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CTOA Results for X65 and X100 Pipeline Steels: Influence of Displacement Rate[1]

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ABSTRACT

The toughness and plasticity of steel generally decreases with increasing testing rate. The crack tip opening angle (CTOA) was measured on two types of commercial pipeline steels API-X65 and API-X100, at a range of displacement rates to characterize rate effects. The testing was conducted at quasi-static and dynamic rates. The crosshead displacements in our test matrix ranged from 0.002 mm/s in the quasi-static mode to approximately 8000 mm/s in the dynamic mode. The quasi-static tests were conducted in a servo-hydraulic uniaxial test machine using Modified Double Cantilever Beam (MDCB) specimens. The dynamic experiments were made on a similar servo-hydraulic uniaxial test machine using the same type of specimen and with the addition of a disc spring setup for the fastest rate. The results of these tests indicate that the rate effect has negligible influence on the CTOA values measured for these materials for the reported rates. The CTOA values measured for the two materials show a small but convincing difference. The resistance to fracture was found to be higher for the X65 steel, as indicated by a higher CTOA and lower crack growth velocity. This paper presents results on the influence of displacement rates from quasi-static to dynamic for the X65 and X100 grade pipeline steels, and discusses a method for optimizing the reduction of the CTOA data.

INTRODUCTION

The increasing need for the transportation of oil and natural gas requires that high-strength steel be evaluated for operational use in the pipeline network. The increase in pressure of operation calls for improved material requirements. For that reason it is important to have reliable mechanical property data to design the pipeline. The Crack Tip Opening Angle (CTOA) is proposed as the material property for characterizing fully plastic fracture.

Papers on CTOA are typically based on quasi-static rates and steady-state crack propagation tests [1, 2]. In cases where there is a large degree of stable tearing during crack propagation, CTOA has been recognized as an indicator of the material's resistance to fracture [3, 4].

Quasi-static crack velocities of 0.002 mm/s to 0.05 mm/s have been reported [2, 5] in the literature. However, pipeline failures in service occur at velocities of near 200 m/s for ductile fracture in steels, and as high as 900 m/s for brittle fracture in steels [6]. Full-scale tests to duplicate these rates are expensive, and laboratory tests such as CTOA and drop weight tear test (DWTT) have not reached these very high propagation rates. This study evaluates the influence of testing rate on CTOA values by use of MDCB specimens, in order to understand how laboratory-scale tests of resistance to crack growth relate to the full-scale tests.

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In this work, actuator displacement rates cover nearly seven orders of magnitude: from 0.002 mm/s to approximately 8000 mm/s.

The influence of rate on the measured CTOA was evaluated for two different grades of high-strength pipeline steels, X65 and X100.

MATERIAL

Two different types of pipeline steels were tested: X65 and X100. Table 1 summarizes the dimensions of the pipelines. The nominal chemical compositions of the two pipeline steels are given in Table 2.

Table 1: Dimensions of the tested pipeline steels.

Steel #	1	2
Grade	X65	X100
O.D. [m]	0.61	1.32
Thickness [mm]	31.5	20.6

Table 2: Chemical composition of the tested steels [%wt].

Steel	C	Mn	P	S	Si	Cr
X65	0.07	1.5	0.009	0.004	0.093	0.13
X100	0.07	1.9	0.008	0.005	0.1	N/A

Steel	Ni	Cu	V	Nb	Mo	Co
X65	0.16	0.11	0.04	0.04	0.003	0.003
X100	0.5	0.3	N/A	N/A	0.15	N/A

The mean tensile properties of the steels are given in Table 3. As expected, the X65 mechanical properties are about 65 % of the X100 mechanical properties. Six tensile specimens were machined from each steel: three longitudinal to the pipe and three transverse to the pipe, with a 6 mm (0.25") diameter and a 25 mm (1.00") gage length. The tensile tests were conducted on a uniaxial servo hydraulic machine with a 100 kN capacity. The tests were conducted in displacement control at a displacement rate of 0.25 mm/s.

Table 3: Mean mechanical properties for the steels.

Steel	Orient.	σ_y [MPa]	σ_{UTS} [MPa]	e_u [%]	e_f [%]
X65	L	492±12	561±9	7.1	25.7
X65	T	519±5	582±5	7.7	20.9
X100	L	705±40	803±6	4.2	20.3
X100	T	794±11	827±5	4.5	19.3

e_u- The uniform elongation.
e_f- The fracture elongation.

The microstructures of the X65 and X100 steels are shown in Figures 1 and 2, respectively. The microstructure of the X65 alloy shows a fine-grained ferritic steel. Typically this grade of steel is described as a ferrite-pearlite microstructure, but this particular steel might be better described as ferrite-carbide, since there is very little pearlite, and the microstructure of X65 varies widely, so this is not unusual. The X100 steel used is an early generation bainitic pipeline steel and shows some evidence of banding of constituents in the microstructure.

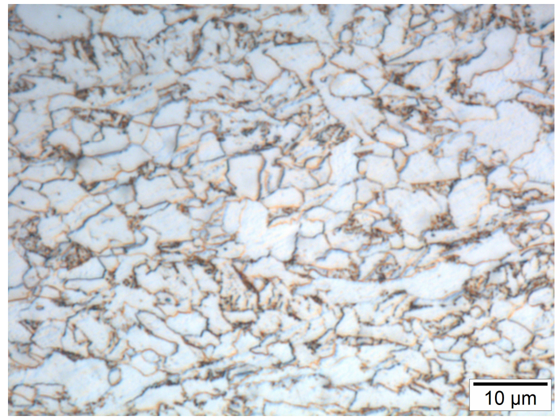

Figure 1: Microstructure of the tested X65 pipeline steel.

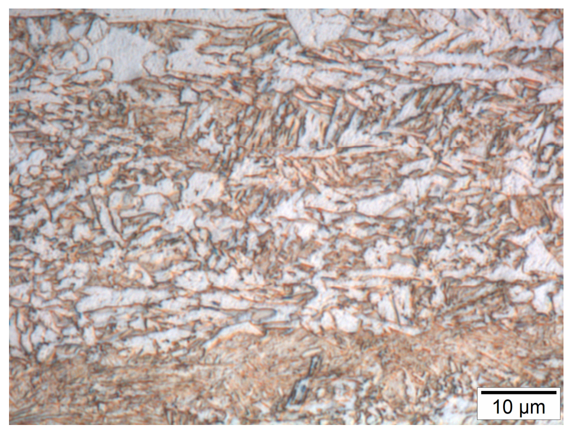

Figure 2: Microstructure of the tested X100 pipeline steel.

CTOA SPECIMEN

In this study, the specimen used was a MDCB design (Figure 3). The MDCB design was discussed in detail in previous papers [7, 8]. Our specimen was 200 mm by 100 mm and had a thickness of 8 mm in the test section. In order to facilitate post-test analysis the test section of the specimens was paint etched with a 0.5 mm by 1.0 mm grid by use of a laser process. Figure 4 shows the configuration of the machined CTOA specimen in the pipe (no flattening required). Both quasi-static and dynamic specimens were initially pre-cracked by use of the procedure outlined in an earlier paper [9].

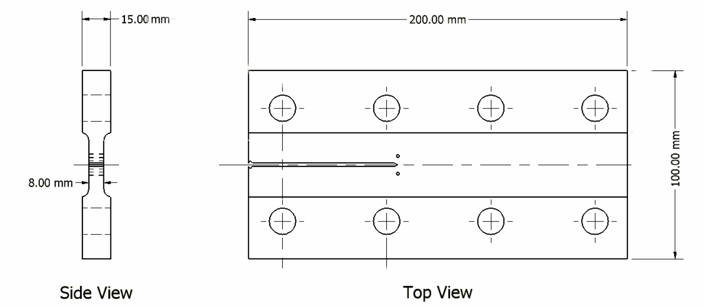

Figure 3: Sketch of the MDCB specimen.

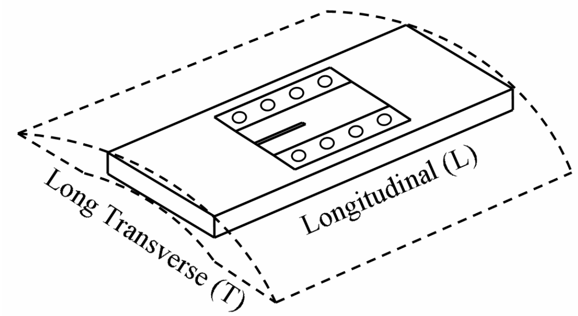

Figure 4: Configuration of the CTOA specimen in the pipeline.

CTOA SETUP AND TESTING PROCEDURE

Both quasi-static and dynamic tests were conducted on uniaxial servo-hydraulic test machines: the quasi-static tests were done on a 250 kN machine, and the dynamic tests on a 500 kN machine. The 250 kN machine and test setup are discussed and described in detail in another report [9], and the test setup on the 500 kN machine is discussed in detail in a companion paper submitted to this conference [10].

CTOA tests on both X65 and X100 specimens were conducted at actuator rates of 0.002, 0.02, 0.2, 3, 30, 300, and 8000 mm/s. The 8000 mm/s displacement rate was attained with a disc spring setup, discussed in detail in the companion paper [10].

Image Acquisition

For the quasi-static tests, the images were captured by a digital camera mounted on an XY stage. The camera and the stage were computer controlled with internally developed macros for commercially available software to follow the moving crack tip and capture pictures during the test. Figure 5 shows the test setup.

For the dynamic tests, a high-speed camera was used (10,000 frames/s). The video was divided into individual frames for the CTOA measurements. Depending on the test rate, the initial recording was triggered manually or mechanically.

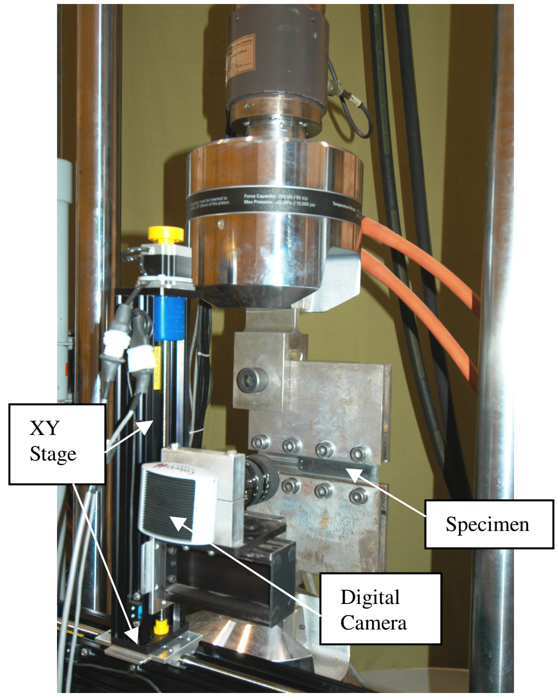

Figure 5: The quasi-static test setup.

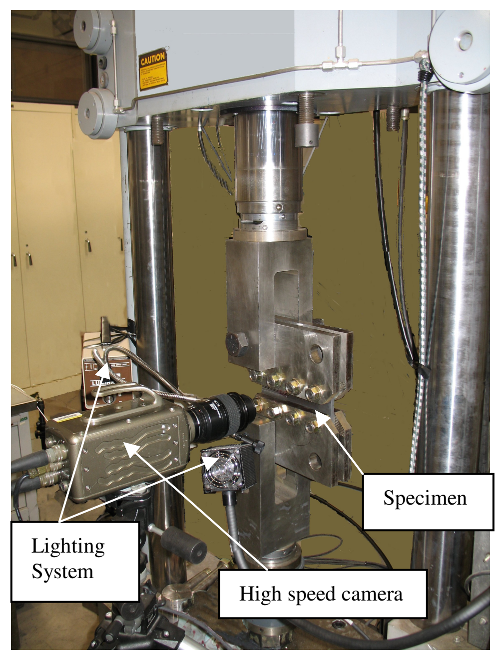

Figure 6: The dynamic test setup, without the spring apparatus.

The camera was fix-mounted to focus on an area of the test section (15 mm by 20 mm), at a position about 30 mm ahead of the initial fatigue crack tip. Figure 6 shows the test setup for the dynamic tests conducted at 3 mm/s to 300 mm/s without the spring apparatus.

Software developed for previous studies was used to measure the CTOA from the captured pictures [11]. The procedure requires the operator to trace the crack tip profile and to mark the grids above and below the crack edge. From this information the software calculates the CTOA by use of various algorithms.

Figures 7 and 8 show images characteristic of those used for the CTOA measurements. The images are from dynamic tests which fractured in two different modes: shear and flat fracture, respectively. The straight lines represent a calculated best-fit line, using several hundred points on the crack tip outline, on each of the top and bottom crack profiles (P method). The triangle and the small circle pairs mark the upper and the lower limits for the raw data used to calculate the CTOA. The other circles along the fracture profile show data points throughout this range used to calculate the CTOA for the P method. The dots, selected by the operator, on the upper and lower grid lines are used to fit lines to calculate the CTOA from the grid deformation (G method). The CTOA values reported in this paper were calculated by use of these two approaches (P and G).

The velocity of the crack growth velocity in the steels was calculated. Time stamps for individual photographs and crack tip position were used to estimate the velocity.

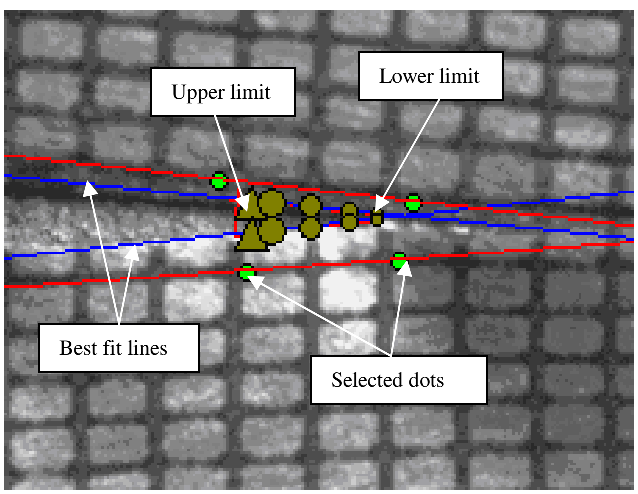

Figure 7: Method for determining the CTOA test of an X100 specimen exhibiting shear fracture. The test was run using a disc springs setup at a test rate of approximately 8000 mm/s.

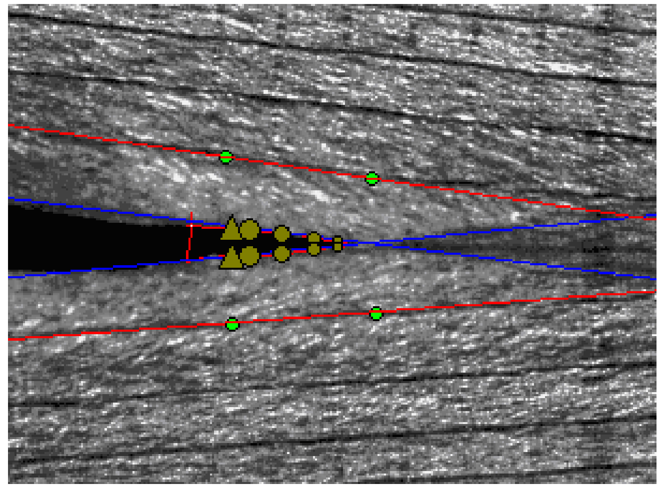

Figure 8: Method for determining the CTOA test of an X65 specimen exhibiting flat fracture. The test was run without using the spring setup at a test rate of ~30 mm/s.

RESULTS AND DISCUSSION

Crack growth velocity measurements

In the dynamic tests, the crack growth velocity was found to vary during the test, due to the test geometry. The general trend of the crack velocity behavior was determined from preliminary setup tests [10]; that behavior is shown schematically in Figure 9. Our reported measurements were focused on the roughly constant velocity region (from 30 mm to 50 mm, Fig. 9) to limit the variation. The average crack growth velocities for the test matrix are given in Table 4.

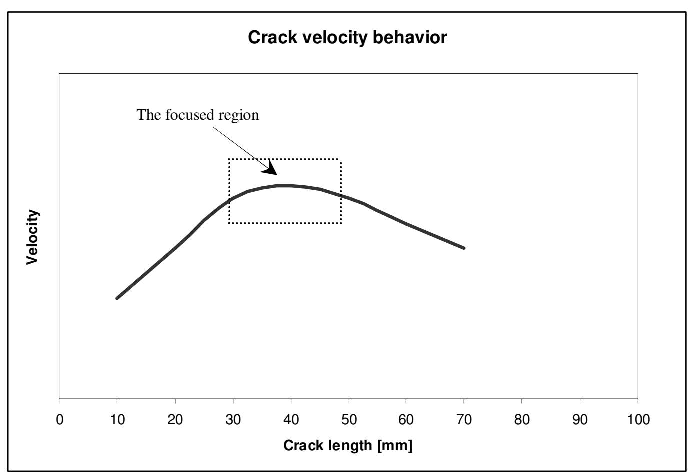

Figure 9: Characteristic behavior of the crack growth velocity; the region from 30 mm to 50 mm was in the field of view.

Table 4: The average crack growth velocities in the 20 mm viewed region (from 30 mm to 50 mm).

Cross head speed [mm/s]	X65 [mm/s]	X100 [mm/s]
0.002	0.0044±0.0021	0.0085±0.0008
0.02	0.044±0.004	0.088±0.019
0.2	0.5±0.06	0.66±0.072
5-3*	9.2±0.6	6.7±0.7
30	45.5±1.5	118±3
300	594±8	762±35
8000 (approx.)	6500±600	7250±600

*The X65 test was conducted at a rate of 5 mm/s and the X100 test was conducted at a rate of 3 mm/s.

The crack velocity directly indicates the material's resistance to fracture. Slower crack velocity for the same driving force, indicates a higher resistance to fracture. In Table 4, the crack growth velocity increases with increasing testing rate, as expected. For the same test rates, the X65 specimens typically had a lower crack velocity than the X100 specimens. This result indicates that the X65 exhibits higher resistance to crack growth than the X100. However, as the rate increases this difference in resistance to crack growth decreases.

Fracture Morphology

At our highest test rate (approximately 8000 mm/s) the CTOA samples always failure in a slant fracture mode, as shown in Figure 10 A and B. This is the failure mode typical for full-scale pipe fractures, shown in Figure 10C. However, details of the fracture modes for both CTOA laboratory specimens and full-scale tests often show mixed-mode (slant and flat) failures. Details of the modes and mechanisms of fracture require further attention to better characterize the effects of velocity and material thickness on the fracture mode, because it is not yet clear that 8000 mm/s test rates resulted in fracture modes representative of the full-scale fractures. In addition, the mechanisms of fracture (ductile, quasi-brittle, shear, tearing, etc.) on both the slant and flat portions of the fracture surfaces can vary, and we believe this to be true in general for other laboratory specimens and full-scale tests for X100 steels [12–14].

CTOA measurements

The mean values for the CTOA at the quasi-static and dynamic rates are summarized in Tables 5 and 6, respectively. Two columns of CTOA values per rate are shown: column P and column G. The test rates are the actuator (cross-head) rates.

Column P is the angle calculated from several hundred points on the crack edges. We find that the P value is a good representation of the surface CTOA, and the G value (from the grid lines) may better represent the bulk CTOA. For now, we measure both for comparison to both types of measurements in the literature [5, 7, 8].

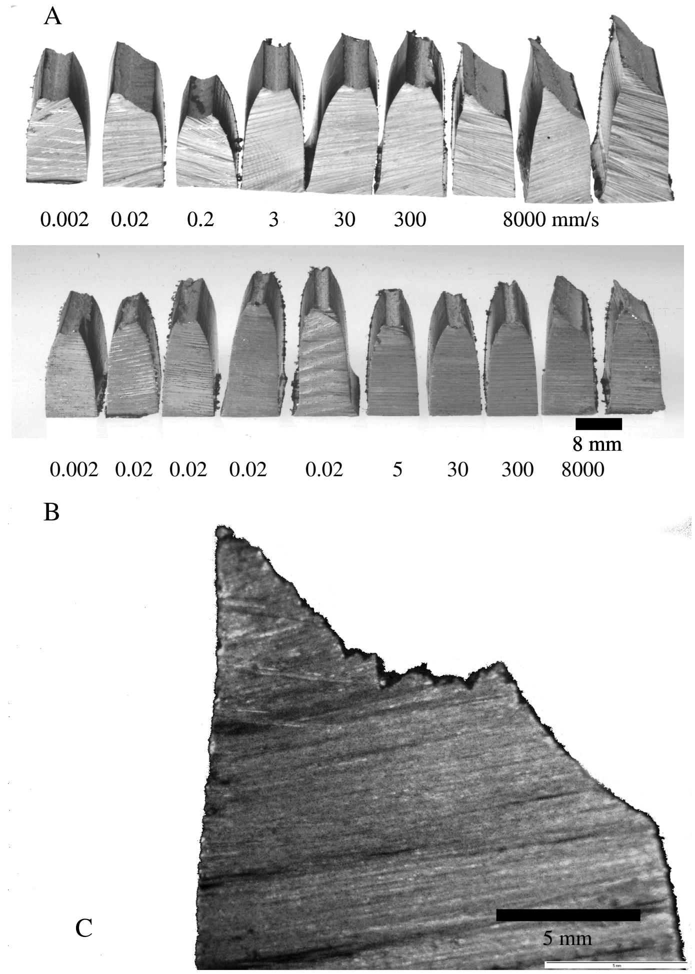

Figure 10: Cross sections of the X100 (A) and X65 (B) CTOA specimens, and a cross section of an X100 52" diameter pipe (C) that was fractured in a full-scale test in 2003. At test rates near 8000 mm/s, both the X65 and X100 show well-developed slant fracture. Occasionally slant fracture occurred at slower testing rates. Mixed-mode fractures were common at testing rates less than 8000 mm/s.

Table 5: The CTOA results of the quasi-static test matrix

Test Rate [mm/s]	API-X 65		API-X 100	
	P	G	P	G
0.002	11.7±1.2°	12.6±1.4°	8.6±1.1°	8.9±1.7°
0.02	11.4±1.2°	13.6±1.0°	8.3±1.8°	9.1±1.8°
0.2	10.5±1.0°	11.9±1.2°	9.3±1.1°	10.0±1.3°

Table 6: The CTOA results of the dynamic test matrix

Test Rate [mm/s]	API-X 65		API-X 100	
	P	G	P	G
3	11.6±2.2°	12.3±1.8°	9.4±1.0°	10.3±1.0°
30	11.0±2.4°	16.1±2.4°	8.8±1.0°	8.9±1.0°
300	11.2±1.1°	11.3±1.7°	8.0±1.6°	10.5±2.4°
8000 (approx.)	11.3±1.7°	10.5±1.7°	8.6±1.1°	9.5±1.5°

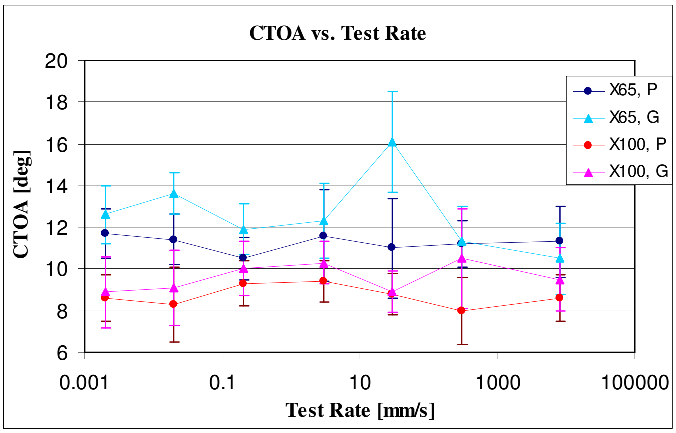

Figure 11: Graph of the CTOA vs. Test rate for the X65 and X100 in the two different approaches P and G.

The values of CTOA, using the P and G approaches, (Tables 5 and 6) are illustrated in Figure 11. The figure shows the differences between the two approaches for the two steels, and the lack of a rate effect on the CTOA values.

The grid angle (G) values reported are typically larger than the P angle values (see Figure 11). This is due to the difference in the degree of plastic deformation between the region of the grid measured and the region of the crack edge. For this reason G angles should be compared only with G angles, and P angles only with P angles. The values from the two different approaches are not interchangeable. At this point, it is not clear which CTOA value (P or G) best represents the material property for a pipeline steel. Either would useful in distinguishing the resistance to crack growth, and a choice will need to be made on which approach to use.

The CTOA for the X65 steel is typically more than 2° higher than the CTOA for the X100 steel, throughout the range of rates evaluated. This result indicates a clear difference in the crack growth resistance between the X65 and the X100. However, the meaning of this magnitude of difference (2°) is not clear to us. The measurement of crack growth velocity does not, conversely, reflect much difference in the crack growth resistance between the X65 and the X100 at the higher rate reported here. More measurements are needed to better understand the uncertainty of the measurement and the significance of the difference in the crack growth velocity measured in this paper.

Difficulties in the CTOA measurements

We identified scatter in the CTOA measurements associated with localized plastic flow, irregular crack growth, operator judgment, and algorithms used for evaluations. Examples include the following:

- Surface defects can cause local deformations at the crack tip not characteristic of the material, as shown in Figure 12. This effect can cause a scatter of 2° to 5° in the CTOA measurement.
- Changes in crack mode and other events occurring along the interior crack front can result in discontinuities and temporary course deviations on the surface of the specimens, as shown in Figure 13. The scatter in the CTOA measurement according this effect can be 1° to 2°.
- Asymmetric plastic flow, (above and below the crack plane) creates scatter in CTOA measurements, as shown in Figure 14. This kind of effect can caused a scatter of 2° to 5° in the CTOA value.
- Operator judgment, bias between operators, and unclear images cause additional uncertainties in CTOA measurement. The scatter in the CTOA value according these difficulties can be 2° to 4°.
- Uncertainties due to algorithms used to calculate CTOA were discussed in a previous report [11]. Here we used the two algorithms, P and G, which typically have smaller scatter (1° to 2°).

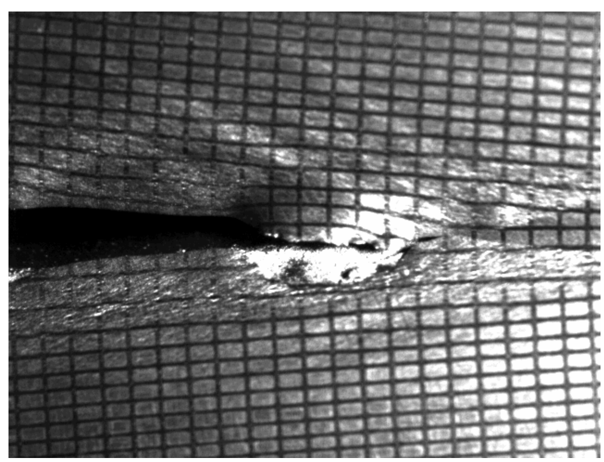

Figure 12: Example of defect on surface resulting in non-characteristic crack tip angles (grid lines are 0.5 mm x 1.0 mm).

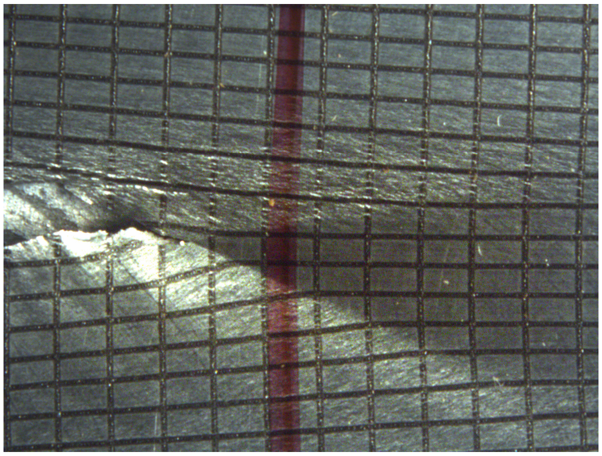

Figure 13: Example of deviation at the crack tip due to a change in the plane of crack propagation, flipping from one shear plane to the other (grid lines are 0.5 mm x 1.0 mm).

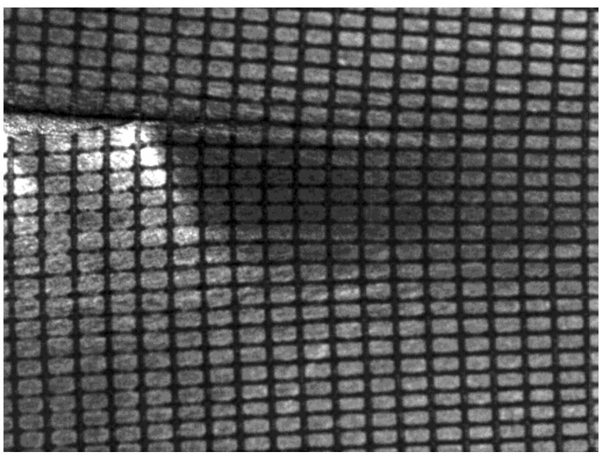

Figure 14: Example of asymmetric deformation at the crack tip, bottom edge is plastically deforming at surface and increasing the measured angle (grid lines are 0.5 mm x 1.0 mm).

To reduce the scatter in CTOA measurement, we developed the following criteria to define regions in which CTOA measurements should be made:

1. Use defect-free regions.
2. Plastic deformation should be symmetric at crack tip.
3. Cracks should be horizontal for at least 3 mm back from the crack tip.
4. Discard images obtained during transitions in the fracture mode.
5. Use the same grid pair for the entire CTOA analysis.

By applying these criteria we reduced the scatter in our CTOA measurement from 4º to 5º to less than 2.5º.

CONCLUSION

This study focused on the influence of the displacement rate and crack velocity on CTOA measurements, as well as on the optimization of the CTOA measurement procedure for commercial pipeline steels.

It was found that the CTOA of X65 and X100 pipeline steels were independent of displacement rate for those rates presented here. On the other hand we found a difference in the CTOA values characteristic of the X65 and X100 steels. This result is supported by the measurements of crack velocity for the X65 and X100 steels. Based on the higher CTOA values for the X65, and the generally lower crack velocities, the X65 steel has the higher resistance to fracture for the steels evaluated here.

Among rates conducted, there was a threshold test rate above which slant fracture mode is always observed. Laboratory tests at higher rates are needed to determine if additional changes to fracture mode occur.

To optimize the CTOA measurement, we identified five criteria that needed to be applied during the CTOA analysis.

ACKNOWLEDGMENTS

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