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Title: Welding in the world. Soudage dans le monde.

Volume: 51

Issue: Special Issue - 2007

Date: July 2007

Article/Paper: Ph. P. Darcis, C. N. McCowan, E. S. Drexler, J. D. McColskey, A. Shtechman, T. A. Siewert; Fracture toughness through a welded pipeline section - crac

Pages: 225-242

(10)

OCLC #: 2451540
ISSN: 0043-2288

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FRACTURE TOUGHNESS THROUGH A WELDED PIPELINE SECTION
- Crack Tip Opening Angle Criterion -

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Keywords: Crack tip opening angle, girth weld, high strength pipeline steel.

Abstract:
Crack tip opening angle (*CTOA*) is becoming one of the more widely accepted properties for characterizing fully plastic fracture. In fact, it has been recognized as a measure of the resistance of a material to fracture in cases where there is a large degree of stable-tearing crack extension during the fracture process.
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 (MDCB) specimen. A digital camera and image analysis software are used to record the progression of the crack tip and to estimate *CTOA*.
We present *CTOA* data on crack growth orientations perpendicular to girth welds, and describe the change in *CTOA* when a running crack reaches a circumferential butt weld. This study will help the gas pipeline industry to better understand the effect of a running crack propagating through a weld.
The results demonstrate a slight improvement of the fracture resistance in the heat affected zone (HAZ) and a slight decrease in the weld metal. *CTOA* is a very promising and convenient fracture criterion for the assessment of ductile fracture resistance in base metals and welds.

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, higher pressure pipelines. The application of high-strength steels in severe conditions will require reliable pipeline designs, as well as inspection and maintenance procedures that will prevent in-service failures. A difficult problem to be solved for the economic and safe operation of high pressure gas lines is the control of ductile fracture propagation. In this case, a safety factor has to be developed for fracture arrest. Thus, accurate prediction of the resistance to fracture for high-pressurized pipelines is one of the issues to be solved for the new pipeline designs.

The concept of overall absorbed fracture energy was traditionally used to design low strength grade pipeline steels against ductile fracture. Initially, the measure of material fracture resistance was constructed on 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 as the full wall thickness fracture surface of this specimen better represented the shear characteristics of the pipe. These failure models worked well for low toughness steels (below 550 MPa yield, Charpy toughness level up to 95 J) [2], but needed corrections for high toughness steels.

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 [2-4]. Some correction factors were suggested [3,4] to set toughness requirements for high strength grade steels. However, the addition of correction factors may not capture the fracture mechanisms for the fracture phenomenon observed.

In parallel to the CVN and DWTT based fracture strategies, pipeline designers have worked on developing new measures of fracture control. Among these, crack tip opening angle (*CTOA*) is becoming one of the more widely accepted properties for characterizing fully plastic fracture [5-8]. *CTOA* is considered a computationally attractive operational parameter that 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 [2,5].

The *CTOA* is based on the *CTOD* (crack tip opening displacement) ductile fracture criterion widely used in the 60's and 70's [9] for fracture assessment of thick-walled pressure vessels. 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. Furthermore, 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 [5,7]. This type of steady-state fracture resistance takes place when the *CTOA* in a material reaches a critical value, as typically occurs in low-constraint configurations. This suggests that a steady-state *CTOA* could be considered to be a material property and used as either an addition or an alternative to the absorbed fracture energy for the assessment of the toughness of pipeline steels. In addition, the *CTOA* criterion is easy to implement in finite element models of the propagating fracture process.

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:

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

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

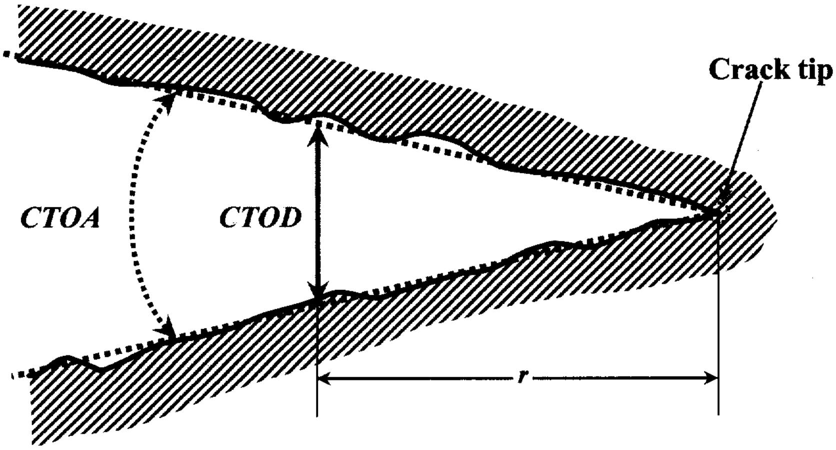

Fig. 1. Definition of *CTOD* and *CTOA* measurements scheme.

The main advantage of *CTOA* is that it can be measured directly from images of the test samples using optics to measure the angle formed by the fractured surfaces adjacent to the crack tip, rather than using a displacement gage. This approach allows for the use of a specimen with a longer ligament for crack growth than that used of a typical *CTOD* specimen. 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 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 use of the *CTOA* criterion in an ECA (Engineering Critical Assessment) 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.

Our current research has applied the *CTOA* concept (using a single specimen *CTOA* test method) to determine the fracture toughness properties of high strength grade welded pipeline sections (X100 steel). A test approach for direct image measurement of the material *CTOA* was developed based on a modified double cantilever beam (MDCB) specimen. This test technique utilized optical imaging (digital camera) to record images of the crack tip for post-analysis of the *CTOA* of the material under study. The angle of the crack edges near the crack tip was measured during crack extension from the captured images. A plot of *CTOA* versus crack length was generated to obtain the critical *CTOA* ($CTOA_c$), which represents the base metal, heat affected zone (HAZ) and weld material fracture toughness.

2. MATERIAL PROPERTIES

An APIX100 high strength grade pipeline steel (outside diameter 52 inch (1.32 m) and 20.6 mm thick) was investigated. Table 1 contains the chemical composition of this steel (weight %).

Table 1. Chemical composition of the X100 tested steel (weight %)

C	Mn	P	S	Si	Cr	Ni	Cu	V	Nb	Mo	Co
0.07	1.90	0.008	0.0005	0.100	N/A	0.500	0.300	N/A	N/A	0.150	N/A

To measure the tensile properties of pipelines, round tensile specimens (6 mm diameter) were machined. Specimens were machined in both axial (longitudinal) and transverse orientations, and all specimens had a gauge length of 25.4 mm. Experiments were performed in a screw driven tensile testing machine of 100 kN capacity, and a closed-loop servo-hydraulic machine of 100 kN capacity. Tests were conducted in displacement control at rates of 0.1 mm/min.
The measured mechanical properties of the X100 steel are shown in Table 2, where $\sigma_{0.2}$ is the yield stress, σ_{UTS} is the ultimate strength, e_u is the uniform elongation, and e_f is the fracture elongation.

Orientation	$\sigma_{0.2}$ **(MPa)**	σ_{UTS} **(MPa)**	$\sigma_{0.2}/\sigma_{UTS}$	e_u **(%)**	e_f **(%)**	e_u/e_f
Longitudinal	694	801	0.87	4.3%	25.0%	0.17
Transverse	797	828	0.96	4.3%	24.5%	0.17

Table 2. Mechanical properties in transverse and longitudinal directions.

A picture of the girth weld cross-section is shown in Fig. 2. For this girth weld, the welding process was shielded metal arc (manual) for the fill and cap. The root welding electrodes are not specified here, because the *CTOA* specimen is machined from the middle of the weld section.
Vickers micro-hardness measurements, using a 500 g weight and a diamond point, indicated a weld over-matching of 4 % and a 10 % under-matching in the HAZ.

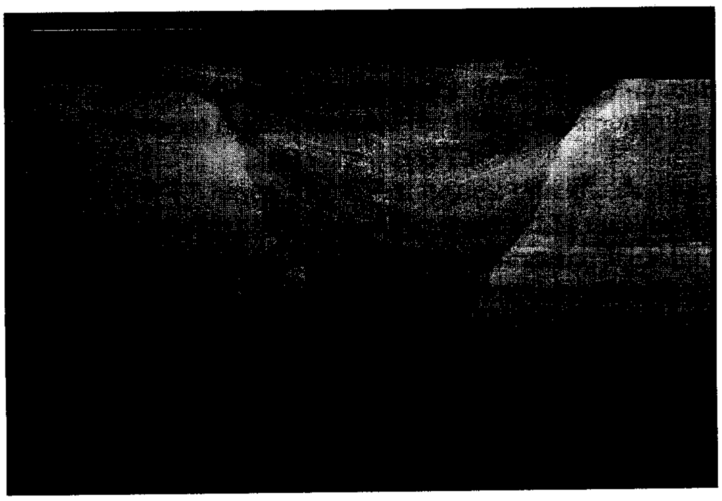

Fig. 2. Girth weld section.

3. *CTOA* SPECIMEN AND TEST SET UP

A modified double cantilever beam (MDCB) specimen was used to conduct the *CTOA* test. This specimen was proposed by several authors [2,10,11]. The MDCB specimen is designed primarily to prevent bending, which has been experienced in both standard and tapered DCB. The modified specimen exhibits the following characteristics:

- It may be cut directly from a pipe, without any flattening.
- The maximum possible width, thickness and ligament provide a large plastic zone. The width and thickness are limited by pipe curvature and wall thickness.
- High constraint in the test section is promoted by two thicker loading arms. This serves two purposes. First, non-negative 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 transition to slant mode shear fracture.
- For ease of *CTOA* measurement, the test section is flat near the crack tip.

The MDCB configuration and dimensions are depicted in Fig. 3.

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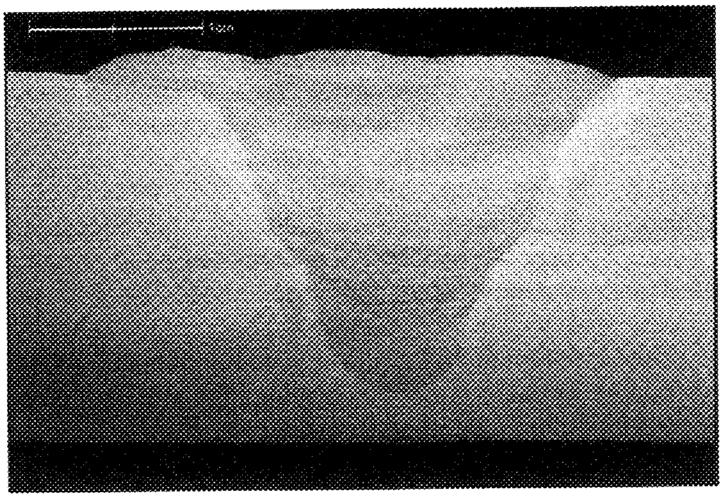

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The MDCB configuration and dimensions are depicted in Fig. 3.

The large in-plane dimensions of the specimens (200 mm × 100 mm) and the long ligament allowed relatively large amounts of stable crack growth. To increase the constraint effects in the high strength grade steel specimens, the arm thickness of the specimens was increased (see details in Fig. 3). This resulted in two thick loading arms and a thin flat side-grooved region on opposite sides of each specimen. The flat side-grooved region was used to study crack growth and for optical measurement of *CTOA* values.

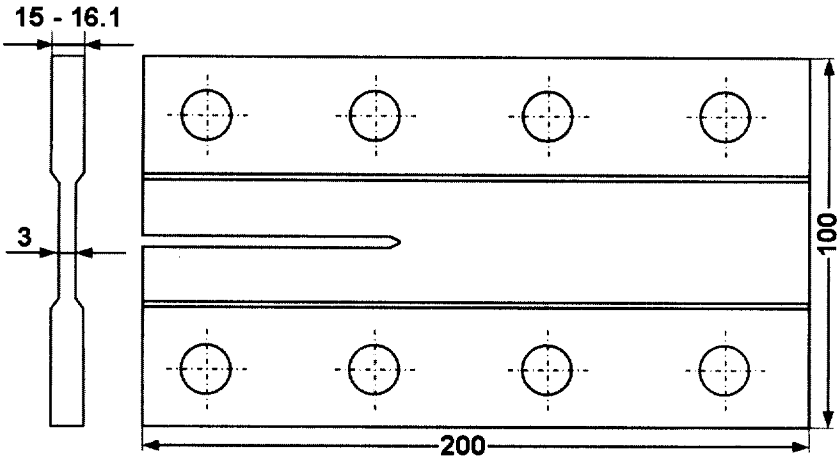

Fig. 3 MDCB specimen, configuration and dimensions (mm).

Test specimens were extracted from plate cut from the longitudinal axis of the pipe. To obtain a flat plate, the thickness of the curved plate was reduced by machining. This eliminated the probable residual plastic strains that would be caused by flatting the plate by use of a straightening procedure. Four specimens were extracted from pipelines in the longitudinal orientation: two with a weld section and two without. A schematic of the specimen-cutting scheme is shown in Fig. 4.

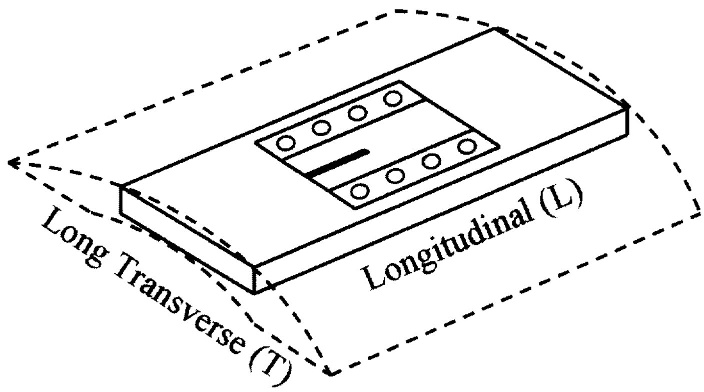

Fig. 4. Orientation of *CTOA* specimen in the pipe.

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 pins).
The loading of the specimen was conducted by means of a pair of thick plate grips bolted to the side surfaces of the specimen (Fig. 5). Two cylindrical pins provided free rotation of the whole assembly (specimen plus loading plates) during the experiments (Fig. 5). The middle reduced section region together with the two thick loading plates increased the constraint levels in the gauge section. The long uncracked ligament and the loading geometry provided a condition of stable shear crack extension in the specimen ligament, similar to that of the real structure. The load-line passes through the left pair of loading holes.

To facilitate the *CTOA* measurement, a fine square mesh, with a spacing of 1 mm × 1 mm was lightly etched by laser on the face of each specimen.

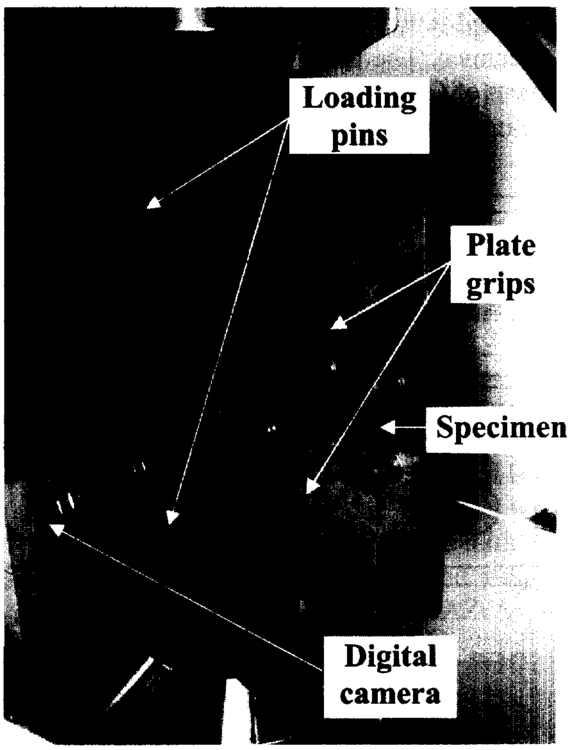

Fig. 5. *CTOA* test set up.

4. MECHANICAL TEST CONDITIONS

Tests were conducted on specimens with a 3 mm gauge thickness with and without a girth weld section. The experiments were conducted on a 250 kN closed loop servo-hydraulic test machine, under opening (mode I) loading and quasi-static conditions, at a low strain rate under displacement control in the range of 0.002 mm/s to 0.02 mm/s. In each test, the time, load, load line displacement, and CMOD gauge were recorded (see Fig. 5 for the test set up).

The specimens were first fatigue pre-cracked following the ASTM standard procedure for conducting crack tip opening displacement (*CTOD*) tests [12]. The pre-cracking loads were selected by maintaining the ratio of stress intensity factor range to the Young's modulus ($\Delta K/E$) below 0.005 $mm^{1/2}$. All specimens were fatigue pre-cracked at a ratio of $R = 0.1$ [13], to a crack-to-width ratio of $a_0/W = 0.3$ to 0.5 (with a specimen width, W, equal to 182 mm, and a_0 equal to the machined notch length (60 mm) plus the initial fatigue pre-crack length).
After the fatigue pre-cracking, the specimens were slowly pulled apart, at the desired displacement rate, causing the advancing crack to tear after reaching maximum load and transitioning to a state of stable tearing.

Two tests were conducted on X100 steel base metal (at 0.02 mm/s) and two with the girth weld (at 0.02 mm/s and 0.002 mm/s).

5. *CTOA* MEASURMENT

Digital images of the propagating crack tip are captured using a camera mounted on an *xyz*-stage (Fig. 5). 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

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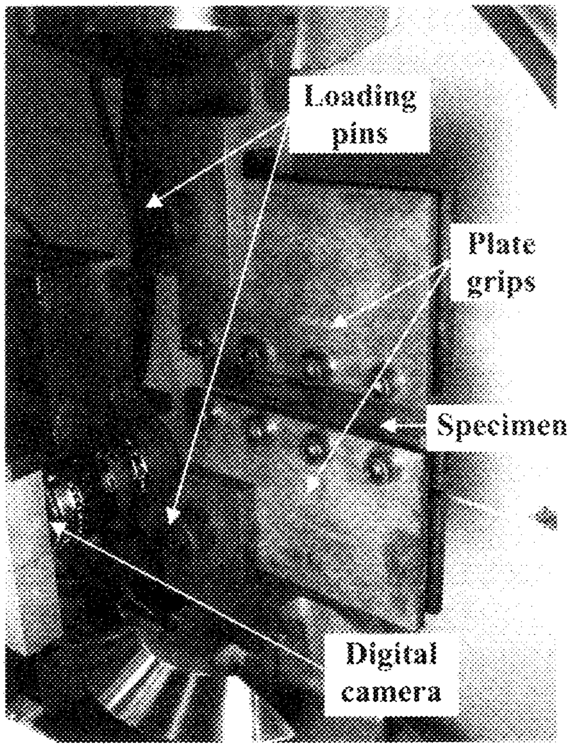

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The *CTOA* is determined with software that requires the operator to trace the profile of the crack tip, and then mark data points along the upper and lower grid lines bounding the crack, as shown in Fig. 6. A series of algorithms are then used to calculate the *CTOA* from the outline (profile) of the crack tip.

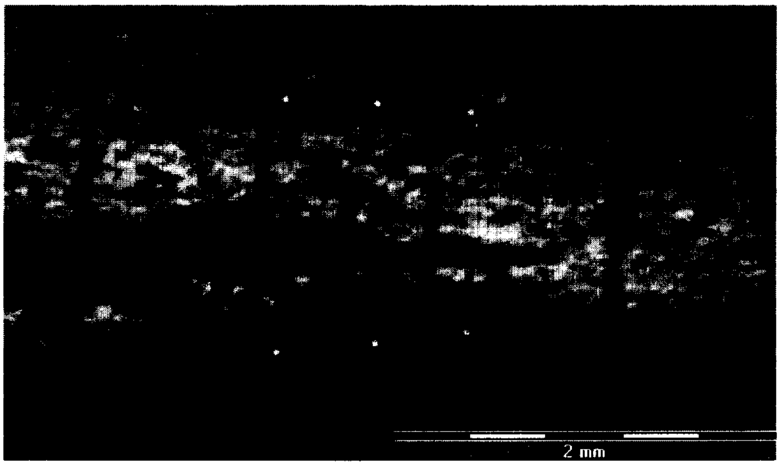

Fig. 6. Crack profile traced manually for *CTOA* determination.

In each image, the *CTOA* is measured by utilizing data from the crack profile within the range of 0.5 mm to 1.5 mm from the crack tip, as prescribed by the ISO draft standard [14] and the ASTM standard [15]. As shown in Fig. 7, 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*.

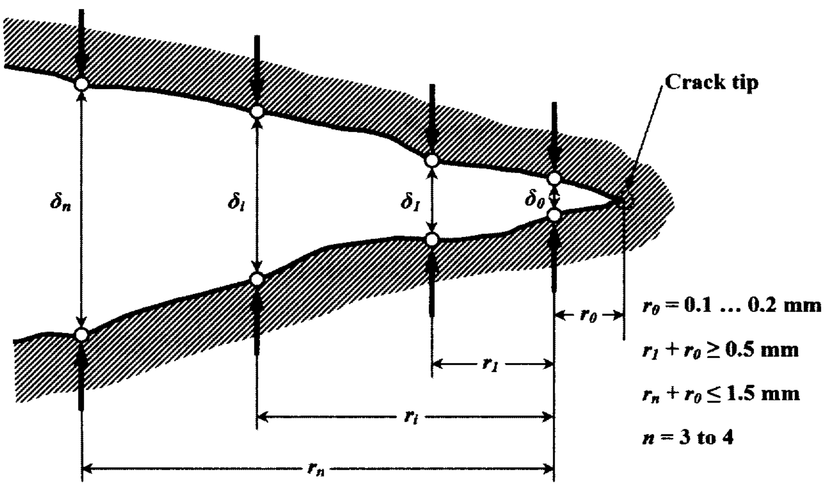

Fig. 7. Method for determining the *CTOA*.

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:

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

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. 7).

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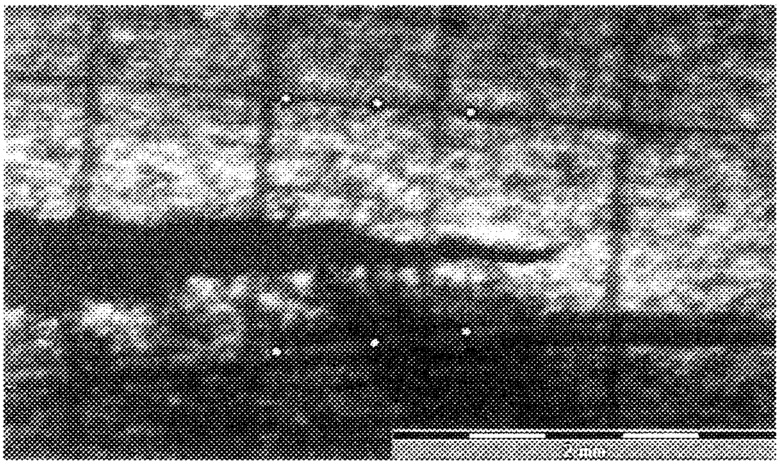

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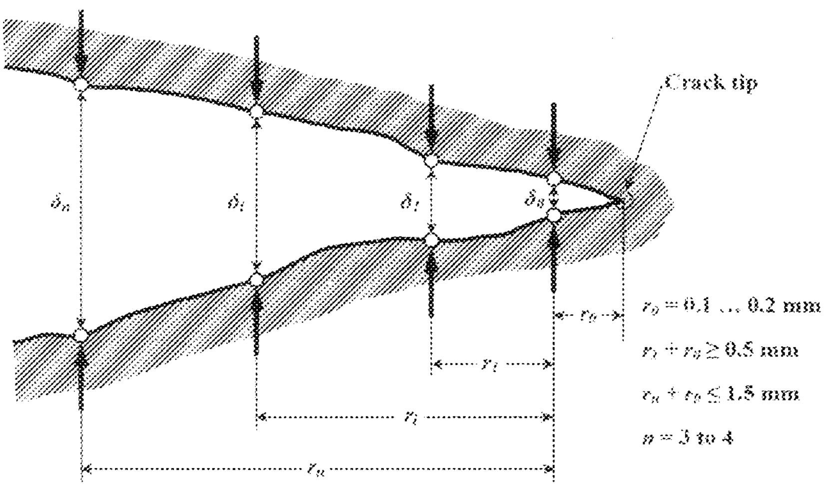

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The mean of the individual $CTOA_{(i)}$ data obtained from a single picture is defined to be the *CTOA* of the growing crack, related to the crack extension Δa:

$$CTOA\big|_{\Delta a} = \frac{1}{n}\sum_{i=1}^{n} CTOA_{(i)}\big|_{\Delta a} \quad (3)$$

5. *CTOA* RESULTS FOR A PIPELINE STEEL AND GIRTH WELD

Extensive combinations of experimental and computational work on gas pipeline steels by Mannucci et al. [7], Wilkowski et al. [8] and others show that the *CTOA* approaches a plateau during the steady state phase of shear crack propagation. This steady state *CTOA*, considered as a material property, is generally preceded by relatively high *CTOA* values during the early stages of cracking after the crack has grown to a size several times the specimen thickness. These two behaviors are also observed in all our tests.

Fig. 8 illustrates the *CTOA* resistance curves for X100 high strength pipeline steel base metal only. This figure represents the *CTOA* results from more than 125 images captured from two *CTOA* specimens.

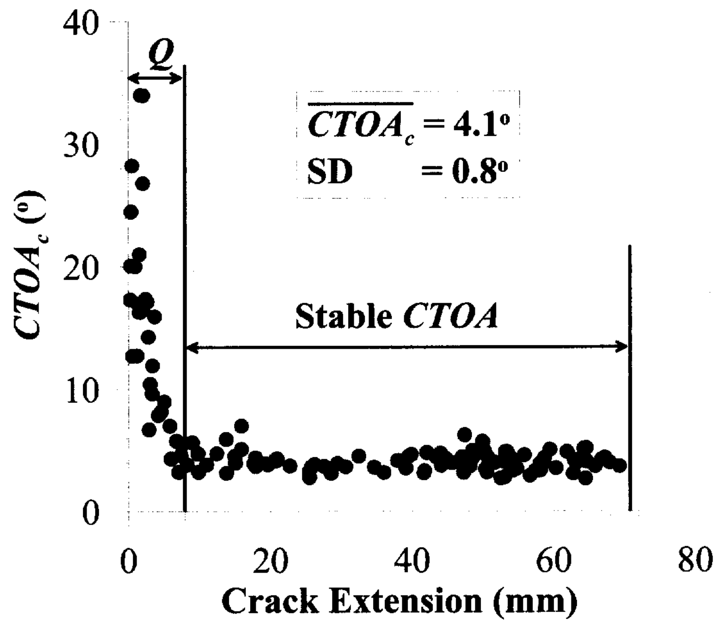

Fig. 8. $CTOA_c$ resistance curves for X100 steel base metal.

In Fig. 8, the initiation $CTOA_c$ was high (around 35°), and it rapidly dropped in the flat-to-slant fracture transition region and approached a constant value (associated with steady state crack growth) at a crack length approximately 1.5 times the specimen thickness (in Fig. 8, *Q* represents the crack extension to achieve stable $CTOA_c$). Flat tearing and tunneling effects dominated the non constant *CTOA* profile during the early stages of crack growth. After the transition, full slant tearing (shear mode) was developed and resulted in a steady state $CTOA_c$ value. The $CTOA_c$ resistance value of 4.1° ± 0.8° was measured for the X100 steel.

Fig. 9 represents the *CTOA* results for the girth weld, from more than 115 images captured from two *CTOA* tests. The same trend is observed at the beginning as in the base metal tests (Fig. 8): the initial $CTOA_c$ is high and it rapidly drops to a constant value as seen previously: 4.2° ± 0.5°. The two different displacement rates (0.02 mm/s and 0.002 mm/s), used for the two different tests, seem to have no effect on the *CTOA* evolution.

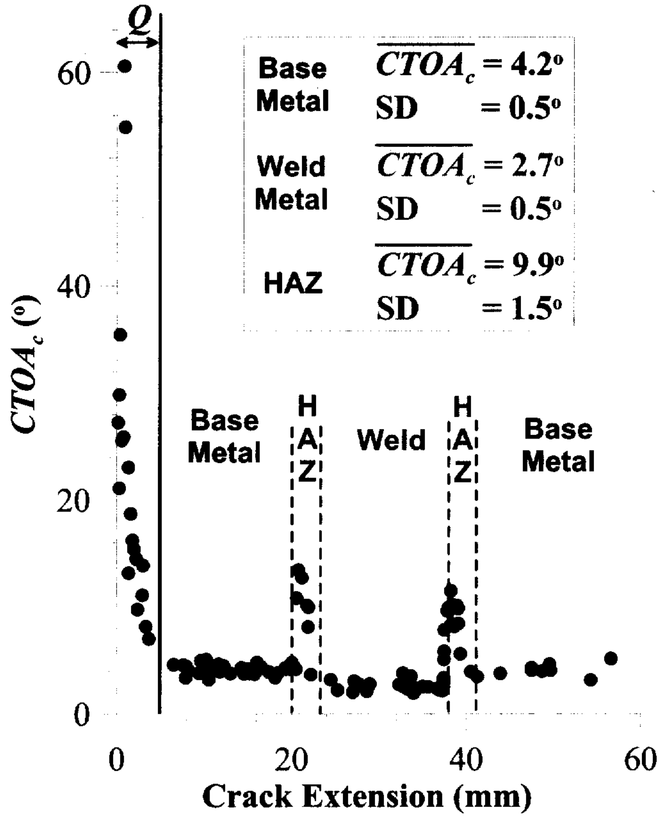

Fig. 9. ***CTOA**$_c$* **resistance curve for X100 steel through a weld section.**

The results in Fig. 9 show that the softer HAZ has higher fracture resistance than the base metal (HAZ *CTOA*$_c$ value of 9.9° ± 1.5° compared with 4.2° ± 0.5° for the base metal). In fact when the crack propagation reaches the weld fusion line 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 fusion line 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 that of the base metal. The *CTOA*$_c$ value decreases from 4.2° ± 0.5° to 2.7° ± 0.5° as it leaves the base metal and enters the weld.

6. CONCLUSIONS AND SUMMARY

The fracture toughness behavior of X100 pipeline steel through a girth weld section was investigated by use of 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. *CTOA* 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 the variety of matching and mismatching welds and base metals.

7. ACKNOWLEDGEMENTS

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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