation energy from the total energy. However, the abnormal fracture appeared regardless of types of notch in the transition region. The shear area fractions (SA%) in the pipe burst test are also plotted in Fig. 7 in order to compare with that in several notched DWTT specimens. The SA% in the pipe burst test is defined shear lip thickness fraction rated same evaluation area as the DWTT SA rating. As shown in Fig. 7, the SA% in the pipe burst test result located near the brittle-to-ductile transition curve in the SPC-DWTT specimen.

Fig. 8 compares fracture appearances at -10 °C and -20 °C for the PN-DWTT specimen, the CN-DWTT specimen, the SPC-DWTT specimen and the tested pipe. As shown in Fig. 8, the clear shear lips can be observed at -20 °C for the tested pipe and it is similar to the normal fracture appearances, which means the brittle crack initiates at the root of notch, in the SPC-DWTT specimens. On the other hand, the abnormal fracture appearances appeared both at -10 °C and -20 °C for the PN-DWTT specimens. It seems that the pre-straining occurred at the hammer impact side due to higher resistance against crack initiation at root of the notch.
Fig. 8. Comparison of fracture appearances; (a) test temperature of -10 °C and (b) test temperature of -20 °C (Con’t)

3.2. Effect of pre-strain on abnormal fracture occurrence in DWTT

Fig. 9 shows the results of the Charpy impact tests and the tensile test for the non-strain and the pre-straining materials. The all tests were conducted at the room temperature. As shown in Fig. 9 (a), for the both compressive and tensile pre-strainings, more than 2 % pre-straining gave 7 to 10 % decreases of the Charpy upper-shelf energy. On the other hand, with regard to tensile properties, as the degree of pre-straining were increased, the tensile strengths were increased, see Fig9 (b). However, the yield strength of the materials subjected to within 5 % compressive pre-straining slightly decreased although the yield strength of the tensile pre-strained materials increased. It seems that decreasing of the yield strength in compressive pre-straining may contribute to a large deformation and local embrittlement prior to crack initiation. Further investigation such as brittle-to-ductile transition curve of Charpy test obtained from pre-strained materials is needed to relate abnormal fracture occurrence to embrittlement behavior caused by pre-straining.

Fig. 9. (a) Charpy absorbed energy and (b) Tensile properties of pre-strained specimens tested at room temperature

Fig. 10. Plastic strain near the crack front for the SPC-DWTT; (a) after the static three-point bending test (b) after the DWTT

Shear area : 100 %
Tested Temp. : -20 °C

Shear area : 95 % Normal fracture
Tested Temp. : -20 °C

Shear area : 66 %
Tested Temp. : -20 °C

Shear area : 65 to 70 %
Temp. : -18 °C

Shear area : 70 to 100 %

PN-DWTT

CN-DWTT

SPC-DWTT

Pipe burst test

Fig. 10. Plastic strain measured at partial gas burst test (a) after the static three-point bending test (b) after the DWTT

AFA

Normal fracture

 Compression Tension (a) Compression Tension Plastic strain measured at partial gas burst test (b)
Fig. 10 compares the plastic strain in the traverse direction near the crack front for the SPC-DWTT tested at -10 °C in between the specimen with AFA and without AFA. Approximately 4.0 % of the compressive pre-straining occurred after the static bending test in the specimen appeared AFA in DWTT while 2.0 % of the compressive pre-straining occurred in the specimen without AFA in DWTT. Fig. 10 (b) shows the plastic strain after the SPC-DWTT. Fig. 10 (b) also shows the plastic strain measured in the partial gas burst test using the scribed grid. The plastic strains in the SPC-DWTT specimen without AFA were lower than that in pipe. On the other hand, for the SPC-DWTT specimen with AFA, the plastic strains at both the hammer impact side and the root of notch side which appeared the brittle fracture were larger than that measured at the fully ductile fracture region. Therefore, the abnormal fracture occurs easily because the range of strain in hammer impact side was relatively high.

4. Conclusions

In this study, the DWTTs with the pressed notch (PN), the chevron notch (CN), the pre-cracked notch (SPC) and the partial gas burst test were conducted in order to compare the brittle-to-ductile transition temperature. The effect of pre-straining near the impact hammer side in the SPC-DWTT specimen was also evaluated at static three-point bending test. Charpy impact specimens were taken from quasi-static loaded and unloaded DWTT specimen to measure the possible influence of pre-straining on toughness. Based on these experiments, the relationship between the pre-straining and the abnormal fracture appearance was considered. The main conclusions obtained in this study are as follows;

- The brittle-to-ductile transition curves in the CN-DWTT and the SPC-DWTT shifted toward a higher temperature side compare to that in the PN- DWTT. However, the abnormal fracture appeared regardless of types of notch in the transition region.
- The fracture appearances in the pipe burst test were similar to that in the SPC-DWTT specimen which is easy to initiate the brittle fracture due to reducing crack initiation energy while the abnormal fracture occurred at near hammer impact side.
- More than 2 % of compressive and tensile pre-straining gave 7 to 10 % decreases of the Charpy upper-shelf energy. Further investigation such as brittle-to-ductile transition curve of Charpy test obtained from pre-strained materials is needed to relate abnormal fracture occurrence to embrittlement behavior caused by pre-straining.
- The abnormal fracture appearance located at above the 85 % SATT occurred due to the pre-strain effect and the deflection due to bending prior to crack initiation.

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