# Exploring Methods for Measuring Pipe Weld Toughness

*A look at the development of a new damage mechanics method for assessing the intrinsic fracture properties of welded pipeline steel*

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Plasticity in the vicinity of a crack tip introduces complex stress-strain distributions and nonuniform material flow associated with ductile fracture processes. The most accepted criteria regarding these complex behaviors are the crack tip opening displacement (CTOD), J-integral, and lately, crack tip opening angle (CTOA). Crack tip opening angle is considered a computationally attractive operational parameter. It provides an alternative to the J-integral criterion and shows promise as a fracture criterion for resistance to crack growth and arrest of unstable ductile cracks (Refs. 1, 2).

The CTOA is based on the crack opening displacement (COD) ductile fracture criterion widely used in the 1960s and 1970s for fracture assessment of thick-walled pressure vessels (Ref. 3). Moreover, the CTOA test was developed to describe the crack growth process for crack propagation analyses in metal sheets, "thin" materials with low to average crack tip constraint. Currently, the CTOA criterion is a widely accepted material property used to characterize fully plastic fracture.

The CTOA can be directly measured from the crack opening profile, related to the geometry of the fracturing structure as illustrated schematically in Fig. 1 and given in the following expression:

$$CTOA = 2\tan^{-1}\left(\frac{CTOD}{2r}\right)$$

where $r$ = 0.5 to 1.5 mm behind the crack tip and, if several measurements are performed, its mean value is used.

In practice, the CTOA is often measured directly from images of the test samples using optics to measure the angle formed by the fractured surfaces just adjacent to the crack tip, rather than using a displacement gauge. This approach allows for the use of a specimen with a longer ligament for crack growth than a typical CTOD specimen, and the long ligament specimen design is thought to be important for better understanding of crack growth in full-sized structures. Thus, crack growth through a weld section can be investigated in a more appropriate way.

A CTOA-based design criterion against 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.

Thus, the use of the CTOA criterion in an engineering critical assessment (ECA) approach can lead to a safe prediction of unstable crack propagation. For example, the propagation of an unstable running crack from a flaw detected in a pipeline girth weld can be evaluated with the knowledge of the resistance, $CTOA_c$, of the welded girth pipeline section.

## CTOA Specimen and Test Setup

A modified double-cantilever beam (MDCB) specimen (Fig. 2) was used to conduct the CTOA test (Ref. 2). The MDCB specimen is designed primarily to prevent bending, which has been experienced in both standard and tapered double-cantilever beam (DCB) specimens. The modified specimen exhibits the following characteristics:

- A large width, thickness, and ligament provide a large plastic zone.
- High constraint in the test section is promoted by two thicker loading arms. This serves two purposes. First, nonnegative, longitudinal strains can be achieved, and second, the loading is predominantly in tension with only a small shear component.
- The test section does not restrain the fracture transition modes.
- The test section is flat near the crack tip for ease of CTOA measurement.

The MDCB configuration and dimensions are depicted in Fig. 2. The large in-plane dimensions of the specimen (200 × 100 mm) and the long ligament allow relatively large amounts of stable crack growth.

The machined notch (1.6 mm height) is 60 mm long (measured from the load-line of the specimen to the notch tip).

The specimen is loaded using a pair of thick plate grips that are bolted to the specimen — Fig. 3. The loading plates in-

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crease the constraint in the gauge section of the thin flat specimens. Two cylindrical pins provide free rotation of the gripped assembly (specimen plus loading plates) during the experiments — Fig. 3. The long uncracked ligament and the loading geometry provide the condition of stable 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 × 1 mm was lightly etched by laser on the face of each specimen.

## CTOA Measurement

Digital images of the propagating crack tip are captured using a camera mounted on an xyz-stage — Fig. 3. The camera and stage are controlled using a personal computer and image analysis software to acquire images during the CTOA test. The captured images have a size of 2048 × 1536 pixels, which resulted in a resolution of about 32 µm per pixel, in the configuration typically used for our testing. Images are acquired and stored, along with time, load, and displacement data, by the software as the crack propagates across the test section of the MDCB CTOA specimen.

The CTOA is determined with software that requires the operator to trace the profile of the crack tip, and then mark data points along the upper and lower grid lines bounding the crack, as shown in Fig. 4. A series of algorithms is then used to calculate the CTOA from the outline (profile) of the crack tip.

In each image, the CTOA is measured by utilizing data from the crack profile within the range of 0.1 to 1.5 mm from the crack tip, as prescribed by the ISO and ASTM draft standard (Ref. 4). As shown in Fig. 5, this method never uses the crack tip, or the region immediately adjacent to it in the calculation of CTOA. Various pairs of points from the crack profile data are used to define best-fit lines, and the intersection of these lines is used to calculate the CTOA.

This method uses an algorithm that selects pairs of points along the crack profile. The pairs of points are used to derive series of $CTOA_{(i)}$ values as follows:

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

where $\delta_i$ 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. 5.

The mean of the individual $CTOA_{(i)}$ data obtained from a single picture is defined to be the CTOA of the growing crack, related to the crack extension $\Delta a$:

$$CTOA\Big|_{\Delta a} = \frac{1}{n}\sum_{i=1}^{n} CTOA_{(i)}\Big|_{\Delta a}$$

## CTOA Results for a Pipeline Steel and Girth Weld

Crack tip opening angle test specimens were extracted from an X100 high-strength pipeline steel. The test specimens were oriented to produce crack growth along the longitudinal axis of the pipe and perpendicular to a girth weld — Fig. 2. The experiments were conducted under crack opening (mode I) loading and quasi-static conditions, at a low strain rate (in the range of 0.002 to 0.02 mm/s) under displacement control. Figure 6 plots the CTOA results from more than 115 images captured from two CTOA tests.

In Fig. 6, the initial $CTOA_c$ is high (around 60 deg), and it rapidly drops as

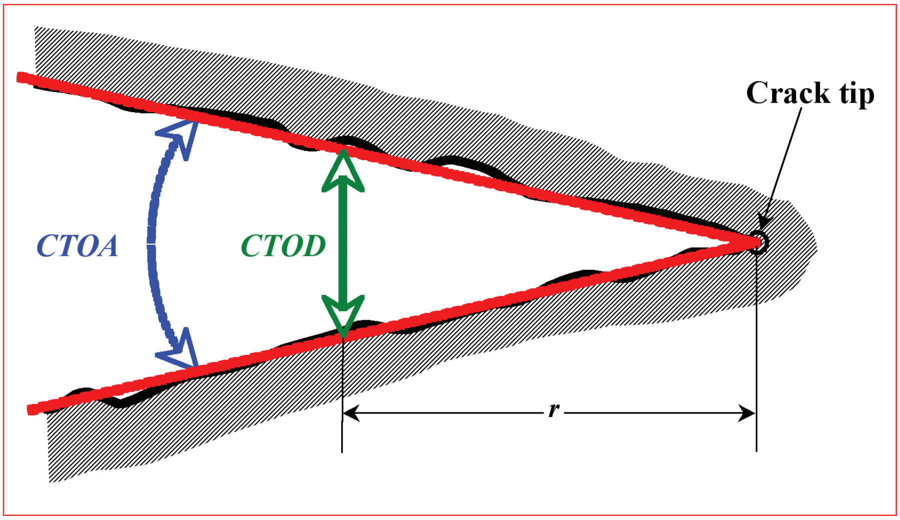


Fig. 1 — Definition of CTOD and CTOA measurement schemes.

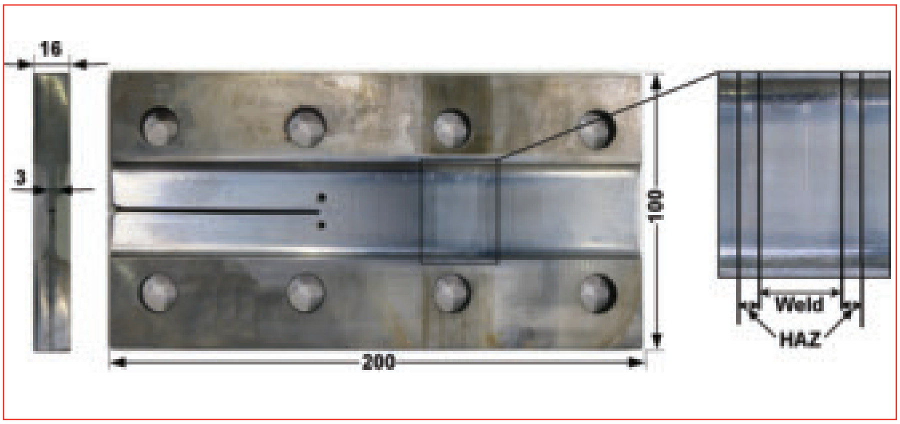


Fig. 2 — MDCB specimen with a weld section exhibiting a heat-affected zone (HAZ). Dimensions given in millimeters.

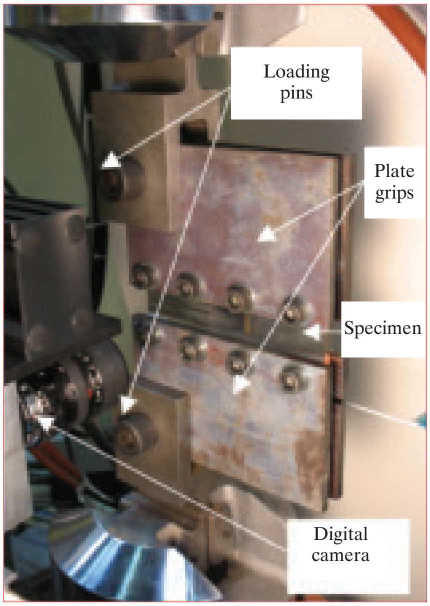


Fig. 3 — CTOA test setup.

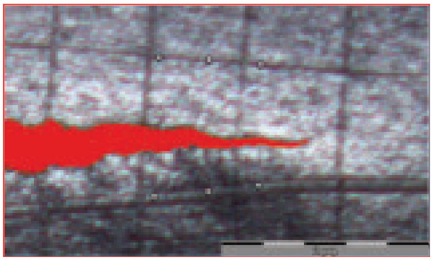

*Fig. 4 — Crack profile traced manually for CTOA determination.*

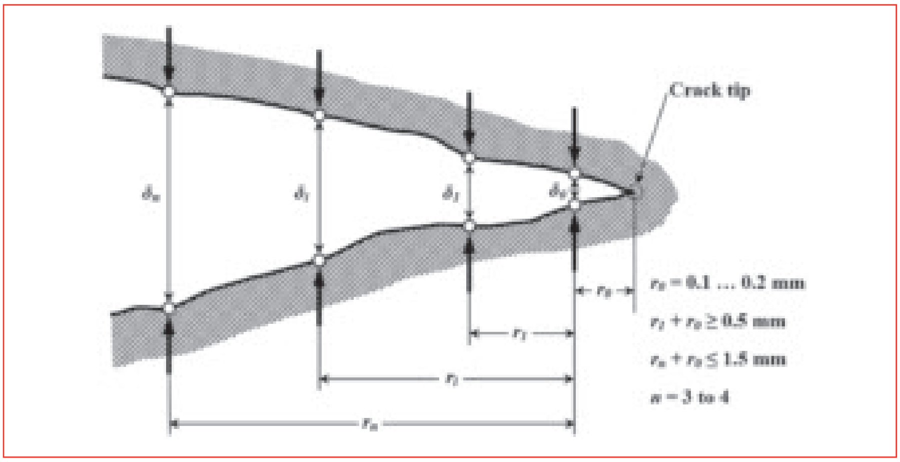


*Fig. 5 — Method for determining the CTOA.*

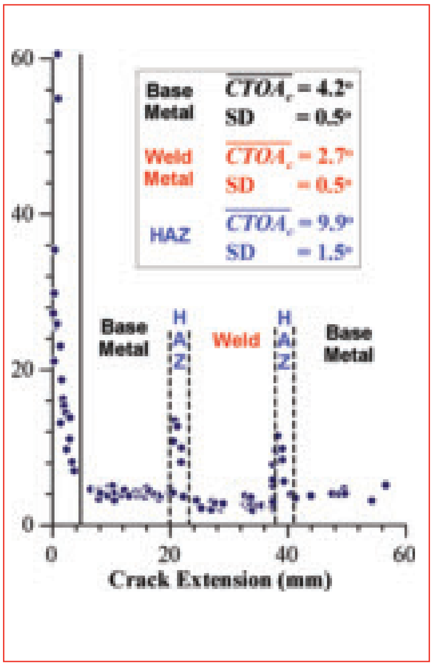


*Fig. 6 — $CTOA_c$ resistance curve for X100 steel through a weld section.*

the blunting at the fatigue precrack tip decreases and crack growth begins. The $CTOA_c$ approaches a constant value at about 5 mm. In this region the fracture orientation changes from being perpendicular to the loading axis to having an angle of about 45 deg to the axis of loading (shear fracture mode). This is referred to as a transition from flat-to-slant fracture, and typically occurs at a crack length of about 1.5 times the specimen thickness. In this transition region, the $CTOA_c$ approaches a constant value, which is associated with steady-state crack growth; it is this $CTOA_c$ value that is used to characterize the resistance to crack growth for a material.

The results in Fig. 6 show that the softer heat-affected zone (HAZ) has higher fracture resistance than the base metal (HAZ $CTOA_c$ value of 9.9 ± 1.5 deg compared with 4.2 ± 0.5 deg for the base metal). In fact, when the crack propagation reaches the weld interface, the crack propagation stops for an instant as the $CTOA_c$ increases, then the crack jumps into the weld metal. The same phenomenon occurs as the crack reaches the interface on the other side of the weld, and then the crack jumps into the base metal. The results also show that the weld zone exhibits a slight decrease in fracture resistance, as compared with the base metal. The $CTOA_c$ value decreases from 4.2 ± 0.5 deg to 2.7 ± 0.5 deg as it leaves the base metal and enters the weld.

## Summary

The fracture toughness behavior of X100 pipeline steel through a girth weld section was investigated using a modified double cantilever beam specimen. A test technique for direct measurement of the steady-state CTOA was presented. 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 using software developed for this study. The results demonstrate a slight improvement of the fracture resistance in the HAZ and a slight decrease in the weld metal. Crack tip opening angle is a very promising and convenient fracture criterion for the assessment of ductile fracture resistance in base metals and welds. Further study is warranted on a variety of matching and mismatching welds and base metals.◆


*Acknowledgments*

The support of U.S. Department of Transportation, Pipeline and Hazardous Materials Safety Administration, is gratefully acknowledged.

BP Exploration is also gratefully acknowledged for contributing the pipeline steel.

The efforts of Hans Windhoff, Olympus Soft Imaging Solutions Corp., helped to develop the software used in this study.


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