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Effects of Pre-Strains on Failure Assessment Analysis to API 5L X65 Pipeline

Jonghyun Baek*†, Youngpyo Kim*, Woosik Kim* and Changsung Seok**

Abstract This paper prescribed the structural integrity of the API 5L X65 pipeline subjected to tensile pre-strain. The effects of pre-strain on the mechanical properties of API 5L X65 pipe were substantially investigated through a variety of the experimental procedures. Axial tensile pre-strain of 1.5, 5 and 10% was applied to plate-type tensile specimens cut from the pipe body prior to mechanical testing. Tensile test revealed that yield strength and tensile strength were increased with increasing tensile pre-strain. The increasing rate of the yield strength owing to the pre-strain is greater than that of the tensile strength. However, the pre-strain up to 5% had a little effect on the decreasing of the fracture toughness. The structural integrity of the API 5L X65 pipeline subjected to large plastic deformation was evaluated through the fitness-for service code.

Keywords: CTOD, Charpy Impact Energy, Fracture Toughness, Pre-Strain, Tensile Strength

1. Introduction

Pipelines have been used as one of the most economical and safe ways for transmitting natural gas which are still being constructed around the world. Pipelines for natural gas transmission may be subjected to plastic deformation by outside force such as ground subsidence, ground liquefaction, cold bending and mechanical damage (Hagiwara et al., 2001; Cosham and Hopkins, 2004).

The integrity assessment of the pipeline is the most important problem to be solved first of all for prevention of any fracture accident of the pipeline. As a result of considerable effort on the integrity assessment, a criterion of fitness for service(FFS) based on the engineering critical analysis(ECA) has been suggested. Codes such as BS 7910, API RP 579 and WES 2805 have been widely used for analysis of the fracture behavior of the pipeline in the gas and oil industry, and these codes suggest that fracture assessment using a failure assessment diagram (FAD) should be performed.

In this study, structural integrity evaluation of the API 5L X65 pipe was conducted by using the BS 7910 procedure. There are 3 levels in the BS 7910 code for evaluating crack-like flaws. The fracture toughness and strength of the components are employed to assess the level 1. The level 2 requires a stress-strain curve data for the material containing the flaw at the assessment temperature in addition to the data employed in the level 1. Tensile test, CTOD test and Charpy impact test over the temperature range from room temperature to -40℃ were performed to evaluate the integrity of the deformed pipeline up to 10% tensile pre-strain by using the BS 7910 code and

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Received: October 1, 2008, Revised: June 9, 2009, Accepted: June 16, 2009. * R&D Division, Korea Gas Corporation, 638-1, Il-dong, Sangnok-gu, Ansan, Gyeonggi-do, 425-790, Korea, ** School of Mechanical Engineering, Sungkyunkwan University, 300, Chunchun-dong, Jangan-gu, Suwon, 440-746, Korea, † Corresponding Author: jhbaek@kogas.re.kr

its results are discussed in this paper.

2. Experimental Procedure

The material used in this study was the API 5L X65 pipe having a wall thickness of 17.5 *mm* and an outer diameter of 762 mm for natural gas transmission. The API 5L X65 pipe has a minimum specified yield strength of 448 *MPa* and an ultimate tensile strength of 530 *MPa* according to API 5L specifications. Axial tensile pre-strains of 1.5% , 5% and 10% were applied to the plate-type tensile specimens extracted from the pipe body prior to mechanical testing to evaluate the pre-strain effect on the material properties of the API 5L X65 pipe. Ultrasonic test was carried out to detect the internal defects of the pre-strained specimens in accordance with of KS B 0896. Defects such as crack or porosity were not detected in all pre-strained specimens. The CTOD specimens for fracture toughness test were prepared from the pre-strained plate-type tensile specimen in Fig. 1. The CTOD test was performed at four different temperatures between 20℃ and -40℃ in accordance with the BS 7448. The Charpy impact specimens were extracted from the pre-strained plate-type tensile specimen whose notch with LS direction was propagated the through thickness from the outer surface of the pipe to inner side of pipe in accordance with the ASTM E23. All tests were conducted in triplicate at each of the different temperatures.

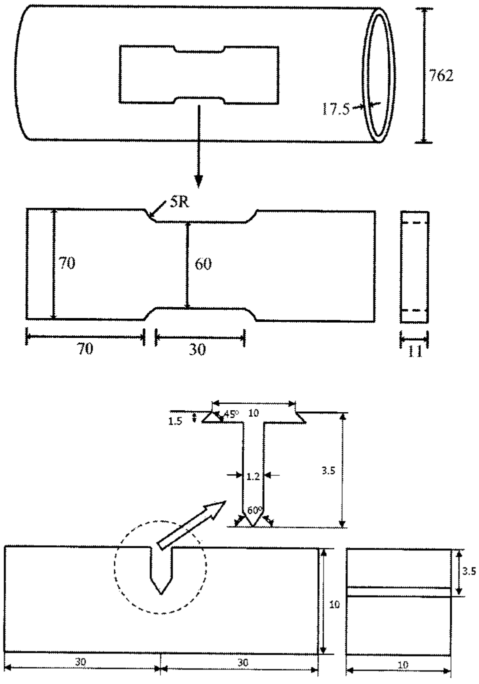

Fig. 1 Plate-type tensile specimen for pre-strain and 3-point bend specimen for the CTOD test

3. Result and Discussion

Yield strength, tensile strength and elongation on the material without pre-strain (virgin material) and with tensile pre-strain of 1.5, 5 and 10% are shown in Fig. 2. The yield strength and tensile strength of materials with 5% and 10% tensile pre-strains considerably increased as compared with the virgin material. The increasing rate of the yield strength owing to the pre-strain is greater than that of the tensile strength. It is indicated from Fig. 2 that the tensile pre-strain has a significant effect on the yield strength. However, the yield strength and tensile strength of tensile pre-strained material of 1.5% somewhat decreased as compared with the virgin material except for the yield strength at -20 and -40°C. The pre-strain of 1.5% corresponds to the yield drop zone in carbon steels without pre-strain. Prediction equations of the yield strength with variation of the temperature were given by the WES 2805 and the BS 7448 as follows

$$YS_{(L)} = YS_{(R)} + \frac{100000}{(491+1.8T)} - 189 \tag{1}$$

$$YS_{(L)} = YS_{(R)} \exp\left[(481.4-66.6\ln YS_{(R)})\left(\frac{1}{T+273}-\frac{1}{293}\right)\right] \tag{2}$$

where $YS_{(L)}$ denotes the yield strength (*MPa*) at the target temperature, $YS_{(R)}$ indicates the yield strength at room temperature and T is the target temperature (℃). Eqns. (1) and (2) are used to estimate the yield strength at target temperature.

However, the above equations can not be applied to estimate the yield strength of the pre-strained material at target temperature because they do not have a component to express the quantity of the pre-strain. Fig. 2 reveals that the yield strength and the tensile strength rise in proportion with the quantity of the pre-strain. We propose in this paper that the estimating equations of the yield strength and the tensile strength with variation of the pre-strain (1.5~10%) and temperature are given in eqns. (3) and (4)

$$YS_{(T)} = YS_{(VR)} - 20.58 + 16.61\text{Prestrain}\% + 6.47(-0.05\text{T} + 1) \tag{3}$$

$$UTS_{(T)} = UTS_{(VR)} - 16.07 + 7.02\text{Prestrain}\% + 11.4(-0.05\text{T} + 1) \tag{4}$$

where $YS_{(T)}$ is the yield strength (*MPa*) at the target temperature, $YS_{(VR)}$ is the yield strength without pre-strain at room temperature, $UTS_{(T)}$ is the tensile strength at the target temperature, $UTS_{(VR)}$ is the tensile strength without pre-strain at room temperature and *T* is the target temperature (℃).

Pre-strain effect on the CTOD and Charpy V-notch energy(CVN) is shown in Fig. 3. The pre-strain had a little influence upon the CTOD up to pre-strain of 5% however the pre-strain of over 5% had a detrimental effect on the fracture toughness. The API 1104 provided the CTOD value for the weld metal to estimate the critical crack size. The minimum CTOD value obtained at or below the lowest anticipated service temperature is 0.127 *mm* or 0.254 *mm* according to the API 1104. The minimum CTOD value obtained at the pre-strain of 10% and -40℃ is 0.209 *mm*. The pre-strain had a slight effect on the CVN up to pre-strain of 5%. The CVN values decreased with decreasing temperature just as the published results (Hagiwara et al., 2001; Cosham and Hopkins, 2004). There is hardly a change of the CVN with variation of the

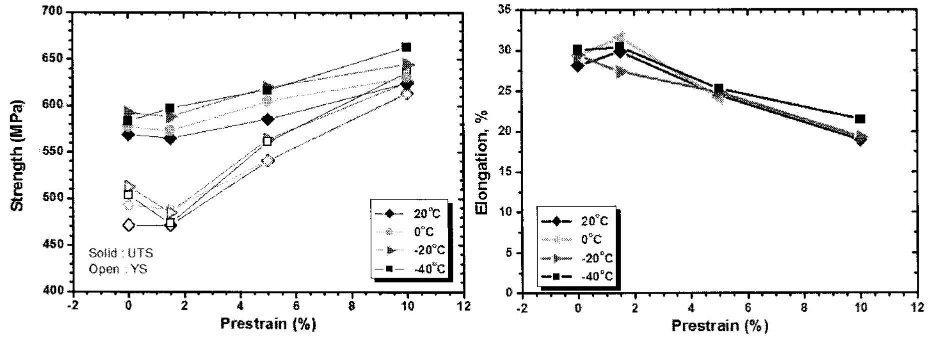

Fig. 2 Yield strength, tensile strength and elongation for the virgin and pre-strained material

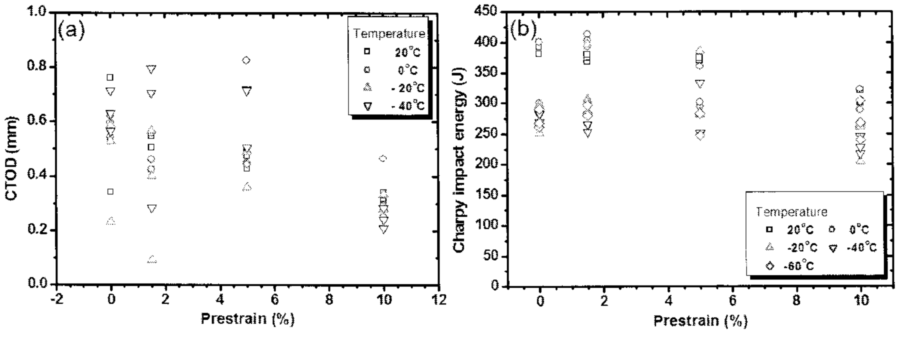

Fig. 3 (a) CTOD and (b) Charpy impact energy for the virgin and pre-strained material quantity of the pre-strain in case of below -40℃, however. The average CVN value prescribed on the pipe body in the API 5L specification is 27 *J* for transverse specimens or 41 *J* for longitudinal specimens below the API X70 grade pipe. It is indicated from Fig. 3 that the pre-strain of 5% has a little effect on the decreasing of ductility of the material employed in this study.

Integrity assessment of the deformed pipeline by using the level 2 in the BS 7910 code was performed for axial surface crack in pipeline. Internal pressure of 8 *MPa* as a primary stress is employed to assess the integrity of the pipeline having a flaw. The primary stress is applied to assess the L_r ratio of the horizontal axis in Fig. 4. L_r, load ratio, is defined as

$$L_r = \frac{\sigma_{ref}}{\sigma_{ys}} = \frac{\sigma_{flow}}{\sigma_{ys}} = \frac{\left(\sigma_{ys} + \sigma_{uts}\right)/2}{\sigma_{ys}} \le L_r^{\max} \qquad (5)$$

where σ_{flow} is the flow stress which is the average of the yield strength and tensile strength and σ_{ref} is reference stress. Reference stress equation of the D.73 in API 579 code is adopted to calculate the L_r ratio in cylindrical structure having an outer surface crack under internal pressure.

Table 1 presents the fracture toughness and CTOD values for the virgin material and material of 10% pre-strain. The CTOD values obtained from 3 point bending test were converted into K_{JC} to calculate the K_r ratio of the vertical axis in Fig. 4. K_r and K_{JC} are calculated as

$$K_r = \frac{K_C}{K_{mat}} = \frac{K_C}{K_{JC}} \le 1 \qquad (6)$$

$$K_{JC} = \sqrt{\frac{J_{crit}E}{1-\nu^2}} = \sqrt{\frac{m\sigma_{flow}CTOD_{crit}E}{1-\nu^2}} \qquad (7)$$

where K_{mat} and K_{JC} are the fracture toughness derived from J_{crit}, K_C is the stress intensity factor, J_{crit} is critical J value (*MPa-m*), $CTOD_{crit}$ is critical *CTOD*(*m*), *m* is conversion constant (1.4), *E* is Young's modulus and ν is Poisson's ratio. Fig. 4 shows a level 2 FAD by means of the BS 7910 code for pipeline having a crack length of 600 *mm* and crack depth range

Table 1 *CTOD* and K_{JC} values

Materials	Temp.	CTOD (*mm*)	K_{JC} ($MPa\sqrt{m}$)	Temp.	CTOD (*mm*)	KJC ($MPa\sqrt{m}$)
Virgin	0℃	0.586	313.3	-40℃	0.636	356.7
10% Pre-strain		0.336	241.2		0.245	226.6

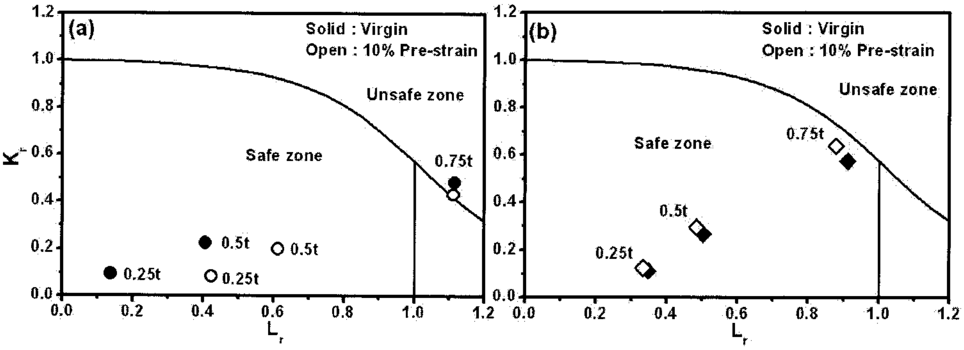

Fig. 4 Level 2 FAD for pipeline having a crack at (a) room temperature (b) and -40℃

from 25 to 75% of wall thickness under internal pressure of 8 *MPa* at room temperature and -40℃. Defects having a crack depth up to 50% of the wall thickness are assessed safe under internal pressure of 8 *MPa*. Defects having a crack depth of 75% wall thickness are appraised unsafe at room temperature. However, defects assessed with mechanical properties obtained at -40℃ are evaluated as a safe state. FAD is comprised of the brittle fracture ratio, K_r, and plastic collapse ratio, L_r. In case of API 5L X65, fracture toughness is less susceptible to temperature variation regardless of pre-strain. Fig. 2 presents that the yield strength and tensile strength are considerably increased with decreased temperature. So, plastic collapse ratio, L_r is increased with decreased temperature as in Fig. 4.

4. Conclusion

Based on the results from the investigation of tensile pre-strain up to approximately 10% for API 5L X65 pipeline steel, following conclusions are drawn. Tensile test revealed that the yield strength and the tensile strength increased with increasing the tensile pre-strain. However, the CTOD and CVN values decreased with increasing tensile pre-strain. However, the pre-strain up to 5% had a little effect on the decreasing of the fracture toughness. In case of defect having a crack depth of 75% of the wall thickness, plastic collapse ratio, L_r , is decreased with decreased temperature due to increasing yield strength.

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