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Dynamic Apparatus for CTOA Measurement in Pipeline Steels[1]

Avigdor Shtechman,[2]
NIST
Boulder, CO, USA

Christopher McCowan
NIST
Boulder, CO, USA

Rony Reuven,
Elizabeth Drexler
NIST
Boulder, CO, USA

Philippe Darcis,[3]
J. Matthew Treinen
NIST
Boulder, CO, USA

Robert Smith, James Merritt
DOT Office of Pipeline Safety
Washington, DC, USA

Thomas Siewert,
J. David McColskey
NIST
Boulder, CO, USA

ABSTRACT

When a crack initiates and propagates in a pressurized pipe, the only thing that might stop this high-velocity event is the release of internal pressure (decompression), resulting in a deceleration in the crack-propagation rate. This deceleration can be achieved through the use of crack arrestors, or the ability of the pipeline material to resist ductile fracture. To evaluate the resistance to crack growth, the crack tip opening angle (CTOA) is used. Recent articles on the CTOA of pipeline steels at quasi-static rates with modified double cantilever beam specimens (MDCB), and at dynamic displacements rates by use of drop weight tear testing have provided data to support this need. These laboratory results from the literature, compared with results of full-scale tests, indicate that details of the fracture mode depend on the rate of fracture. To further study the dependence among the rate, fracture mode, and CTOA, a dynamic test apparatus was designed to perform CTOA testing of MDCB specimens, so that comparisons to quasi-static and full-scale results could be made. This new apparatus consists of a 500 kN uniaxial hydraulic test machine capable of stand-alone displacement rates of 300 mm/s, and a disc spring apparatus that is used to further accelerate the testing displacement rate. Initial results of the testing show that full slant fracture mode is observed at the highest rates tested for X65 and X100 steels. Maximum crack velocities approaching 10 m/s were recorded with high-speed photography. CTOA measurements were typically made at a position about 30 mm ahead of the pre-fatigue crack, over a distance of about 20 mm in the steady-state crack propagation regime. In this paper, we describe the high-speed apparatus, discuss the relationship among specimen configuration, crack speed, and CTOA, and present initial results on X65 and X100 pipeline steels.

Keywords: Cantilever beam; crack tip opening angle; crack velocity; CTOA; displacement rate; dynamic; fracture surface evaluation; high rate test; modified double optical angle measurement; pipeline steels; plastic flow; rate effects; quasi-static; X100; X65.

INTRODUCTION

The increasing demand for natural gas as an alternative energy source implies continued growth of gas pipeline

[1] Contribution of an agency of U.S. government, not subject to copyright.
[2] Current address: NRCN, P.O.Box 9001, Beer-Sheva, Israel.
[3] Current address: Tenaris, Via Xalapa, Veracruz, Mexico.

installations. This trend requires large-diameter, high-pressure gas pipelines with material properties sufficient to prevent in-service failures.

Options for the safe design of pipelines with the ability to arrest a running crack includes the use of a pipeline steel that has sufficient toughness to arrest a running crack, and/or crack arrestors. To use either option effectively, good measures of the resistance to crack growth, and arrest of running cracks are required.

Rivalin [1] used an apparatus to test pipeline material at speeds up to 15 m/s to approximate full-scale tests in the laboratory. His apparatus achieved crack velocities of approximately 20–40 m/s for pipeline steels.

Crack tip opening angle (CTOA) has been suggested as a method to characterize fully plastic fracture in a pipeline steel [2,3]. There have been a number of recent papers on the use of CTOA for pipeline steels and on the fact that it is considered a computationally attractive operational parameter that provides an alternative to the *J-R* (resistance) curve and shows promise as a fracture criterion for resistance to crack growth.

With the exception of the drop weight tear test (DWTT), there are few CTOA data available at relatively high rates. Wilkowski, *et al*. [4], documented dynamic rates of 15 m/s with the DWTT on X70 steel.

CTOA data can be acquired at quasi-static rates through use of the MDCB specimen geometry [5, 6]. The MDCB specimen geometry provides sufficient area for steady-state crack growth, but has not been tested at high rates because of the lack of experimental equipment to do so. Here, equipment designed to provide testing rates from about 3 mm/s to 8000 mm/s with MDCB specimens is described. The goal of this apparatus was to achieve crack morphologies similar to those seen in pipeline crack-propagating events.

DESIGN OF THE TEST APPARATUS

The main concern in the design of the dynamic test apparatus was to achieve a rapid, constant crack velocity in the region of the specimen where measurements would be made. A fast, but constant, actuator velocity was necessary in order to achieve this goal. A relatively high (300 mm/s) actuator velocity could be obtained with the use of the modified test machine, but higher velocities were needed. (The velocities of ductile cracks in high-strength pipeline steels are hundreds of meters per second.)

To achieve higher velocities, a spring array (disc springs) was inserted into the load line, as shown in Figure 1. Clevises were fabricated for the specimen design and loading rates (Figure 2). The force and displacement are controlled through the use of disc springs, and can be increased or decreased by changing the number and/or thickness of the individual springs. This apparatus may be used on any test machine of similar design. Theoretically, this dynamic apparatus allows a maximum velocity of the grips to approach 20 m/s. The stored elastic potential energy of the spring is relied upon to generate a high velocity that is reasonably constant over the increment of crack growth measured.

Table 1: Disc Springs data

Type	O.D. [mm]	I.D. [mm]	Thickness [mm]	Free Height [mm]	Load at 75 % deflection [kN]
1	249	127	11.3	19.3	214.8
2	249	127	9.4	17	119.4

Two different sized springs were used in the dynamic apparatus. Calculations from Table 1 show that the actuator displacement and force necessary to break the specimen would require 22 springs: 10 of the type 1 spring and 12 from type 2 (Figure 3).

High-speed camera 1 (see Figure 1) was used to collect digital images for the evaluation of CTOA and crack velocity in the specimen. Capture speeds of 10,000 frames per second were adequate for the tests conducted with the spring setup.

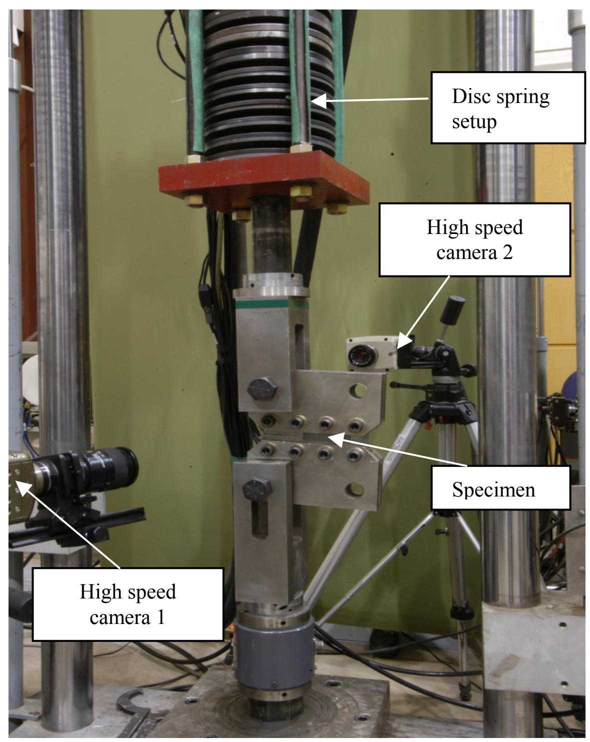


Figure 1: The dynamic apparatus.

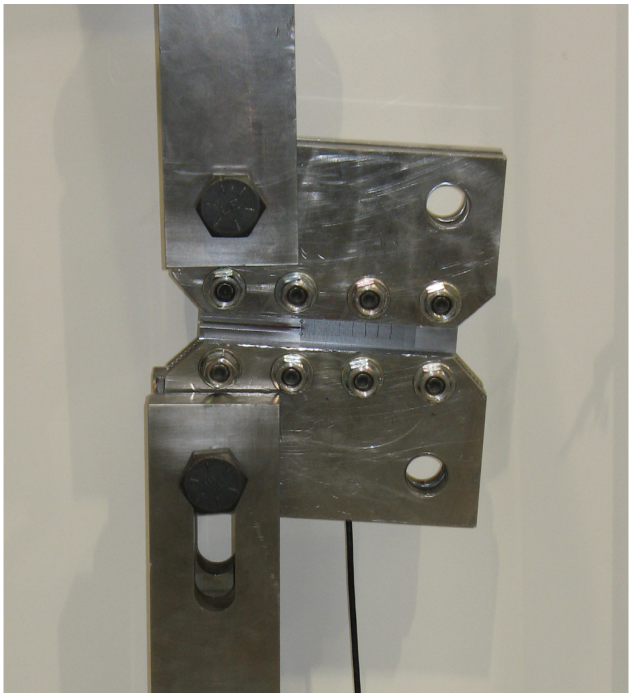
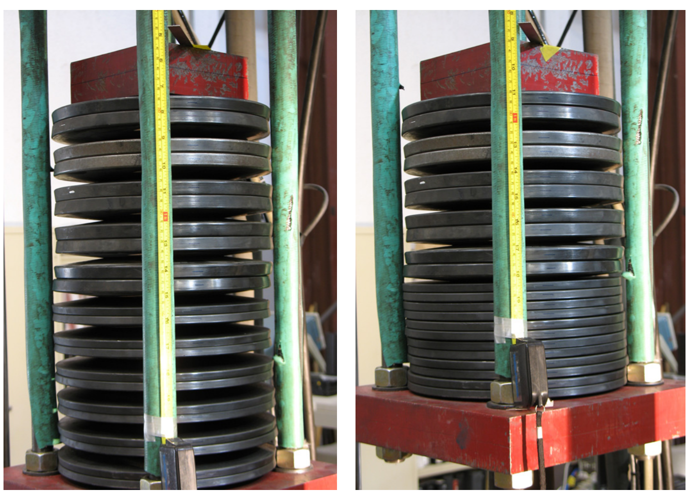


Figure 2: A gripped specimen.



A. **B.**

Figure 3: The spring setup (A) in the unloaded position and (B) in the maximum loaded position.

A shutter speed of 10 µs was used. Typically an area on the sample of about 15 mm by 20 mm was imaged.

Crack velocity was measured on several specimens to evaluate changes in velocity over the length of the specimen. These data show, as expected, that the crack propagation velocity is not constant and varies substantially along the length of the specimen.

Figure 4: Schematic depiction of crack velocity versus crack length.

Figure 4 shows the behavior of the crack velocity schematically. The crack velocity increases during the first 20 mm of propagation, and within the next 10 mm to 20 mm it reaches a maximum value that is essentially maintained for the next 10 mm. After about 40 mm to 50 mm (from the starting point) the crack starts to decelerate until the end of the test. Based on these data, CTOA measurements were made in a region 30 mm to 50 mm from the end of the fatigue crack.

THE MATERIAL AND THE CTOA SPECIMEN DESIGN

The pipeline steels used for this work were API-X65 and X100. A MDCB specimen was used to conduct the CTOA tests. The 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 fracture.
- For ease of CTOA measurement, the test section is flat near the crack tip.

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 grinding. This eliminated the probable residual plastic strains that would be

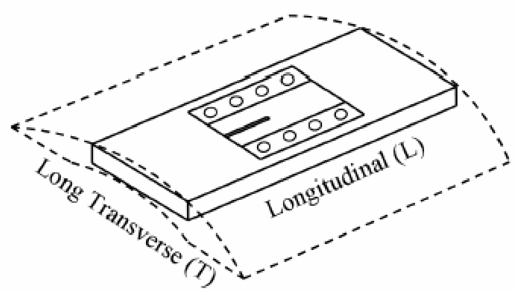


Figure 5: Orientation of CTOA specimen in the pipe.

caused by flattening the plate using a straightening procedure. A schematic of the specimen scheme is shown in Figure 5.

The MDCB configuration and dimensions are depicted in Figure 6. The large in-plane dimensions of the specimen

(200 mm × 100 mm) and the long ligament allow relatively large amounts of stable crack growth. To increase the constraint effects in the high-strength steel specimens, the arm thickness of the specimens was almost twice the thickness of the test section (see details in Figure 6). This resulted in two thick loading arms and a reduced-thickness test section. The specimen was gripped via two pairs of thick plates bolted to the side surfaces of the specimen. Thick gripping plates further increased the constraint levels in the test section.

To facilitate the CTOA measurement, a grid with a spacing of 1 mm × 0.5 mm was fused onto the surface by a laser (Figure 7). This approach was adopted because the grid lines remain visible during extensive plastic deformation of the surface.

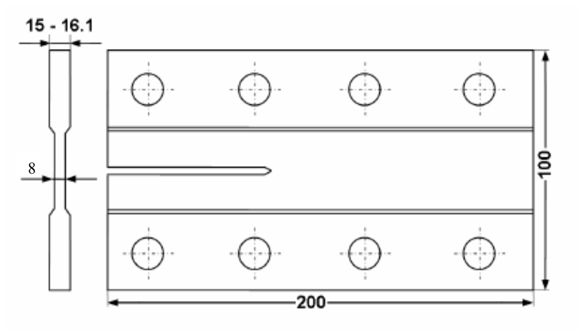


Figure 6: MDCB specimen, configuration and dimensions (mm).

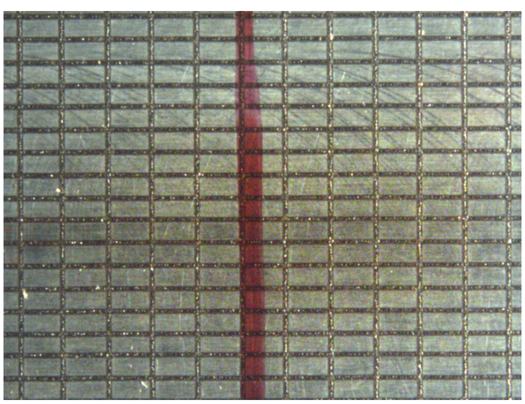


Figure 7: The rectangular 1.0 mm X 0.5 mm mesh on the CTOA sample. The surface is coated with a special paint and the laser fuses it to the surface of the specimen.

EXPERIMENTAL RESULTS AND DISCUSSION

Spring Setup, Displacement and Force

The displacement of the springs was measured during loading. Figures 3 A and B show pictures of the spring setup in the initial (0 kN) and final (160 kN) positions, respectively. The measurements were made in increments. A tensile force of 13 kN was applied at each increment up to a final load of 160 kN. Table 2 summarizes the measurements of displacement and force for the spring setup. Figure 8 shows that the force versus displacement behavior for the spring is best represented by a curve, but for simplicity a linear regression (Equation 1) was applied to the force-displacement data to estimate the spring constant of the apparatus. The potential energy of the spring setup can be calculated by substituting Equation 1 into Equation 2.

$$f_{(x)} = 1.6987 \cdot x + 9.1194 \quad \textbf{(1)}$$

$$E_P = \int_0^X f_{(x)} dx \quad \textbf{(2)}$$

The force function is $f_{(x)}$, where X is the displacement of the springs during loading, and E_p is the potential energy.

When CTOA tests were conducted on the X65 and X100 alloys, the maximum spring displacements measured were 76 mm and 89 mm, respectively. These displacements differ due to the difference in maximum load needed to initiate crack growth in the respective alloys. The potential energies associated with these displacements for the X65 and X100 tests were 5.6 kJ and 7.5 kJ, respectively.

Table 2: Force and displacement for the spring setup.

Step	1	2	3	4	5	6
Force [kN]	13	27	40	53	67	80
Displacement [mm]	6	11	17	23	30	39

Step	7	8	9	10*	11	12**
Force [kN]	93	107	120	134	147	160
Displacement [mm]	46	55	65	76	86	89

* Testing load for the X65 pipeline steel.
** Testing load for the X100 pipeline steel.

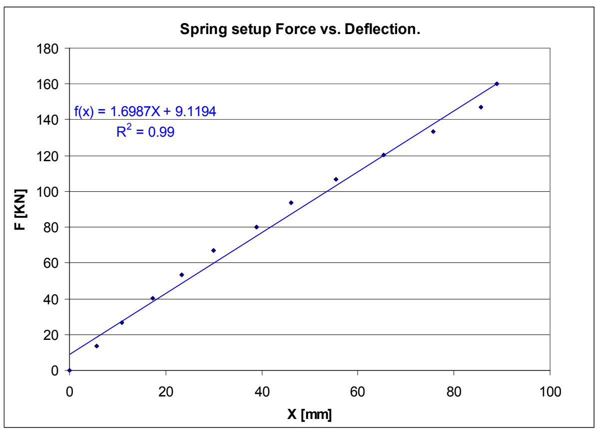


Figure 8: Force-displacement for the spring setup during loading.

Spring Setup, Velocity

The velocity of the upper grip was measured for the spring setup to obtain estimates of the displacement velocity for the X65 and X100 CTOA tests. The measurements were made with a high-speed camera 2 (see Figure 1) focused on a scale fixed to the grip. Displacements were measured over a distance of 140 mm for both the X65 and X100 steels, and results are given in Table 3. The measurements were made for each 20 mm segment over the 140 mm distance measured. Differences between displacement velocities due to steel type are indicated, which may be due to the difference in the fracture resistance of the steels. However, the initiating forces in these tests also vary with steel type and are expected to have some influence on rates.

CTOA Testing

This apparatus was used to test a total of 12 MDCB specimens. Data show that there is a difference between the two grades of steels, but no obvious changes in CTOA with testing rates. This is further discussed in a companion paper to this conference [7].

Table 3: Measurements of the grip velocity in the spring setup tests in 20 mm increments.

Dist. [mm]	20-40	40-60	60-80	80-100	100-120	120-140	F [kN]
X65 [m/s]	6.67	6.67	6.67	6.67	6.67	N/A	134
X100 [m/s]	7.3	8.0	7.6	N/A	N/A	N/A	160

Fracture Mode

A study of the fracture surfaces among the suite of test rates reveals differences in fracture modes (Figure 9). At displacement rates of up to 300 mm/s, the failure mode was flat or mixed mode (Figure 9a). When the disc spring apparatus was used, the specimen always failed in a slant mode (Figure 9b). The X100 running crack resembled that seen in full-scale burst tests, although details of the fractures were not identical.

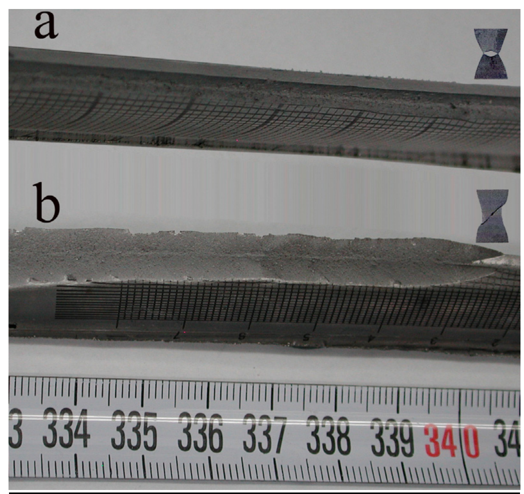


Figure 9: Fracture surfaces of samples tested at (a) 300 mm/s showing a flat fracture mode and (b) 8000 mm/s showing a slant fracture mode.

CONCLUSIONS

A servo-hydraulic machine was modified to enable an actuator velocity of 300 mm/s, resulting in a crack velocity of about 600 mm/s, significantly less than that needed to duplicate the 200 m/s to 500 m/s crack velocity occurring in a pipeline. To that end, a spring apparatus was designed and implemented for use in CTOA measurement. This apparatus achieved a crack velocity approaching 10 m/s and consistently resulted in slant fracture mode for both alloys. This is the failure mode typically observed for full-scale tests.

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REFERENCES
[1] Rivalin F., Pineau A., Di Fant M., Besson J., 2001, "Ductile tearing of pipleline-steel wide plate I. dynamic and quasi-static experiments", Engineering Fracture Mechanics, 68, pp. 329-345.
[2] Brocks, W., K. Schwalbe, and Zebst, U., “Structural Integrity Assessment of Thin-Walled Structures,” Advanced Engineering Materials, 8, 5, 2006, pp. 319-327.
[3] Pussegoda, N., Verbit, S., Dinovitzer, A., Tyson, W., Glover, A., Collins, L., Carlson, L., and Beattie, J., 2000, “Review of CTOA as a Measure of Ductile Fracture Toughness,” In: Ellwood JR, editor. Proceedings of the 2000 International Pipeline Conference, vol. 1. New York: The American Society of Mechanical Engineers, pp. 247-254.
[4] Wilkowski, G., Wang, Y.Y., and Rudland, D., 1999, “Summary of Recent Efforts on Characterizing Propagating Ductile Fracture Resistance of Linepipe Steels,” Proceedings, The International Conference on Advances in Welding and Technology: Pipeline Welding Technology, Galveston, TX.
[5] Hashemi, S. H., Howard, I. C., Yates, J. R., Andrews, R. M., and Edwards, A. M., 2004, “A Single Specimen CTOA Test Method for Evaluating the Crack Tip Opening Angle in Gas Pipeline Steels,” Proc. 5th International Pipeline Conference, paper No. IPC04-0610, Calgary, Alberta, Canada.
[6] Shterenlikht, A., Hashemi, S. H., Howard, I. C., Yates, J. R., and Andrews, R. M., 2004, “A specimen for studying the resistance to ductile crack propagation in pipes,” Engineering Fracture Mechanics, 71, pp. 1997-2013.
[7] Reuven, R., Drexler, E., McCowan, C., Shtechman A., Darcis, P., Treinen, M., Smith, R., Merritt, J., Siewert, T., and McColskey, D., 2008, “CTOA Results for X65 and X100 Pipeline Steels: Influence of Displacement Rate,” Proc. Int. Pipeline Conf. 2008