Crack Tip Opening Angle: Applications and Developments in the Pipeline Industry*

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Abstract

One of the most difficult safety problems associated with gas pipelines to be solved is the control of ductile fracture propagation. To address this issue, the crack tip opening angle (CTOA) criterion is becoming one of the more widely accepted properties for characterizing fully plastic fracture. Our current research has applied the CTOA concept in pipeline characterization. A test technique for direct measurement of CTOA was developed that uses a modified double cantilever beam specimen. In this article, CTOA data on high-strength API X100 pipeline steel are presented. Different optical measurement methods are evaluated, which use the crack edges and the specimen surface grid lines. Crack growth in the base metal and through pipeline girth welds was studied. The effect of specimen thickness on CTOA results was noticeable, with thicker specimens producing a greater resistance to fracture. Finally, the influence of the crack velocity on CTOA was found to be minimal.

1. Introduction

The increasing demand for natural gas as an alternative energy source implies continued growth of gas pipeline installations. This trend compels the natural gas transmission industry to consider the construction of larger-diameter high-pressure pipelines that use high-strength steels. The application of high-strength steels in severe conditions will require reliable pipeline designs, as well as the control of ductile fracture propagation. In this case, a safety criterion has to be developed for fracture arrest.

Initially, the measure of a material's resistance to fracture was estimated with the basis of Charpy V-notch (CVN) shelf energy, such as the Battelle two curve model (TCM) [1]. Later, fracture arrest/propagation models were calibrated against dynamic drop-weight tear-test (DWTT) data. It has become clear that extrapolating the existing experimental absorbed fracture-energy relations in order to assess the fracture resistance of higher strength grades of modern pipeline steels introduces significant errors [2]. Thus, in parallel with the CVN- and DWTT-based fracture strategies, pipeline designers have worked on developing new measures to control fracture. Among these, crack tip opening angle (CTOA) is becoming one of the more widely accepted properties for characterizing fully plastic fracture [3,4].

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In cases where there is a large degree of stable-tearing crack extension during the fracture process, CTOA has been recognized as a measure of the resistance of a material to fracture [3-7]. The CTOA can be measured directly from the crack-opening profile, related to the geometry of the fracturing structure, and is given in the following expression: $CTOA = 2\tan^{-1}(CTOD/2r)$, where $CTOD$ is the crack tip opening displacement and r is the distance behind the crack tip.

A CTOA-based design criterion for crack propagation is usually written in the form: $CTOA_{max} < CTOA_c$, where $CTOA_{max}$ is a measure of the maximum crack driving force calculated from a knowledge of the dimensions, material properties, and operating conditions, and $CTOA_c$ is the resistance of the material to crack growth (material fracture toughness). Thus, the CTOA criterion can be used in an engineering critical assessment approach and leads to a safe prediction of unstable crack propagation.

Our current research has applied the CTOA concept in pipeline characterization. A test technique for the direct measurement of CTOA is presented through the use of a modified double cantilever beam (MDCB) specimen. CTOA data on high-strength API X100 pipeline steel are presented. Different optical measurement methods are evaluated. Crack growth in the base metal and through pipeline girth welds is studied. The effect of specimen thickness on CTOA results is estimated. Finally, the influence of the crack velocity on CTOA is evaluated.

2. CTOA Specimen and Test Set-Up

Our testing effort uses the MDCB specimen type. This specimen has been proposed by several authors [5,6,7]. It is designed primarily to prevent bending, which has occurred in both standard and tapered double cantilever-beam (DCB) designs. The MDCB configuration and dimensions are depicted in Fig. 1a, presented here in the case of a weld section. The large in-plane dimensions of the specimens and the long ligament allow relatively large amounts of stable crack growth. We evaluated two thicknesses in the test section, 3 mm and 8 mm.

Test specimens were extracted with their long dimension along the longitudinal axis of the pipe, so the specimens have a T-L orientation (per ASTM E2472), where

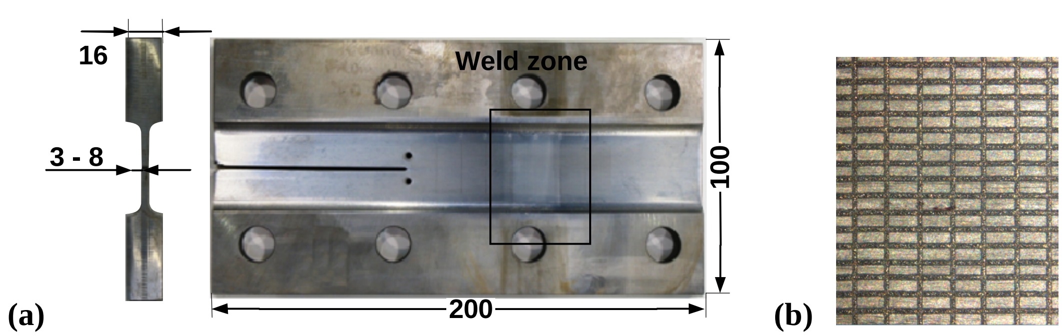

Figure 1. (a)MDCB specimen (dimensions are in mm), and **(b)** magnified view of the grating (1 mm × 0.5 mm).

T is the transverse and L the longitudinal direction. The thickness of each curved plate was reduced by machining to obtain a flat plate without mechanical flattening. An initial straight notch (1.6 mm width) was machined through the specimen thickness. The notch length was 60 mm (measured from the load-line of the specimen, corresponding to the center of the left pair of gripping holes). Two pair of loading plates, 10 mm thick, were bolted to either side of the specimen and were gripped for prefatigue and testing (Fig. 2). The two thick loading plates increased the constraint levels in the gauge section of the specimens. The two cylindrical pins provided free rotation of the gripped assembly (specimen plus loading plates) during the experiments. The long uncracked ligament and the loading geometry provided for stable shear crack extension in the specimen ligament, similar to that of the real structure. To facilitate the CTOA measurement, a fine square mesh with a spacing of 1 mm × 0.5 or 1 mm was lightly etched by laser on the reduced section of each specimen (Fig. 1b).

3. Material Properties

An experimental pipe made of API X100 grade high-strength steel (outside diameter 1.32 m (52 in) and wall thickness 20.6 mm) was investigated. The girth weld was made by use of a shielded metal arc (manual) electrode for the fill and cap. To measure the tensile properties of the pipeline base metal, weld and HAZ, round tensile specimens were used; all tensile specimens had the same geometrical characteristics: round specimen with 6.35 mm diameter and 25.4 mm gauge length, machined according to ASTM E08. The base-metal tensile specimens were machined in both axial (longitudinal) and transverse orientations. In order to characterize the girth weld section, tensile tests were performed throughout the weld section, in the axial (longitudinal) and transverse (all-weld metal) directions. The longitudinal specimens crossed the girth weld, and included the weld and HAZ in the gauge length. For these specimens, as in the base-metal tensile tests, an extensometer was used to measure the global elongation of the weld and the two HAZ.

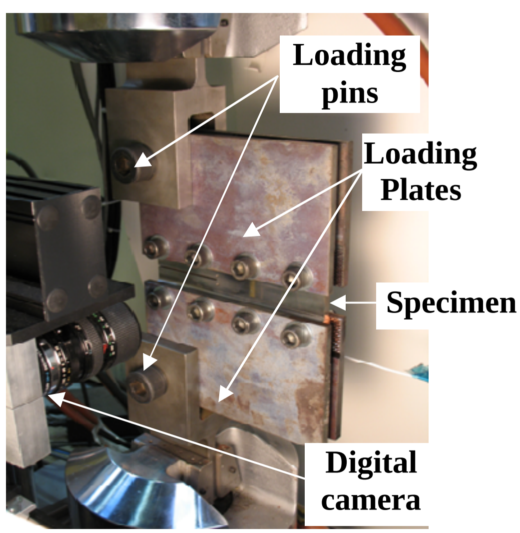

Figure 2. CTOA test set up.

The tensile tests were conducted in displacement control at a rate of 0.1 mm/min. A summary of the tensile properties of the base metal and the weld is shown in Table 1, where $\bullet_{0.2}$ is the yield stress, $\bullet_{UTS}$ is the ultimate tensile strength, e_u is the uniform elongation, and e_f is the failure elongation.

Table 1. Tensile mechanical properties of the base metal and the girth weld.

Orientation	$\bullet_{0.2}$ **(MPa)**	$\bullet_{UTS}$ **(MPa)**	$\bullet_{0.2}/\bullet_{UTS}$	e_u **(%)**	e_f **(%)**	e_u/e_f
Base Metal Transverse	798	827	0.97	4.1	19.3	0.21
Base Metal Longitudinal	732	806	0.91	4.6	20.3	0.23
Girth Weld Longitudinal	602	717	0.84	3.9	11.4	0.35
Girth Weld Transverse	772	844	0.92	8.8	22.3	0.39

4. CTOA Test Conditions

Both quasi-static and dynamic CTOA tests were conducted with uniaxial servo-hydraulic test machines: the quasi-static tests on a 250 kN machine and the dynamic tests on a 500 kN machine. Quasi-static tests were conducted on specimens with 3 mm and 8 mm gauge thicknesses, both with and without a girth weld section. Specimens for dynamic CTOA tests had a gauge thickness of 8 mm and were base metal. CTOA tests were conducted at actuator rates of 0.002, 0.02, 0.2, 3, 30, 300, and 8000 mm/second. All specimens were fatigue pre-cracked at a ratio of $R = 0.1$, to a crack-to-width loading ratio of $a_0/W = 0.36$ to 0.38. After fatigue pre-cracking, the specimens were pulled (stressed), at the desired displacement rate, which caused the advancing crack to tear after reaching maximum load and the base-metal specimens transitioned to steady-state stable tearing.

5. CTOA Measurement

Digital images of the propagating crack tip were captured by use of a camera. For the quasi-static tests, the camera and an XY stage were computer controlled to follow the moving crack tip and to capture pictures during the test. For the dynamic tests, a fixed high-speed camera was used (10,000 frames/sec). Following capture, the video was divided into individual frames for the CTOA measurements. The initial recording was triggered manually or mechanically, depending on the test rate.

In each image, the CTOA was directly measured by use of data in the ranges prescribed by the ISO draft standard [8] and the ASTM standard [9]. Within these ranges, we used the following four approaches to measure the CTOA:

- Method 1 used data from the crack profile to fit lines from the crack tip to pairs of reference points back from the crack tip (from 0.5 mm to 1.5 mm). For this method, the crack tip was always included in the calculation of the CTOA, and the CTOA was calculated at the crack tip (see Figs. 3a and 4a).
- Method 2 used data from the crack profile to fit lines from reference points (from 0.1 mm to 0.2 mm behind the crack tip) to pairs of reference points in the

increment from 0.5 mm to 1.5 mm behind the crack tip. This method never includes the crack tip in the calculation of CTOA (Fig. 4b).

- Method 3 used data points marking the upper and lower grid lines to fit lines for the CTOA calculation. This method used points chosen by the operator on grid lines etched on the sample. The grid line pair closest to the crack edge was used, and the CTOA was directly measured by fitting lines to points chosen and calculating the angle at the intersection of these lines. Each line was fitted with 2 to 10 points located within the increment 0.5 to 1.5 mm from the crack tip.
- Method 4 used data points to define the crack edges. The operator identified points along the crack profile, a spline was fitted to those points, and two intersecting lines were fit to the spline. Scores to a hundred points were used to define each best-fit line. The CTOA is the intersection of the upper and lower line fit.

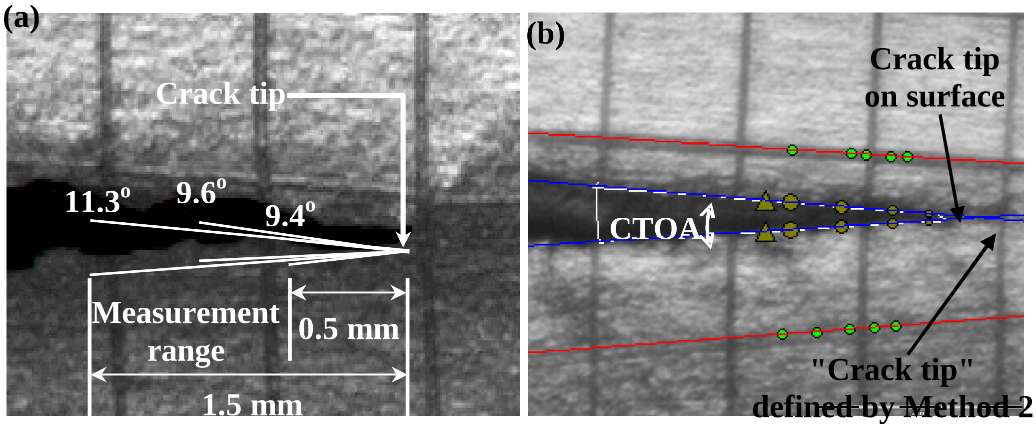

Figure 3. (a) Measurement range for critical CTOA values (Method 1); (b) Crack tip location and CTOA measurement.

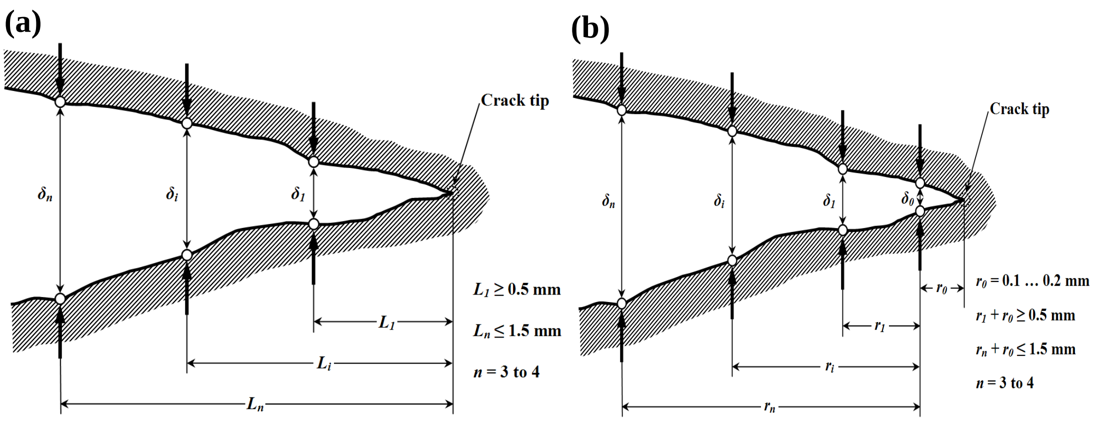

Figure 4. (a) Method 1 and (b) Method 2 for determining the CTOA. For both methods n was set equal to 3, $L_1 = r_1 + r_0 = 0.5$ mm, $L_2 = r_2 + r_0 = 1$ mm, and $L_3 = r_3 + r_0 = 1.5$ mm (r_0 was set to 0.15 mm).

Method 1 used an algorithm that located the crack tip in the profile data, and then selected pairs of points along the crack profile at prescribed distances from the tip to calculate CTOA (Fig 4a). The pairs of points were used to derive a series of $CTOA_{1(i)}$ values as follows:

$$CTOA_{1(i)}\Big|_{\Delta a} = \frac{\delta_i}{L_i}\Big|_{\Delta a} \quad \text{(rad)}, \tag{1}$$

where δ_i is the distance between the two points located at the position i, and L_i is the distance between the crack tip and the location i (Fig. 4a).

Method 2 used an algorithm that selected pairs of points along the crack profile at the same distances from the crack tip as those used in Method 1, but the crack tip location was neglected in the CTOA calculations. This approach is expected to yield CTOA values equivalent to the manual method prescribed in the ISO and ASTM test methods, where the pairs of points were used to derive a series of $CTOA_{2(i)}$ values as follows:

$$CTOA_{2(i)}\Big|_{\Delta a} = \frac{\delta_i - \delta_0}{r_i}\Big|_{\Delta a} \quad \text{(rad)}, \tag{2}$$

where δ_i is the distance between the two points located at the position i, and r_i is the distance between two locations i = 0 and i (Fig. 4b). One interesting difference between Method 1 and Method 2 is that the fitted line segments used to calculate CTOA for Method 2 define a "predicted crack tip location" at the intersection of the lines (see Fig. 3b).

6. CTOA Results and Discussion

6.1. Comparison of Optical Measurement Methods for Quasi-Static Tests

Fig. 5 illustrates the CTOA resistance curves for the base material, performed on a specimen with a gauge thickness of 8 mm. The initial CTOA resistance values were high, as expected (blunting effect), but rapidly decreased throughout the

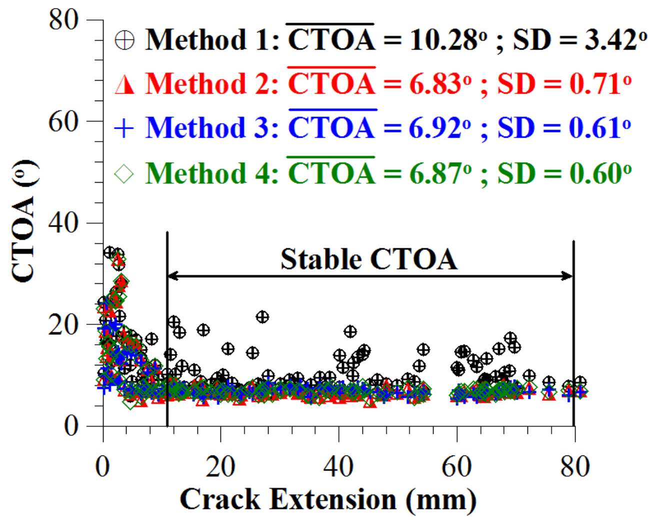

Figure 5. CTOA resistance results: comparison of four optical methods.

transition region of flat-to-slant fracture and approached a constant value (associated with steady-state crack growth corresponding to the beginning of ductile tearing) at crack lengths approximately equal to the specimen thickness. Flat tearing and tunneling effects dominated the CTOA profile during the early stages of crack growth. The calculated values for CTOA within the steady-state region (Fig. 5) showed some dependence on the measurement method used. The following trends are noted:

- Method 1 had the highest scatter in CTOA and also resulted in the highest average CTOA values for the steels. Method 1 depends on accurately locating the apparent crack tip and is the most sensitive method for local deformations in regions adjacent to the apparent crack tip. The higher standard deviation obtained for this method on the steel evaluated here is due primarily to compliance effects (such as blunting) on the crack edges (at the free surface), complex crack-tip geometries, and the difficulty of accurately identifying the exact location of the crack tip on the free surface (due to experimental factors).
- Method 2 had lower standard deviations in CTOA measurements, and the mean CTOA values generally agreed with Method 3 for quasi-static rates.
- Method 3 had a smaller standard deviation in CTOA values.
- Method 4 usually had the smallest values for CTOA and smallest standard deviations, for quasi-static and dynamic tests [6,7] .

These trends when comparing the four methods were already observed in [6,7] for six other pipeline steels. In the following, only method 4 will be used.

6.2. Specimen Thickness Effect

Fig. 6 presents the CTOA resistance curves for specimens with gauge thicknesses of 3 mm (a) and 8 mm (b) for the base metal API X100 pipeline steel. A CTOA resistance value of $4.2^{o} \pm 0.5^{o}$ was measured for the 3 mm gauge specimens and $6.9^{o} \pm 0.6^{o}$ for the 8 mm gauge specimens. We believe that this dependence on

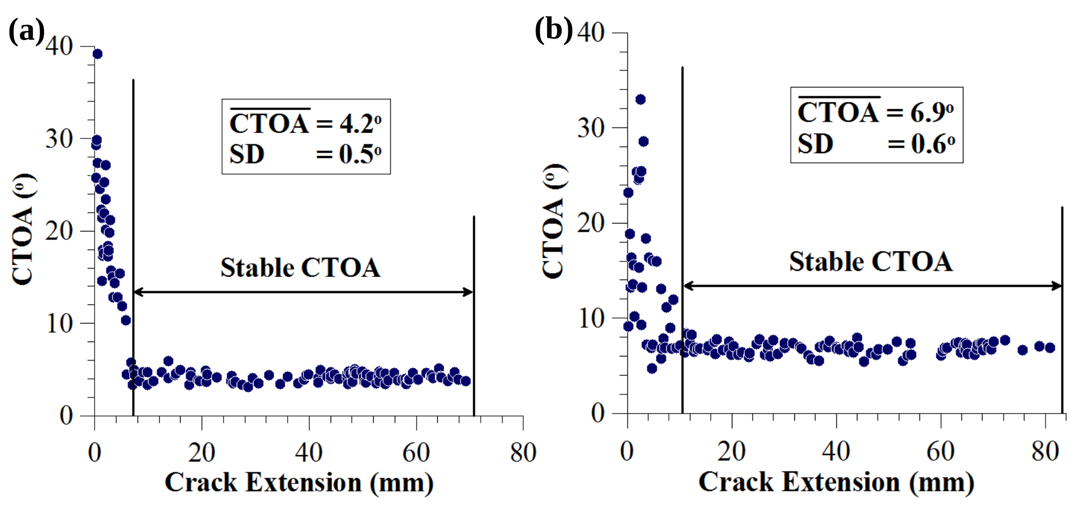

Figure 6. CTOA resistance curves for base metal of X100 steel for (a) 3 mm and (b) 8 mm gauge thickness specimens.

thickness of the CTOA arises from fracture under plane-stress conditions. Slant fracture is a key indicator of plane stress, typically occurring in thin sheets or plates, and is certainly closely related to the very low strain-hardening capacity of the X100, and is confirmed by the high $\bullet_{0.2}/\bullet_{UTS}$ ratios (see Table 1). Under plane stress, measures of toughness (such as *K*, CTOA or energy dissipation rate calculations) increase with thickness, rising to a broad maximum as plane stress gradually changes to plane strain [10], and thereafter decreases with thickness until a plateau is reached in plane-strain conditions. Thus, the ductile fracture toughness seems to achieve a broad maximum with thickness when large plasticity occurs at the crack tip. Based on this assumption, the 8 mm gauge thickness would appear be more representative of the properties of ductile pipeline fracture than the 3 mm gauge thickness. This has been confirmed in a comparison of the thickness-reduction measurement between these specimens and a full-scale burst test performed with the same pipeline steel. Furthermore, the results for the 8 mm gauge thickness are very similar to results obtained from drop-weight tear tests (7^o reported by Mannucci et al. [11]) and those from tests on full pipes (8.6^o reported by Berardo et al. [12]) performed with similar API X100 steels.

6.3. CTOA Resistance Across the Girth Weld

Fig. 7 represents the CTOA resistance curves across the girth weld for a specimen with a gauge thickness of 8 mm (more representative of the full-scale conditions). During testing, crack propagation stops briefly at the weld fusion line, the CTOA increases, then the crack jumps into the weld metal. Interestingly, this occurs again as the crack stops at the fusion line prior to jumping back into the base

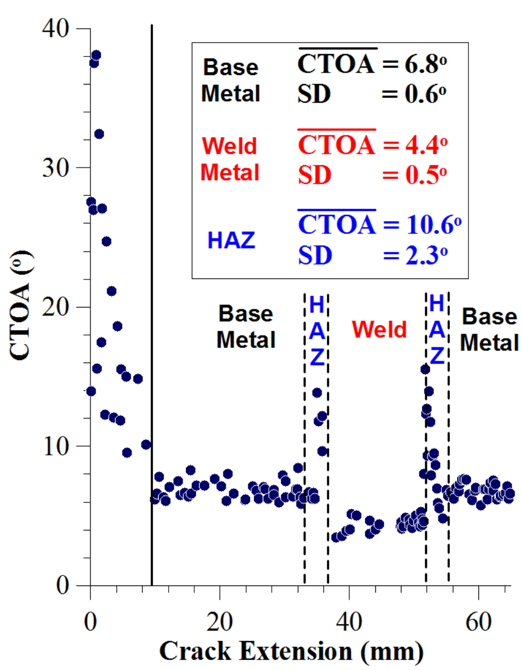

Figure 7. CTOA resistance curves for X100 steel through a girth-weld section.

metal. This suspected interface effect is likely convoluted with changes in material properties associated with the HAZ, and complicates the interpretation of CTOA here. For example, if the interface effect stops the crack growth and re-blunting occurs, a higher CTOA value might be expected even if material properties remain constant. This phenomenon, similar to the initiation test phenomenon, is not representative of a steady-state event, as would be found with stable tearing, and the HAZ CTOA values need to be seen in a qualitative way rather than in a quantitative way. Thus, only the slight decrease in fracture resistance in the weld zone, compared to the base material, could be considered representative of the girth weld steady-state crack propagation.

6.4. Influence of the Crack Velocity on CTOA Material Strength

The CTOA response as a function of the crack velocity is reported in [7], for a crack velocity range of 0.002 mm/s to 8 m/s (a typical crack speed during a burst test of a pipeline is 300 m/s [13]). The results showed that the CTOA is independent of the crack velocity for this pipeline steel, which validates the utility of quasi-static tests for studying the running-crack phenomenon in pipelines. This work [7] also points out the difficulty encountered with optical CTOA measurement methods at high crack velocity.

7. Conclusions and Summary

The stable tearing behavior of a high-strength grade (API X100) pipeline steel has been successfully measured for base metal and across girth welds with a modified double cantilever beam (MDCB) specimen. Optical imaging was used to record the uniform deformation of a crack edge on a specimen surface. The CTOA was determined during steady-state crack growth by a direct measurement method. Different methods of CTOA measurement were compared and performed at different crack rates. A higher fracture resistance was obtained for the thicker specimens. We assume that this difference is due to effects of constraint at the crack tip, and we propose to test thicker specimens more representative of the full pipeline thickness. The value for the steady-state CTOA resistance for the base metal API X100 steel was 6.9° from the thicker MDCB specimen. This result is consistent with data reported for quasi-static tests, for dynamic tests (drop-weight tear tests) and for full pipeline tests. The weld specimen CTOA results demonstrate that the fracture resistance at the HAZ/fusion line is higher than that for the base metal, and the CTOA for the weld metal is slightly lower than that for the base metal. CTOA test results showed that this criterion seems independent of the crack velocity. Finally, the CTOA criterion is a very promising and convenient fracture criterion for assessment of ductile fracture resistance of high-strength pipeline steels.

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