# Effects of Welded Microstructure on Fracture Toughness and Crack Propagation Behavior of API 5L-X65 Pipe

Eddy A. Basuki[1)], Ikhsan Septiansyah[1)], Akhmad A. Korda[1)], Hilman Hasyim[3)]
[1)]Department of Metallurgical Engineering, Bandung Institute of Technology
[3)]PT. Karakatau Steel, Indonesia
basuki@mining.itb.ac.id

***Abstract*--** **Fracture toughness of three diffent zones in welded API 5L-X65, namely base metal, heat affected zone and center weld, were studied in conjuction with the implementation of pipeline project for natural gas transmission in western part of Indonesia. ASTM standard method has been used for fracture mechanics tests from which the curves of load in kN vs. extension in mm have directed to the application of CTOD parameter. The results of analysis showed that the HAZ had the highest CTOD value compared with that of base metal and centre weld. Fracture surface examinations using scanning electron microscope (SEM) confirm that the HAZ has ductile fracture while the centre weld and the base metal have brittle fracture. Based on fracture toughness values obtained, precrack resistant of the pipe was analysed using leak before break criterion. It was found that the centre weld is the weakest zone. The results were used to predict wheater the pipe will break or leak during the operation of the pipe. The simulation results showed that during operation, this pipe will leak before break. Nevertheless, the pipe will break before leak when the pressure is higher than 10 Mpa. Therefore, for the operation of API 5L-X65, it is suggested that the internal pressure in the pipe should less than this critical value.**

***Index Term*--** **fracture toughness, crack propagation, leak before break, API 5L-X65, welded pipe.**

## I. INTRODUCTION

In proposed gas transmission facilities of South Sumatera West Java (SSWJ) project conducted by State Gas Company of Indonesia, steel pipe of API 5L X65 grade manufactured by PT. KHI Pipe Industries will be used. This pipeline is expected to have mechanical properties suitable with the operating condition of the pipeline and exhibits good resistance for various failures that might occur during operation. API 5L-X65 is a group of high strength low alloy (HSLA) steels that have been widely employed[(1)] for transmission of natural gas in some islands of Indonesia. This type of pipeline has been design to comply with the mechanical properties required for the operation of the pipeline. Adjustment in chemical composistion during steel making and microstructural modification during thermo-mechanical controll process (TMCP) are normally implemented in steel sheet production to meet with mechanical properties requirement. Pipeline production, however, involes welding that change the microstructure at certain zone of the steel pipe due to the heating and cooling cycles as well as effect from filler materials [(2)]. Consequently, different mechanical properties in different zones might occur in the pipe system. In the operations of pipeline, special requirement is normally made for the materials to have good resistance to all modes of possible failures. One of the most frequent failure modes in pipeline and structure is crack failures caused by combination of both load and corrosion[(3)].

This study focuses on the crack propagation behavior of pipeline made of API 5L-X65 due to both cyclic and monotonic loads using fracture mechanics test. This test provided the values of fracture toughness of the materials that can be used for further evaluation on the resistance of the pipe to resist crack propagation using leak before break analysis. A series of fracture toughness tests have been done to obtain the values of $K_{IC}$ and CTOD of the specimens for three different regions, *i.e.*, base metal, heat affected zone (HAZ) and center weld. Detail observation using SEM was carried out to gain the cause of this microstructural different and types of crack propagation. The information obtained from this study could be used to manage the operation of the pipeline in the field, especially to know the maximum internal pressure allowed to be operated in the pipeline system. For PT. Krakatau Steel as the steel maker and PT. KHI Pipe Industries as the pipeline manufacturer, the results of this study would be used to evaluate the production of steel and pipeline for pipeline project in the country.

## II. EXPERIMENTAL WORK

The material used for this experiment was a circular welded steel pipe that had API 5L-X65 grade. This pipe had outer diameter and wall thickness of 812.8 mm and 14.3 mm, respectively. Samples for fracture toughness tests were prepared from three different zones, *i.e.*, center weld, HAZ and base metal. Each test variable was carried out for two different samples of similar zone to have the average data of the two samples. Chemical composition and mechanical properties of the material are respectively shown in Table 1 and Table 2.

Table I
Chemical composition of the material

| C | Si | Mn | Cu | Ni | Cr | V | P | S |
|---|---|---|---|---|---|---|---|---|
| 0.052 | 0.242 | 1.10 | 0.1606 | 0.237 | 0.1152 | 0.0818 | 0.0065 | 0.0027 |

| Al | N | Mo | Ti | Nb | B | Nb+V+Ti | Al/N | CE |
|---|---|---|---|---|---|---|---|---|
| 0.0375 | 0.0046 | 0.025 | 0.0021 | 0.0027 | 0 | 0.134 | 8.15 | 0.29 |

Table II
Mechanical properties of the material

| No. | Mechanical Properties | |
|---|---|---|
| 1 | Young modulus, E (Gpa) | 207 GPa |
| 2 | Ultimate tensile strength, $\sigma_{UTS}$ (MPa) | 627.03 Mpa |
| 3 | Yield strength, $\sigma_{YS}$ (MPa) | 547.03 Mpa |
| 4 | Elongation (%) | 38.4% |
| 5 | Yield Ratio (%) | 87% |

ASTM E1290 standard [4,5] allows one of five typical specimen configurations for fracture toughness determination, *i.e.*, compact tension specimen (CT-specimen), disk shape compact specimen, single edge notched bend (SENB), arc shape specimen and middle tension specimen (MT-spesiment). This study used CT-spesimen where the dimension is shown in Fig. 1 (a). Initial crack formation was carried out at room temperature.

The geometry for all specimens was essentially the same, *i.e.*, 10 and 32 mm for thickness (B) and wide (W), respectively. The geometry factor (Y) was calculated using the following equation [5].

$$Y = \frac{\left(2+\frac{a_0}{W}\right)\left(0.886+4.64\frac{a_0}{W}-13.32\left(\frac{a_0}{W}\right)^2+14.72\left(\frac{a_0}{W}\right)^3-5.6\left(\frac{a_0}{W}\right)^4\right)}{\left(1-\frac{a_0}{W}\right)^{3/2}} \quad (1)$$

As the length of the notch was 16 mm and the minimum pre-crack for fatigue load was 1.3 mm, then $\left(\frac{a_0}{W}\right)$ = 0.54 and Y = 11. Based on ASTM E1290 [5], the rasio $\left(\frac{a_0}{W}\right)$ = 0.45 ≤ $\left(\frac{a_0}{W}\right)$ ≤ 0.55. Therefore, with $\left(\frac{a_0}{W}\right)$ = 0.54 and W = 32 mm, the value of $a_0$ is 17.3 mm. The maximum fatigue load for this condition should comply with one criterion of the following equations [5].

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$$P_f = \frac{0.4\,Bb_0{}^2\sigma_y}{(2W+a_0)} \quad (2)$$

$$\frac{\Delta K}{E} \leq 0.005\sqrt{mm} \quad (3)$$

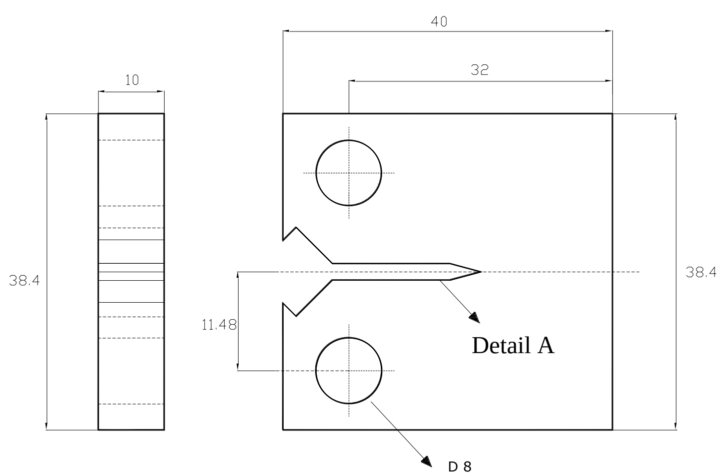
Where $B_0 = W - a_0$ and B is the specimen thickness, while E is Modulus Young. For B = 10 mm and $b_0 = W - a_0$, or it is equal with 4.70 mm, therefore when $\sigma_y = \frac{\sigma_{ys} + \sigma_{uts}}{2}$, $P_f$ would be equal 6.24 kN. Moreover, when R = 0.1, it could be found that $P_{max}$ = 6.24 kN and $P_{min}$ = 0.62 kN. For the second criterion, when E = 207 Gpa and $\Delta K = 5.10^{-3} \times 207.10^{9}$ = 1035 MPa $\sqrt{mm}$, using the following equation (5,6),

$$\Delta K = \frac{\Delta F . Y}{B. \sqrt{W}} \quad (4)$$

it could be found that ΔF is 5.32 kN. According to ASTM E1290, load in criterion 2 was used for precrack formation of the specimens.

In order that the cracks, due to fatigue load, apparently appear, the tip of the sample should have maximum radius of 0.08 mm. The specimens were attached by two pins from which the load was applied. After fatigue loading that produce pre-cracks, monotonic loads were then applied until the specimens break. In this test, the crack opening rate was controlled by clip gauge attached on the flaw of the specimens, and according to ASTM E1290 standard, it should be in the range of 0.55 – 2.75 Mpa $\sqrt{m}$ /s. From this test, several curves that relate loads and crack openings would be obtained and used for further calculation. When the curves of different specimens indicate small plasticity, then the fracture toughness would be based on $K_{1C}$, while for those with high plasticity, crack tip opening displacement (CTOD) should be used.

A universal testing machine with maximum capacity of 250 kN where a servo controller attached was used for this experiment, as shown in Fig. 1(b). This machine was equipped with a computer used to collect data obtained from a censor. To identify the modes of crack propagation for each part of the pipe, SEM observations were implemented. Analysis on all fracture surfaces of the samples was carried out to obtain the phenomena of crack propagation for diffenet zones in the pipe. These fracture surfaces would also be used to analyze the fracture toughness behavior obtained from the fracture toughness tests.




(a)

(b)

Fig. 1. Configuration of CT-Spesimen and Universal Testing Machine used in this study.

## III. RESULTS AND DISCUSSION

The fracture surfaces images of all samples showed the occurence of two different fracture zones, *i.e.*, fracture due to fatigue and static loads, respectively, as shown in Fig. 2. As the tip of fatigue crack is not normally straight, the average of crack lengths was measured from the average of crack lengths with difference of less than 5%, as shown schematically in Fig. 3. For monotonic load, the resulted outputs of the fracture tests were presented in curves that relate load and displacement. In fracture tests, the curves would be similar with that shown in either Fig. 4 for CTOD or Fig. 5 for $K_{1C}$. The degree of plasticity in the material could be identified easily from these curves. The $K_{IC}$ parameter is used for fracture toughness calculation when the plasticity is low, while CTOD parameter is used when the plasticity is high.

CTOD parameter is used to determine the fracture toughness(7) by measuring the displacement with a clip gage attached on the sample during test. The curves provide values of $F_U$, $F_M$, $V_U$ when a straight line parallel with the linear line in the curve is made crossing the curve, as shown schematically in Figure 6. When $F_U$, $F_M$, $V_U$ values are determined then the CTOD can be calculated either as $\sigma_c$, $\sigma_u$, $\sigma_m$, depending on the un-stable crack length. It would be $\sigma_c$ when the un-stable crack length $\Delta a_p < 0.2$ mm (0.008 inch), $\sigma_u$ when the un-stable crack length $\Delta a_p > 0.2$ mm (0.008 inch) and $\sigma_m$ when at the first time reach the maximum load at stable condition (plastic zone). The $\Delta a_p$ is physical crack extension defined as follows.

$$\Delta a_p = a_p - a_0 \tag{5}$$

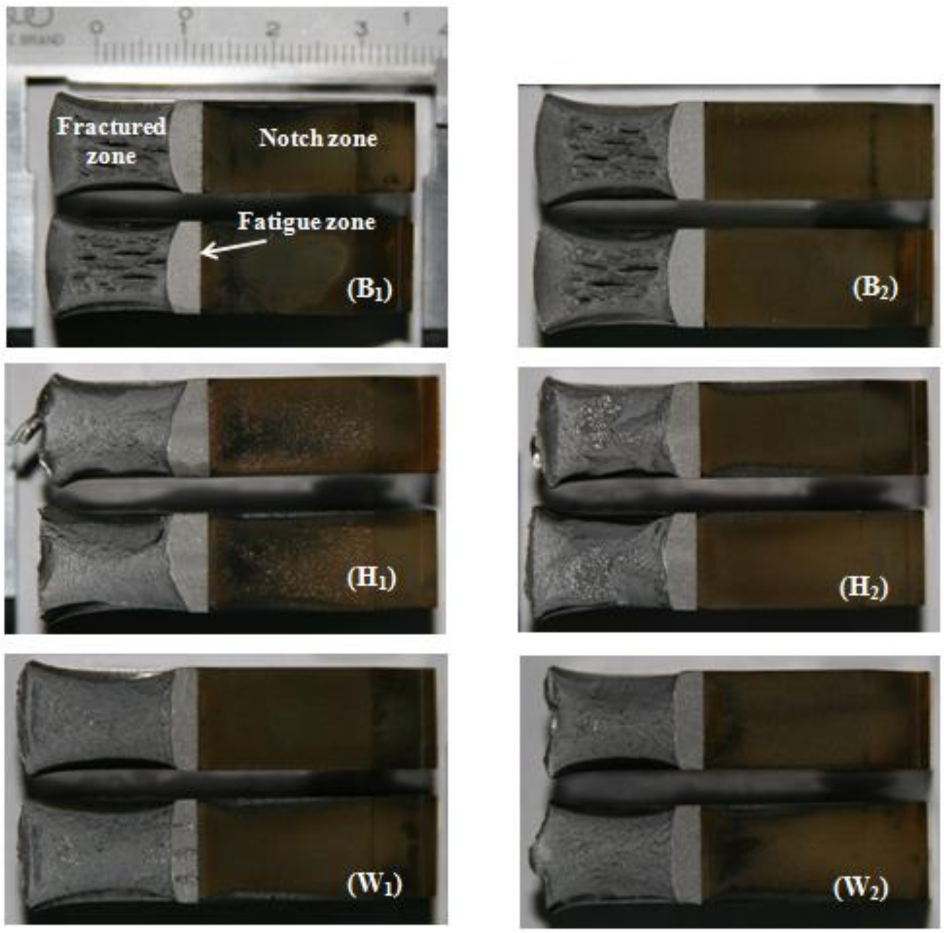



Fig. 2. Fracture surfaces of three different zones of the samples, i.e., base metal (B), HAZ (H) and center weld (W).

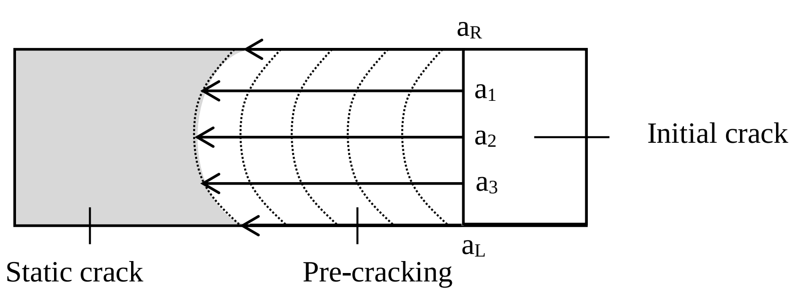



Fig. 3. Illustration to define average crack length.

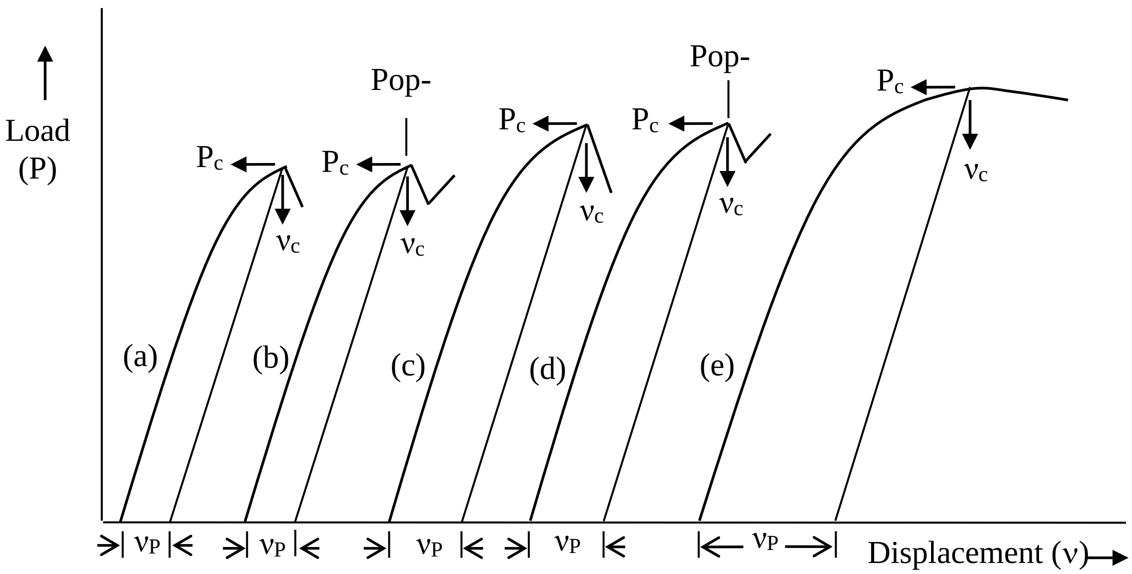



Fig. 4. Several different possible curves of loads versus displacement for CTOD [5].

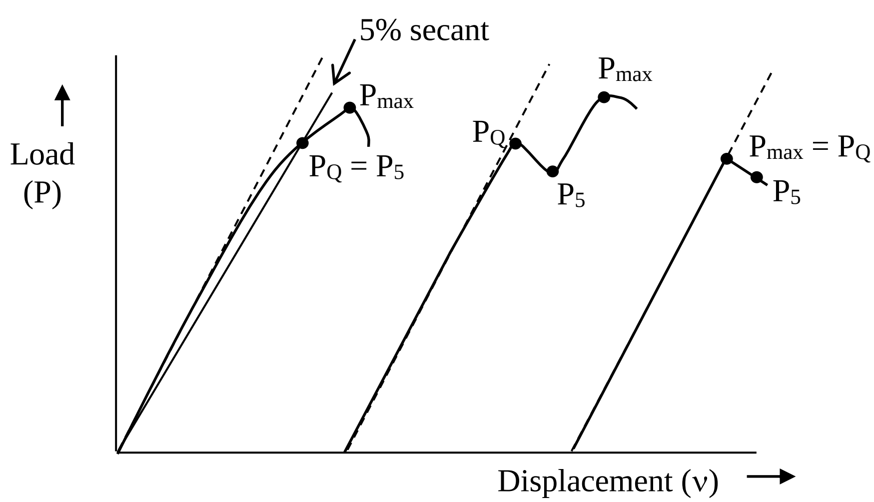



Fig. 5. Different possible curves that relate load and displacement for determination of values [5].

From the above obtained data, the CTOD can be calculated using the following equation [8,9].

$$\delta = \frac{K^2(1-\nu^2)}{2\sigma_{ys}E} + \frac{r_p\,(W-a_0)\nu_p}{[r_p\,(W-a_0)+a_0+z]} \quad (6)$$

Where ν is Poisson's ratio, which is equal with 0.33, while $r_p$ is equal 0.46 (for CT-s when $0.5 \le \frac{a_0}{W} \le 0.55$) and z equal 0 (for CT-s). For the determination of $K_{1C}$, curves of either load vs. displacement (crack opening) or load vs. force line change can be used. From these curves, the value of $P_Q$ can be determined when the ratio of $P_{max}/P_Q$ <1.1. Eventually, the value of $K_Q$ can be obtained using the following equation[9].

$$K_Q = \frac{P}{B\sqrt{w}}\, f\left(\frac{a}{w}\right) \quad (7)$$

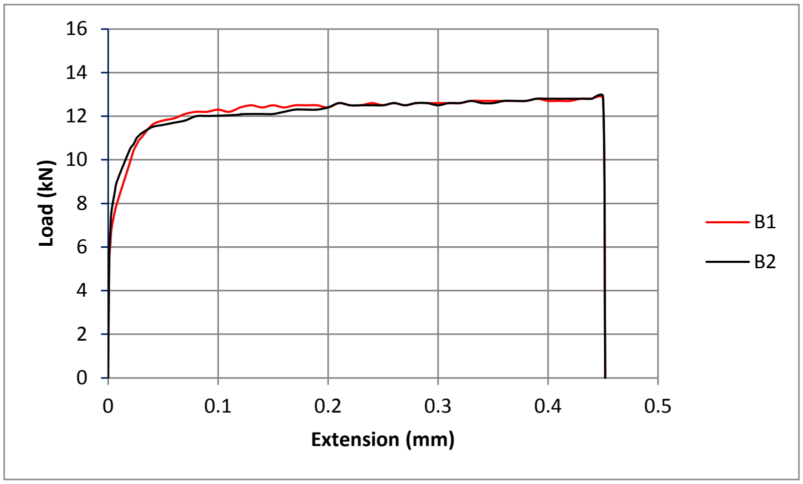
where f(a/w) is a geometry function that for the specimen used in this experiment can be calculated from the following equation[9].

$$f\left(\frac{a}{w}\right) = \left(2+\frac{a}{w}\right)\left[0.886 + 4.64\,\frac{a}{w} - 13.32\left(\frac{a}{w}\right)^2 + 14.72\left(\frac{a}{w}\right) - 5.6\left(\frac{a}{w}\right)\right] \Big/ \left(1-\frac{a}{w}\right)^{3/2} \qquad (8)$$

Meanwhile, the value of $K_Q$ is $K_{IC}$ when the following criteria is fulfilled[10,11].

$$B \geq 2.5\left(\frac{K_{1C}}{\sigma_y}\right)^2 \qquad (9)$$

Based on the tests results of load vs. displacement curves, as shown in Fig. 6 and measurement data on the crack surface as shown in Table 3, it is clearly seen that the material had large plastic zone, so that CTOD is more appropriate for fracture toughness determination. Tables 4 up to 6 show the data derived from the test curves for fracture toughness calculation, each for different zone, which are heat affected zone, base metal and center weld zone.

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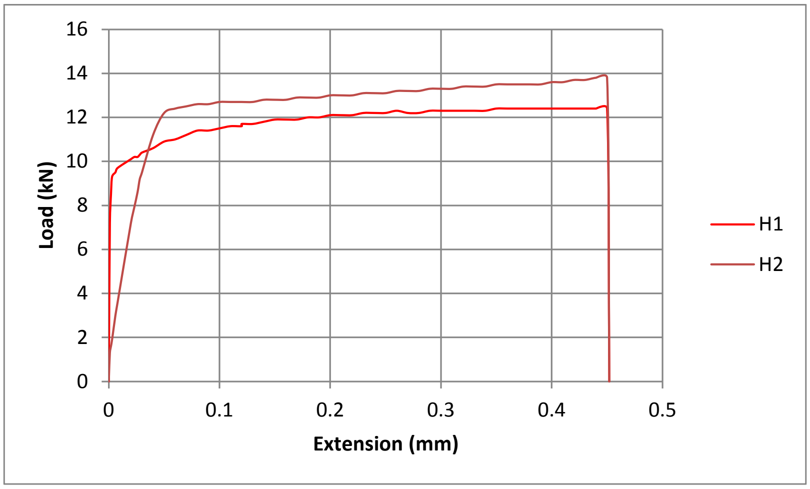


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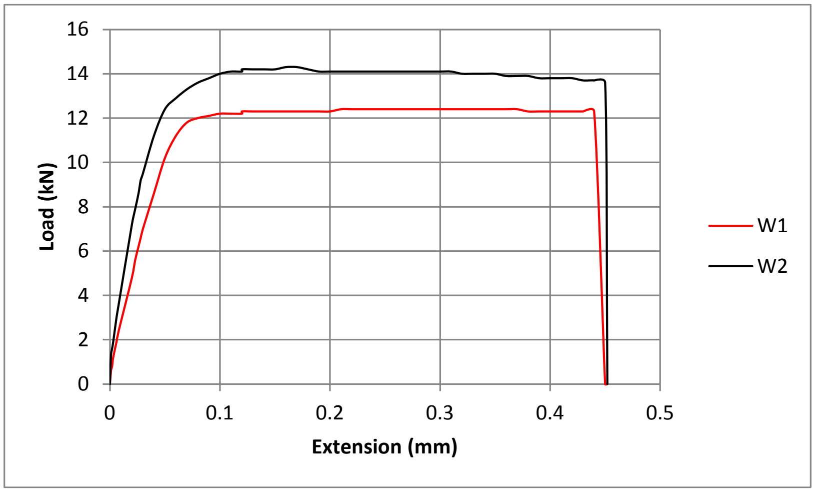



(c)

Fig. 6. Load vs. extension curves for (a) base metal zone, (b) heat affected zone, and (c) center weld zone.

Table III
Geometries of crack lengths after fatigue crack test

| Sample | Size (mm) | $a_L$ (mm) | $a_r$ (mm) | $a_0$ (mm) | Cycle | Sample |
|---|---|---|---|---|---|---|
| $B_1$ | $A_1$ | 3.3 | 2.75 | 2.35 | 17.5 | 16700 |
| | $A_2$ | 3.35 | | | | |
| | $A_3$ | 3.2 | | | | |
| $B_2$ | $A_1$ | 3.25 | 2.6 | 2.7 | 17.6 | 15600 |
| | $A_2$ | 3.4 | | | | |
| | $A_3$ | 3.4 | | | | |
| $H_1$ | $A_1$ | 3.1 | 3.2 | 2.4 | 17.4 | 28700 |
| | $A_2$ | 3.4 | | | | |
| | $A_3$ | 4.05 | | | | |
| $H_2$ | $A_1$ | 2.85 | 2.45 | 2.35 | 17.25 | 27500 |
| | $A_2$ | 3.1 | | | | |
| | $A_3$ | 3 | | | | |
| $W_1$ | $A_1$ | 2.2 | 2.15 | 2 | 17.45 | 23500 |
| | $A_2$ | 2.25 | | | | |
| | $A_3$ | 2.25 | | | | |
| $W_2$ | $A_1$ | 3.1 | 2.45 | 2.55 | 17.6 | 25500 |
| | $A_2$ | 3 | | | | |
| | $A_3$ | 3.05 | | | | |

Table IV
Data obtained from load displacement curves used for calculation

| Specimen | | $F_Q$ (kN) | $F_m$ | $V_m$ (mm) | $a_0$ (mm) |
|---|---|---|---|---|---|
| Base metal (B) | $B_1$ | 9.400 | 12.833 | 0.15 | 17.543 |
| | $B_2$ | 9.567 | 12.670 | 0.20 | 17.612 |
| | Average | 9.484 | 12.752 | 0.175 | 17.578 |
| HAZ (H) | $H_1$ | - | - | - | - |
| | $H_2$ | 9.143 | 12.087 | 0.270 | 17.445 |
| | Average | 9.143 | 12.087 | 0.270 | 17.445 |
| Weld (W) | $W_1$ | 9.143 | 14.258 | 0.146 | 17.458 |
| | $W_2$ | 9.118 | 12.831 | 0.133 | 17.633 |
| | Average | 9.130 | 13.544 | 0.139 | 17.546 |

Note : $H_1$ was not included due to sample failure.

Table V
Geometry factor (Y) and intensity factor (K) of the specimens

| Specimen | $A_0$ (mm) | W (mm) | $a_0$ / W | Y | K (Mpa mm$^{1/2}$) |
|---|---|---|---|---|---|
| $B_1$ | 17.543 | 31.300 | 0.5605 | 11.7873 | 2.7038 |
| $B_2$ | 17.612 | 31.825 | 0.5534 | 11.4987 | 2.5569 |
| $H_1$ | 17.445 | 31.750 | 0.5494 | 11.3428 | 2.4331 |
| $W_1$ | 17.458 | 32.075 | 0.5443 | 11.1445 | 2.8057 |
| $W_2$ | 17.633 | 32.100 | 0.5493 | 11.3375 | 2.5675 |

Table VI
CTOD of each zone of the samples

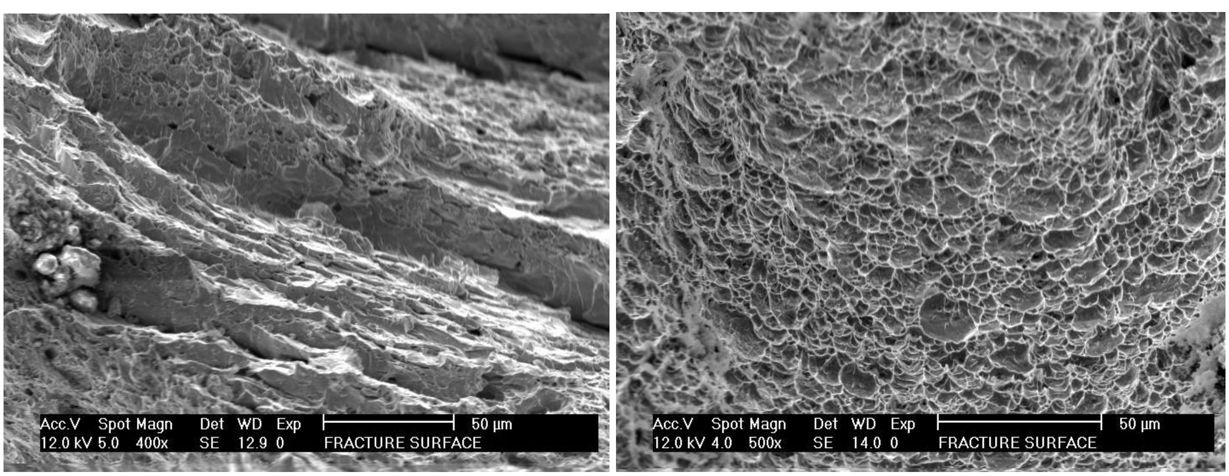
| Specimen | | CTOD (mm) |
|---|---|---|
| Base metal | $B_1$ | 0.04119 |
| | $B_2$ | 0.05613 |
| | Average | 0.04866 |
| HAZ | $H_1$ | - |
| | $H_2$ | 0.07669 |
| | Average | 0.07669 |
| Center weld | $W_1$ | 0.04212 |
| | $W_2$ | 0.03779 |
| | Average | 0.03995 |

The standard used in this study, *i.e.*, ASTM E1290 [5], has clearly provided the procedure for CTOD determination by using criteria given in equation 8. For this standard to fulfill, geometry factor (Y) and intensity factor (K) are required. Table 5 shows geometry and intensity factors of the samples for different zones. By using equation 4 [5] and provided data for V (poisson ratio) = 0.33, Z (for CTs) = 0, E (Gpa) = 207 and $\sigma_{Ys}$ (MPa) = 547.03, then the CTOD of each zone were obtained as shown in Table 5. It is clearly seen from the table that CTOD values of all samples are in the range of 0.04-0.08 mm, which are less than 1 mm. Based on several literatures [12,13], these results apply for toughness values for materials with coarse grains structures resulted from heat treatment process during hot rolling or thermomechanical control process. When equation 9 is used with $\sigma_{YS}$ = 547.03 MPa and E = 207 Gpa resulted from the test, then the values of $K_{1C}$ for base metal, HAZ and centre weld can be obtained respectively 65.768, 82.565, 59.591 Mpa. $m^{1/2}$. From these fracture toughness values, it is concluded that the API 5L X65 pipeline has resistance for fracture in the order of HAZ, base metal and finally center weld.

$$\delta = 2U_y = \frac{4}{\pi}\frac{K_1^{\ 2}}{\sigma_{ys} E} \qquad (10)$$

### 3.3. Microstructural Investigation

Microstructures shown in Fig. 7 represent fracture surfaces of the samples for three different parts of API 5L X65 pipeline. The base metal has combination of both brittle and ductile type of fractures as seen clearly in Fig. 7 (a). A fully dimple structure, however, is also seen on the fracture surface of the HAZ region (Fig. 7.b) indicates that ductile fracture occurred in this region. Therefore, high toughness is expected and this meets well with that obtained from the test result. The microstructure of surface fracture on the center weld is shown in Figure 7(c). Moreover, it is seen clearly that transgranular fracture occurred as the fracture propagated along the grain boundaries, and consequently this region is expected has experienced brittle fracture. This finding complies with that obtained from the test results showing that center weld has low fracture toughness even though its strength is high. It is believed that this type of fracture occurred due to several causes, *i.e.*, the lack of slip system in the grains, precipitation of brittle phases and segregation of elements along the grain boundaries of solidified grains.




(a) (b)

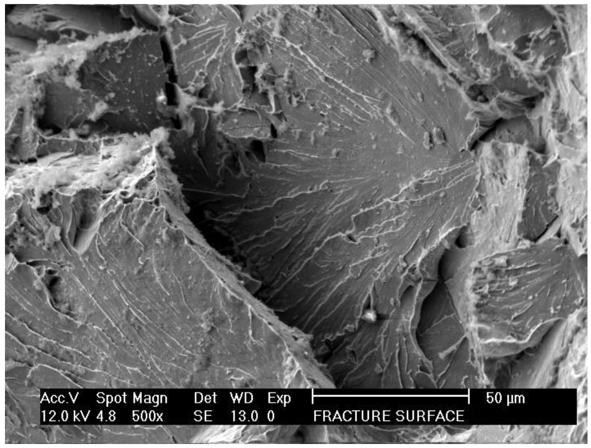



Fig. 7. Fracture surface of (a) base metal, (b) HAZ and (c) center weld.

### 1.6. Evaluation for Leak Before Break

The condition of pipeline system during operation can be predicted through a certain calculation based on the properties obtained from fracture test. A method called as leak before break has been developed to simulate the pipeline system having certain pre-crack for various internal pressures when the pipe leak before eventually it breaks. From fracture toughness test results, *i.e.*, CTOD and $K_{1C}$, three different zones, *i.e.*, based metal, HAZ and center weld, of a circular welded API 5L-X65 has been evaluated in this study. Semi-elliptical pre-crack perpendicular to its hoop stress was used and therefore its stress intensity can be expressed as stated in equation 10 and the value of $a_c$ for each part or zone of the pipe can be determined [14]. The parts of the pipe would be leak when $a_c$ greater than t, meanwhile they would be break if $a_c$ less than t [15].

$$K_1^2 = \frac{1.21\, a\, \pi\, \sigma^2}{Q} \quad (10)$$

where Q is flaw shape parameter that can be obtained from the following equation.

$$Q = \Phi^2 - 0.212\left(\frac{\sigma}{\sigma_0}\right)^2 \quad (11)$$

Parameters used for further calculation are as follows, t (pipe thickness) = 14.3 mm, $\sigma_{YS}$ = 547.03 MPa, E (Young modulus) = 207 Gpa, and $\sigma$ (Hoop Stress) = 171.48 MPa. With assumption that 2a equal c as shown schematically in Fig. 8, the ratio of a/2c is 0.25, while the ratio of $\frac{\sigma}{\sigma_0} = \frac{171.48}{547.03} = 0.313 \cong 0.4$. When these ratios are matched to Figure 9, then the flaw shape parameter Q is 1.47. Therefore, using equation 9, the values of $a_c$ for base metal, HAZ and center weld are, respectively, 45.87 mm, 73.26 mm and 38.16 mm.

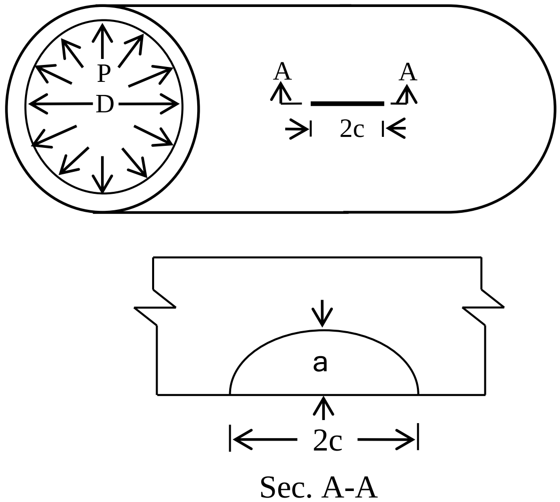



Fig. 8. Schematics of flaw shape

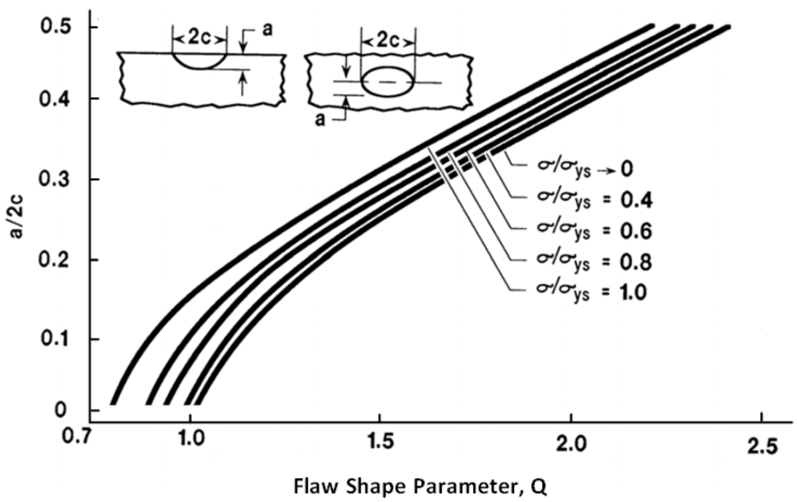



Fig. 9. Relations between a/2c vc. Q for different $\sigma/\sigma_o$ (16).

The results of calculation on leak before break, the values of $a_c$ for the three different parts of pipe are higher than the value of t which is 14.3 mm. Therefore, it can be concluded that the pipe will leak before it break. In order to predict the condition of the pipeline during operation, simulation was carried out considering the pressure variation of the fluid flow in side of the pipeline. With this simulation, the maximum internal pressure of the fluid that cause break will be obtained as shown in Table 7. The simulation results shown in Table 7 indicate that when the pressure reaches 10 MPa, the center weld of the pipeline will break. As this is the minimum pressure that cause break for the weakest part of the steel pipe, it is suggested that the pressure of the internal fluid flow inside of this pipeline should be lower than 10 MPa.

Table VII
Crack depth and prediction of leak and break

| Internal pressure (MPa) | | 6 | 8 | 10 | 11 | 12 |
|---|---|---|---|---|---|---|
| Base metal | Crack depth ($a_c$), mm | 45.87 | 26.15 | 16.74 | 13.83 | 11.62 |
| | Prediction of pipeline condition | leak | leak | leak | break | break |
| HAZ | Crack depth ($a_c$), mm | 73.26 | 41.2 | 26.38 | 18.32 | 13.46 |
| | Prediction of pipeline condition | leak | leak | leak | leak | break |
| Centre weld | Crack depth ($a_c$), mm | 38.16 | 21.47 | 13.74 | 11.36 | 9.54 |
| | Prediction of pipeline condition | leak | leak | break | break | break |

## IV. CONCLUSION

The results of the test and calculations that follow for fracture toughness of three different zones of the API 5L-X65 pipeline, it can be concluded that heat affected zone has the highest toughness, followed by base metal and center weld. The different in fracture toughness of these three zones supported by the fact that HAZ has coarse grain compared with that other zones that makes this region has lower strength but higher toughness. Moreover, this result is supported by the type of fracture surfaces on the three zones of the specimens. Investigation on the type of fracture indicated that fully ductile fracture occurred in the HAZ region, while center welds had brittle fracture. Evaluation on leak before break criteria for API 5L-X65 pipeline indicates that all three regions have critical crack depth ($a_C$) are less than the pipe wall thickness (t), and therefore, all parts of the pipeline will leak before it breaks. The center weld will break at pressure 10 MPa and higher, while HAZ and base metals break at pressures 13 and 11 MPa, respectively. Consequently, it is suggested that the internal pressure of the pipeline should less than 10 MPa. It is suggested that further study needs to be done for different weld compositions with the aims to achieve relatively similar toughness with that of base metal and heat affected zone. Other fracture mechanics test, such as J-integral, is required to compare with that CTOD values obtained in this study. With complete fracture toughness data for the steel pipe, this will increase the safety factor of the facilities and these will strengthen the confidence for the implementation of the SSWJ Project.

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