Temperature to Support Fully Ductile Initiation of Surface Crack in a Pipe

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Abstract

Due to its body-centered-cubic or BCC crystal structure, carbon steel exhibits a transition behavior of toughness along temperature. The fracture is fully brittle with very low toughness at low temperature, known as lower shelf, and is fully ductile with saturated high toughness at high temperature, known as upper shelf. For the transition regime of temperature in between, the steel can exhibit mixed brittle and ductile fracture. This transition behavior is well represented by the transition curve from a Charpy-V-Notch or CVN test. In quasi static fracture mechanics based tests, such as J-integral test or crack-tip-opening-displacement or CTOD test, the specimen can exhibit stable crack extension and early unstable crack extension, such as pop-in, if tested at multiple temperatures. In general transportation pipeline, the surface crack focused by integrity assessment is low constrained and initiates at a static status before failure. Thus, its transition regime is at a much lower temperature than that of a dynamic CVN test or a quasi-static but high constrained standard J-Integral or CTOD test. Thus, A crack feature in a pipe may fail in fully ductile mode with burst pressure related to the toughness at upper shelf even if the tests at the operating temperature fall into the transition or even low shelf regime. In this paper, an approach is provided to calculate the temperature supporting fully ductile initiation of a surface crack in a pipe based on available tests data. A worked example is also provided to demonstrate the application. Certain challenges and potential needs for extra tests are also discussed.

Introduction

Toughness characterizes the resistance of a material to cracking. Carbon steel exhibits a transition behavior of toughness along temperature due to its body-centered-cubic crystal structure [1]. At low temperature, the fracture in carbon steel is brittle with a minimum toughness insensitive to temperature, which is known as lower shelf regime. After the temperature increases above certain level, the toughness starts to increase with the elevating temperature and the fracture shows mixed brittle and ductile behavior, which is known as transition regime. The toughness eventually reaches a saturated level and becomes insensitive to temperature again, which is known as upper shelf regime. To evaluate the integrity of a pipeline with cracks, it is critical to know the position of the carbon steel pipe in the transition regimes at its operating temperature. If the crack is determined to be fully ductile, the toughness at upper shelf can be used for the integrity assessment.

The transition behavior can be revealed by toughness related tests conducted at various temperature. A frequently used one is Charpy-V-Notch, or CVN, test. The measured impact energies are plotted against test temperatures to form a transition curve. To mark the position of transition regime, the Shear Area Transition Temperature, or SATT, is defined when 85% area in the final fracture surface of the broken coupon is shear which characterizes the amount of ductile deformation. The SATT is sensitive to the sizes of CVN coupons. Drop Weight Tearing Test, or DWTT, is another typical test in which the coupon reserves the full wall thickness of the pipe. Study has shown that the transition

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temperature from DWTT matches the Fracture Propagation Transition Temperature, or FPTT, in the steel pipe [2].

CVN, DWTT and crack propagation are dynamic processes involving high deformation rates. The transition temperature drops significantly for much slower crack initiation. Kiefner [3] reported a series of tests conducted at Battelle for investigating the difference between the FPTT and the Fracture Initiation Transition Temperature, or FITT. Figure 1 shows the FPTT and the FITT of through-wall flaws on two pipes with the same diameter and grade but different wall thicknesses. The FITT was 60 °F below the FPTT in the 0.375-in thick pipe as shown in Figure 1 (a) and 90 °F below the FPTT of the 0.500-in thick pipe as shown in Figure 1 (b). Figure 2 shows the tests from specimens with a surface crack of 50% wall thickness deep and 6-inch long. No FITT was observed even at the lowest tested temperature which was 136°F below the FPTT. The slight rise in failure pressure at reduced temperature inside the ductile fracture initiation regime is expected as the yield strength of the material increases with decreasing temperature. In the following discussion, the FITT of the through wall crack and surface crack are labelled as FITT-H and FITT-S, respectively.

The quasi-static fracture mechanics based lab tests may better indicates FITT. The classical J-integral or CTOD (Crack Tip Opening Displacement) tests are conducted on CT (Compact Tension) or SEN(B) (Single-edge-Notched Bending) specimens. The high constrained condition at crack tip in these classical tests tends to provide conservative toughness and transition temperature. The Single-Edge-Notched Tension, or SEN(T), test has lower constrained condition at crack tip, which is more similar to a surface crack in the pipe. Podlasek and Eiber [4] conducted tests on pipes used in the Alyeska oil pipeline. Their results in Figure 3 suggested the temperature dependence of through wall crack initiation matched that from CTOD tests with SEN(B) specimens. Due to the reduced constrain at crack tip, the FITT-S of a surface crack is lower than the FITT-H of a through wall crack. The comparison between Figure 1 and Figure 2 has showed such difference. Wilkowski et al. [5] compared the transition temperature between their SEN(T) and SEN(B) tests as shown in Figure 4. The results showed at least 50 °F drop of SEN(T) represented FITT-S from SEN(B) represented FITT-T. Such drop was more significant for shallower surface cracks. Sugie at Kawasaki Steel Company [6] conducted full scale burst tests on 24-in diameter 0.375-in wall thickness Grade B line pipes with surface cracks with depth at 50% of wall thickness. Figure 5 shows clear decrease in transition temperature of the burst tests on pipes with surface cracks from that of CTOD.

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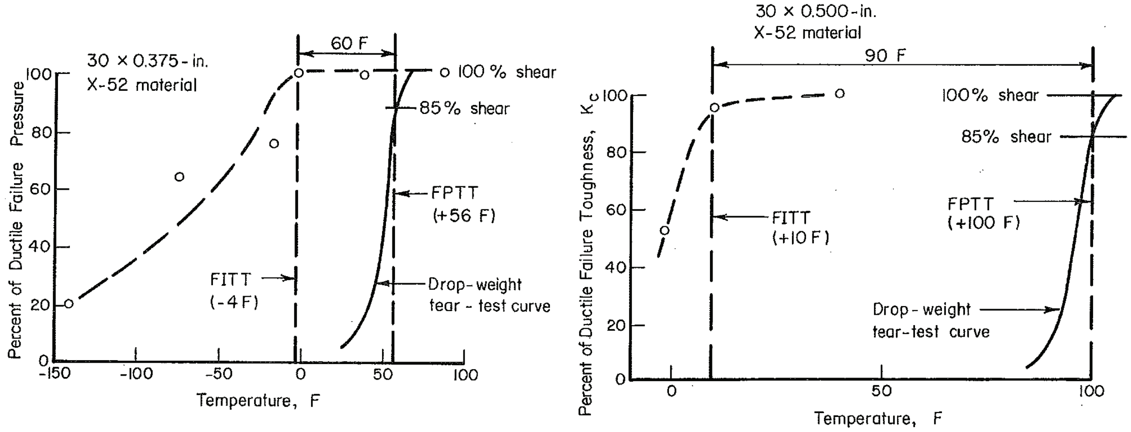

(a) *(b)*

Figure 1. FPTT and FITT of through-wall flaws from Battelle's tests [3]

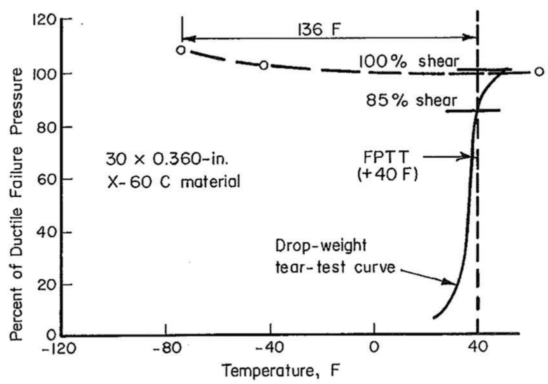

Figure 2 FITT and FPTT of surface flaws from Battelle's tests [3]

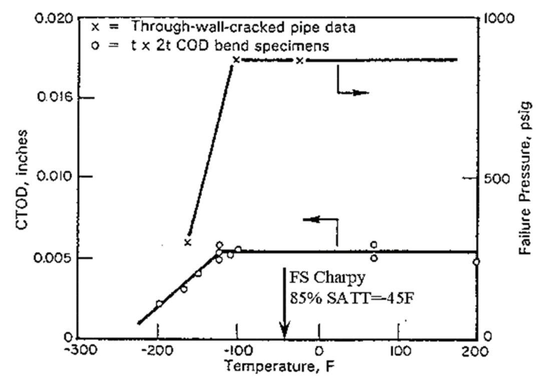

Figure 3. FITT of Through-wall crack and CTOD Tests [4]

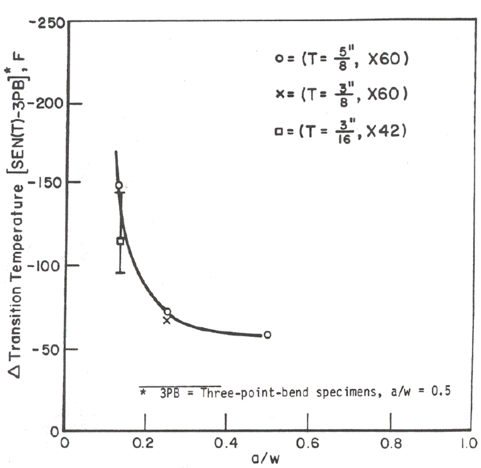

Figure 4. Comparison of FITT-S and FITT-H through SEN(T) and SEN(B) [5]

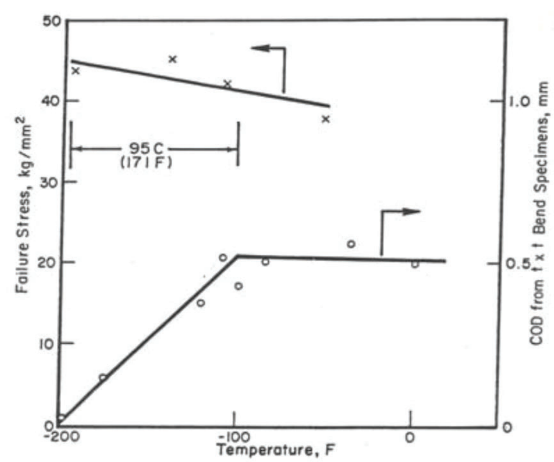

Figure 5. CTOD tests and full-scale burst test with surface crack [6]

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From the descriptions above, the transition temperature depends on dimensions (such as CVN coupon size and pipe wall thickness), the deformation rate, and the crack tip constrained condition. Many research works have been conducted trying to establish quantitative relationship among the transition temperature at different conditions. Maxey et al. [2] reported the difference in transition temperature between DWTT and CVN with different pipe wall thickness and CVN coupon sizes as shown in Figure 6. A standard CVN coupon has a square cross section of 10 mm x 10 mm or 0.394 in x 0.394 in. However, it is generally impractical to retrieve such standard sized coupon from an onshore line pipe due to available wall thickness and pipe curvature. Subsize coupons are used with rectangular cross section where the width is still kept at 0.394 in but the thickness is reduced to only a fraction of the full size.

As shown in Figure 6, the difference between the FPTT and SATT depends on both CVN coupon size and pipe wall thickness. Based on Maxey et al.'s work, Rosenfeld [7,8] developed generalized equations for converting between FPTT and SATT from CVN tests with several frequently used coupon sizes. Recently, the equations were further improved and extended to CVN with any coupon sizes by Zhang and Rosenfeld [9], which will be adopted in the next version of ASME FFS-1/API 579 standard. Wilkowski and Rudland [10] developed an approach to determine the FITT-S from CVN data for nuclear steel piping. The work has been adopted by ASME B&PV Section XI [11]. Wilkowski et al. [12] later demonstrated that their approach could also be applied on transportation pipelines through the tests on two vintage line pipes in a PRCI sponsored project. An Excel calculator was also provided as a deliverable of the project. More recently, Wilkowski et al. [13] updated this conversion from CVN to FITT-S for line pipes by improving the data fitting for thin wall pipes as the original approach was developed for nuclear piping with much thicker wall. This updated conversion is limited between FITT-S and CVN tests. More flexible approach would be desired if the available data is from tests other than CVN or the concern is about the fully ductile crack propagation instead of initiation.

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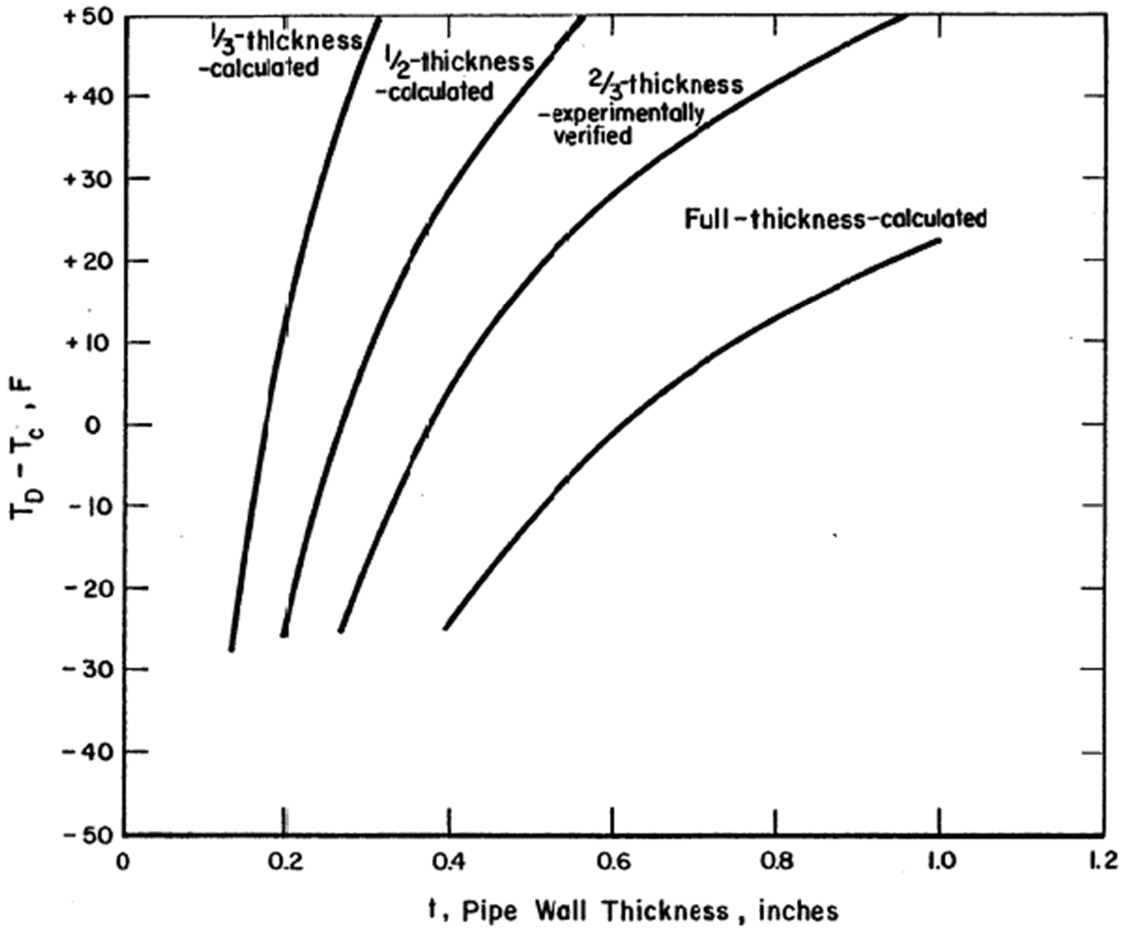

Figure 6. Transition temperature difference between DWTT (T_D) and CVN (T_C) at various pipe wall thickness and CVN coupon sizes [2]

In this paper, a group of simplified equations and a flowchart are provided to help estimating whether a crack in a steel line pipe would behave in a full ductile regime based on the available tests. The approach is developed by summarizing the pioneer works described above into a systematic procedure and with flexibility for various application scenarios. A worked Example is also offered to demonstrate the application. Some related topics are also discussed.

Transition Temperature in A Pipe

Based on the description in the previous section, the conversation among transition temperatures can be divided into three substages as

- SATT to FPTT: from the transition temperature of CVN test to that of crack propagation
- FPTT to FITT-H: from the transition temperature of crack propagation to that of a through wall crack initiation
- FITT-H to FITT-S: from the transition temperature of a through wall crack initiation to that of a surface crack initiation

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Based on the available tests and the needs of the integrity assessment, all or only part of the substages would be applied. The units of variables in all the equations below are Fahrenheit degree and inches.

SATT to FPTT

Zhang and Rosenfeld [9] proposed the converting equation matches Maxey's plot represented in **Figure 6** as

$$T_{\mathrm{FPTT}} = T_{\mathrm{SATT}} + 104.86\left(\frac{t_{\mathrm{C}}}{t_0}\right)^{-0.568} - \frac{81.4}{\sqrt{t_{\mathrm{w}}}} \tag{1}$$

where T_{FPTT} is FPTT, T_{SATT} is SATT. The t_{C} is the thickness of the CVN coupon, $t_0 = 0.394$ in is the thickness of a full standard sized CVN coupon, and t_{w} is the wall thickness of the pipe. The SATT is generally determined from the transition curve from CVN test data points at various temperatures. There are various methods for fitting the transition curve and Zhang [14] compared two frequently used ones recently. If the SATT is achieved from full standard sized coupons or the equivalent full-size SATT is used, the equation is simplified to

$$T_{\mathrm{FPTT}} = T_{\mathrm{SATT}} + 104.86 - \frac{81.4}{\sqrt{t_{\mathrm{w}}}}$$

If the CVN data are only available at a single temperature T_0, the SATT can be estimated as

$$T_{\mathrm{SATT}} = T_0 - B\ln\left(\frac{S_{\mathrm{A}}}{1 - S_{\mathrm{A}}}\right) + A \tag{2}$$

Where S_{A} is the shear area in the CVN test coupon and the coefficients A and B are calculated from the ratio of coupon thickness over the standard coupon thickness, t_{c}/t_0, as

$$A = -33.249\left(\frac{t_{\mathrm{C}}}{t_0}\right)^2 + 83.662\left(\frac{t_{\mathrm{C}}}{t_0}\right) + 4.8088$$

$$B = -17.642\left(\frac{t_{\mathrm{C}}}{t_0}\right)^2 + 46.415\left(\frac{t_{\mathrm{C}}}{t_0}\right) + 3.3314$$

FPTT to FITT-H

As shown in **Figure 1**, the through wall crack initiation transition temperature, $T_{\mathrm{FITT-H}}$, is lower than the crack propagation transition temperature. In reference [12] and the accompanied Excel calculator, Wilkowski et al. proposed a simplified constant differential of 75 °F as

$$T_{\mathrm{FITT-H}} = T_{\mathrm{FPTT}} - 75 \tag{3}$$

FITT-H to FITT-S

The transition temperature of initiating a surface crack, $T_{\mathrm{FITT-S}}$, is lower than that of initiating a through wall crack due to the less constrain at crack tip as shown in Figure 4 and **Figure 5**. Such temperature differential decreases with the increase of surface crack depth. The rate of such reduction slows down after the surface crack depth exceeding half of wall thickness. For simplicity purpose, a constant reduction of 51 °F is selected regardless of surface crack depth as

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$$T_{\mathrm{FITT-S}} = T_{\mathrm{FITT-H}} - 51 \quad (4)$$

The 51 °F is based on the differential between a 75% wall thickness deep surface crack and the through wall crack from reference [12] and the accompanied Excel calculator. The same amount of differential between FITT-H and FITT-S is also adopted in ASME B&PV Section XI Appendix C Table C-8321-2 for all pipe thicknesses as shown below.

Table 1. Onset of Upper-Shelf Behavior for Axial and Circumferential Flaws Based Metals and Weldments (Table C-8321-2 in ASME B&PV Section XI Appendix C)

	Temperature, °F (°C)	
Wall Thickness, in. (mm)	**Surface Flaws**	**Through-Wall Flaws**
≤0.25 (≤6)	−45 (−43)	6 (−14)
0.375 (10)	−4 (−20)	49 (9)
0.50 (13)	22 (−6)	73 (23)
0.625 (16)	35 (2)	86 (30)
0.75 (19)	43 (6)	94 (35)
1.00 (25)	52 (11)	104 (40)
1.25 (32)	58 (15)	110 (43)
1.50 (38)	63 (17)	114 (46)
1.75 (44)	66 (19)	118 (48)
2.00 (51)	70 (21)	121 (50)

The latest updated by Wilkowski et al. [13] to their previous work in [12] focused on updating the conversion between SATT and FPTT. The conversion between FPTT, FITT-H and FITT-S remains the same.

Guidance on Determine Fracture Mode Based on Available Tests

For an integrity assessment of crack-like features in a pipeline, it is important to determine the fracture mode. If a fully ductile mode can be confirmed, the toughness at upper shelf should be used in the assessment even if the tests exhibit transition behavior at the operating temperature of the pipeline.

A flowchart in **Figure 7** is provided to guide the evaluation of fracture mode.

- If the available test is CVN, the SATT can be determined from the transition curve or Equation (2) if the CVN data are only available at a single temperature. The FPTT is then derived from SATT following Equation (1). If DWTT test is available, the transition temperature of DWTT can be used directly as FPTT. For the assessment of crack propagation, fully ductile mode can be assumed if the operating temperature at the failure, or the lowest expected operating temperature for design purpose, is above FPTT. For the assessment of a surface crack initiation, proceed to next steps.
- The FPTT determined from CVN or DWTT in the previous step can be used to calculate the FITT-H following Equation (3). If classical fracture mechanics based lab tests from CT or

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SEN(B) specimens are available, the transition temperature from these tests can be used directly as FITT-H according to reference [4] and **Figure 3**.

- The FITT-H from the previous step can conservatively determine the FITT-S following Equation (4). If SEN(T) test is available, the transition temperature from the test can be used directly as FITT-S. The upper shelf toughness should be used to calculate the burst pressure of a surface crack if the operating or design temperature is above FITT-S since the crack initiation is fully ductile.

It should be noticed that the flow chart cannot be used in the reverse direction, that is, the tests from CT/SEN(B) or SEN(T) cannot be used to derive the FPTT as the simplified constants used in Equation (3) and (4) are conservative.

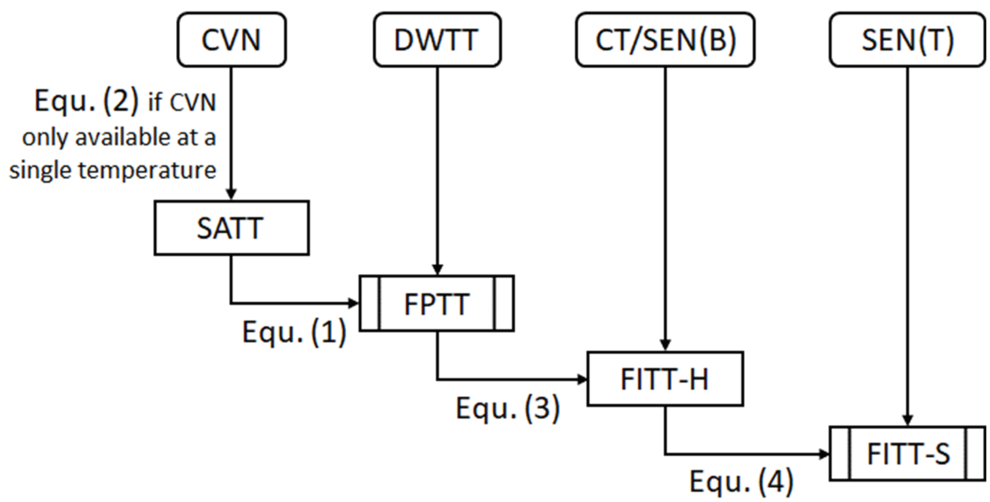

Figure 7. Flowchart to determine fracture mode based on available tests

Worked Example

In reference [12], a 1948 vintage line pipe was studied with both CVN and SEN(T) tests.
The pipe was 22-in diameter and 0.344-in thick X46 ERW pipe. The CVN test was conducted with reduced thickness coupon equal to 43% of a full size one. The SATT is 86 °F.
From Equation (1),

$$T_{\mathrm{FPTT}} = 86 + 104.86(0.43)^{-0.568} - \frac{81.4}{\sqrt{0.344}} = 117\ °\mathrm{F}$$

As a result, the crack is unlikely to propagate along this pipe in fully ductile mode under normal operating condition. Following Equation (3)

$$T_{\mathrm{FITT-H}} = 117 - 75 = 42\ °\mathrm{F}$$

and equation (4)

$$T_{\mathrm{FITT-S}} = 42 - 51 = -9\ °\mathrm{F}$$

Thus, the surface crack initiation is still fully ductile when the pipe is buried.

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The SEN(T) tests[i] on this pipe showed that the coupon tested at -33 °F exhibited small ductile tearing and the one tested at -20 °F showed full ductile behavior. Thus, the FITT-S for fully ductile initiation of a surface crack should be somewhere between -33 °F and -20 °F, which confirms the estimated FITT-S of -9 °F following the developed procedure is acceptable and conservative.

Discussion

As described in above sections, FITT-S > FITT-H > FPTT. For modern gas pipelines, the design code, such as ASME B31.8 Section 841.1.2 [15], has requirement on shear area percentage of testing at specified low temperature to minimize the likelihood of brittle crack propagation. The pipeline satisfying such requirement would guarantee the fully ductile initiation of a surface crack. For vintage gas pipeline built before such requirement established, however, the transition temperature from the samples in the pipeline should be evaluated. It is possible that a surface crack may initiate in a fully ductile manner but propagate as a through wall crack with mixed brittle-ductile mode in pipes as shown in the Worked Example section. If needed, different toughness should be used to assessment burst pressure of a surface crack and the control of crack propagation after the surface crack breaking, respectively. There is no crack propagation concern in a liquid pipeline[ii] as the pressure reduces quickly after rupture.

The classical fracture mechanics based lab tests with CT and SEN(B) specimens are generally conducted at ambient temperature. If the coupon exhibits fully ductile behavior, it ensures the fully ductile initiation of a surface crack per Equation (4) for most buried pipelines. However, brittle or mixed brittle-ductile behavior may be observed in these tests, that is, the unstable crack extension occurs before achieving slow stable crack extension. For such scenario, more CT/SEN(B) tests are needed at higher temperature until the transition temperature is found. Alternatively, the test can be repeated at a level equal to 51 °F plus the interested temperature which is the operating temperature of the studied failure or the lowest expected operating temperature for design purpose. If the coupon exhibits fully ductile behavior at this temperature level, the ductile initiation of a surface crack can be confirmed.

The SEN(T) test is preferred to be conducted at the interested temperature to confirm the fully ductile initiation of a surface crack.

Finally, the paper presented the approach to determine FITT-S. If the operating temperature is above FITT-S, the toughness at upper shelf should be used for the integrity assessment. However, finding the toughness value for burst pressure calculation in the transition regime when the operating temperature is below FITT-S is more complicated. In the transition regime, the brittle crack initiation

[i] The crack depth in the SEN(T) coupons is between 45% and 55% of the thickness due to the different fatigue crack extension during pre-cracking.

[ii] Except pipeline carrying carbon dioxide in dense phase.

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is a statistical event due to the nonhomogeneous nature of the material at microscale. Thus, statistical models, such as master curve method, should be used to determine the adequate toughness based on failure probability [1].

Conclusion

The paper introduces the approach to determine the temperature to support fully ductile initiation of a surface crack in a line pipe. If the operating temperature is above this limit, the toughness at upper shelf should be used for the integrity assessment. The approach was developed by summarizing the pioneer works by many researchers especially Wilkowski and his coworkers. A flowchart is provided to help the users determine the temperature limit for their integrity assessment needs from various tests. A worked example demonstrates the accuracy and conservatism of the approach.

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