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MEASUREMENT OF CTOA OF PIPE STEELS USING MDCB AND DWITT SPECIMENS (DRAFT)

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ABSTRACT
Two types of specimen for crack tip opening angle (CTOA) measurement have been investigated for pipeline applications, i.e., the modified double cantilever beam (MDCB) (at NIST) and the drop-weight tear test (DWTT) specimen (at CANMET). Results of effects of specimen types, thicknesses and loading rates on CTOA are summarized and discussed. The main observations include: (i) For both MDCB and DWTT specimens tested at quasi-static loading rate, crack front tunnelling (i.e., with a deep triangular crack-tip shape) was present in high-strength steels; (ii) For DWTT specimens, CTOA values measured optically at the surface were significantly higher than those from the simplified single-specimen method (S-SSM) and measured at mid-thickness [on sections cut using electric discharge machining (EDM)]; and (iii) CTOA values from surface measurement of MDCB specimens were comparable to those derived from S-SSM of DWTT specimens, but the surface values of DWTT were higher than those of MDCB specimens.

KEYWORDS: CTOA, MDCB, DWTT, ductile fracture, fracture toughness, pipe steel, test method

INTRODUCTION
The crack tip opening angle (CTOA) has been proposed as a material parameter for control of fast ductile fracture propagation and arrest of axial cracks in pipelines for at least 25 years [1-3]. It has become of special interest with the introduction of high-strength pipe steel to pipeline construction. However, a reliable mill test is still under development. Two types of specimen for CTOA measurement have been investigated for pipeline applications, i.e., the modified double cantilever beam (MDCB) and the drop-weight tear test (DWTT) specimen. The configuration of the MDCB specimen is such that the stress state ahead of the crack is likely closer to that of an axial crack in a pipe than that of the DWTT specimen, but it is more difficult to machine, test and analyze data for the MDCB specimen. The DWTT specimen is routinely used in pipe mills to ensure ductile fracture, and measurement of CTOA can be done readily with the simplified single-specimen CTOA method (S-SSM) using load vs. deflection data [4]. This method delivers a CTOA value averaged through the thickness, which is validated in this work and is a significant advantage for specimens exhibiting tunnelling. In this work, CTOA measurements from MDCB and DWTT specimens for pipe steels have been compared along with the effect of the crack tunnelling, loading rate and thickness on CTOA. The advantages and disadvantages of both types of specimen are discussed.

MATERIALS AND EXPERIMENTAL PROCEDURES
Twelve commercial pipe steels were used in this work. The experimental parameters investigated were specimen type, thickness, loading rate and CTOA measurement method. Details of materials, parameters and procedures are described below.

MATERIALS
The type, grade and pipe geometry of the steels are summarized in Table 1. The chemical compositions and mechanical properties of the steels are given in Tables 2 and 3. The production years of steels N1 to N11 are not available but, based on the sulphur contents, N1 to N5 steels (i.e., low strength steel) are likely old vintage steels and N6 to N11 steels were manufactured by modern pipe steel procedures. Steels C2 and C4 are typical modern X70 and early generation X100 steels, respectively.

Table 1. Type, grade, outside diameter (D) and wall thickness (t) of pipes tested.

Steel	Nominal API 5L Grade	Pipe Type	D (mm)	t (mm)	D/t	Year Manufactured
N1	N.A. (~X70)	UOE	508.0	9.7	52.4	Not available
N2	X52	UOE	508.0	8.1	63.5	
N3	Grade B	UOE	558.8	7.4	75.5	
N4	N.A. (~X52)	UOE	508.0	7.9	64.3	
N5	N.A.	UOE	558.8	7.8	71.6	
N6	X65	UOE	508.0	26.3	19.3	
N7	X65	UOE	584.2	31.5	18.5	
N9	X100	UOE	1320.8	20.6	64.1	
N10	X100	UOE	1219.2	20	61.0	
N11	X100	UOE	1219.2	20	61.0	
C2	X70	Spiral	914.4	13.7	68.2	2004
C4	X100	UOE	1219.2	14.6	85.3	2002

Table 2. Chemical composition of pipe steels (wt %).

Steel	C	Mn	Si	Al	Nb	Ti	Cu	Cr	Ni
N1	0.06	1.46	0.28	–	0.054	–	0.11	0.02	0.10
N2	0.24	1.03	0.057	–	0.007	–	0.038	0.024	0.064
N3	0.27	0.36	0.009	–	0.005	–	0.015	0.029	0.021
N4	0.18	0.52	0.043	–	0.005	–	0.054	0.021	0.021
N5	0.25	0.97	0.061	–	0.007	–	0.046	0.019	0.066
N6	0.07	1.48	0.094	0.031	0.04	0.03	0.12	0.12	0.17
N7	0.07	1.59	0.092	0.030	0.03	0.02	0.10	0.13	0.14
N9	0.08	1.56	0.325	0.039	0.04	<0.01	0.09	0.03	0.21
N10	0.07	1.90	0.10	–	–	–	0.30	–	0.50
N11	0.07	1.90	0.10	–	–	–	0.30	–	0.05
C2	0.04	1.56	0.24	0.039	0.069	0.013	0.31	0.07	0.11
C4	0.06	1.75	.06	0.012	0.045	0.008	0.28	0.028	0.13

Steel	P	S	Mo	Ca	Sn	B	N	Ce	V
N1	0.01	<0.01	0.025	–	–	–	–	–	0.045
N2	0.016	0.013	0.016	–	–	–	–	–	0.002
N3	0.005	0.015	0.007	–	–	–	–	–	0.003
N4	0.026	0.010	0.009	–	–	–	–	–	
N5	0.013	0.012	0.017	–	–	–	–	–	0.002
N6	0.008	0.004	0.003	–	–	<0.0002	–	–	0.04
N7	0.009	0.004	0.003	–	–	<0.0002	–	–	0.04
N9	0.011	0.003	0.006	–	–	<0.0002	–	–	0.04
N10	0.008	0.0005	0.15	–	–	–	–	–	-
N11	0.008	0.0005	0.15	–	–	–	–	–	-
C2	0.010	<0.009	0.20	0.0021	0.014	0.0003	0.008	0.001	0.003
C4	0.036	0.036	<0.030	–	–	–	–	–	<0.010

Table 3. Average transverse tensile and Charpy properties of the steels (3 samples).

Steel	YS (MPa)	UTS (MPa)	Elongation (%)	Area Reduction (%)	N	Y/T	CVN (J)
N1	543	606	28	NA	NA	0.90	NA
N2	448	576	26	NA	NA	0.78	NA
N3	255	459	38	NA	NA	0.56	NA
N4	428	560	22	NA	NA	0.76	NA
N5	250	454	35	NA	NA	0.55	NA
N6	521	587	NA	NA	NA	0.89	NA
N7	517	579	25.7	NA	NA	0.89	NA
N9	797	828	24	NA	NA	0.96	247
N10	912	916	18	NA	NA	0.9951	268
N11	832	868	17.5	NA	NA	0.96	260
C2	576	650	29.5	78.1	0.117	0.89	303
C4	805	853	19.7	76.3	0.050	0.94	223

SPECIMENS

Specimens employed in this work are (1) Modified double cantilever beam (MDCB), (2) Drop-weight tear test (DWTT), and (3) Modified DWTT (M-DWTT).

The MDCB specimen was proposed to characterize CTOA of pipe steels by Shterenlikht, et al., [5,6] and later further exploited at NIST [7-11]. Figure 1 shows the configuration and dimensions of the MDCB specimen [7]. This specimen configuration was designed to apply tensile loading but prevent bending loading [5,6]. Loading was applied using a pair of thick plate grips bolted to the side surfaces of the specimens (Figure 2 [7]). As the MDCB specimen has a reduced gauge section, it can be machined from curved pipe without flattening. The machined notch depth is 60 mm and the ratio of total length after fatigue precracking (a) to width (W) is between 0.3 and 0.5 (W = 182 mm). A comparison of advantages and disadvantages of MDCB and DWTT specimens will be made later.

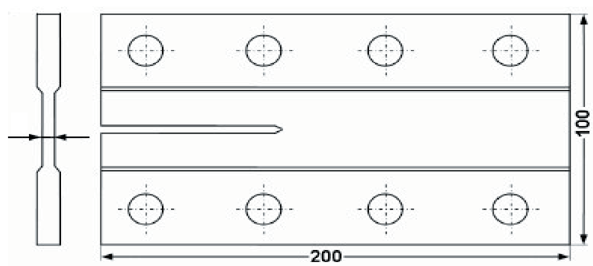


Figure 1. Configuration and dimensions (in mm) of MDCB specimen.

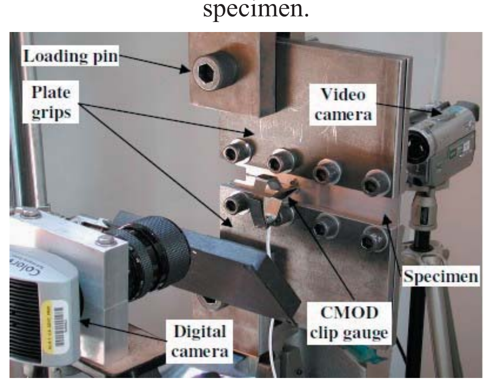


Figure 2. Quasi-static CTOA test set up for MDCB specimen.

DWTT specimens are routinely tested in pipe mills. When the DWTT specimen was first proposed to measure CTOA of pipe steel, a two-specimen method using two machines-notch depths (a = 10 mm and 38 mm) as shown schematically in Figure 3 was adopted to deduce fracture propagation energy [12]. Note that the two-specimen CTOA method has been used for high-strength steels and has shown problems [e.g., 13,14]. When a single-specimen CTOA method is used, only a single shallow-notched DWTT specimen (notch depth a = 10 mm) is needed to obtain a value of CTOA. The DWTT specimen is usually full pipe thickness, machined from a flattened pipe section and tested in three-point bending with support span of S = 254 mm. A test set-up for quasi-static DWTT testing is shown in Figure 4; anti-buckling guides were usually required during testing.

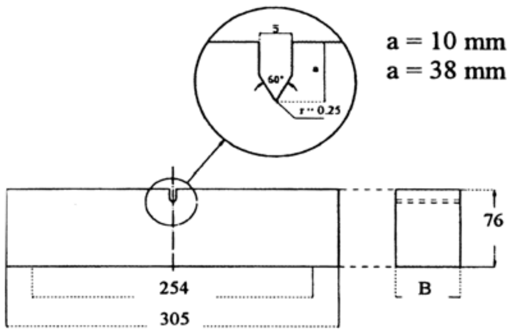


Figure 3. Configuration and dimensions (in mm) of DWTT specimens [12].

Figure 4. Quasi-static CTOA test set-up for DWTT specimen.

In an effort to test some 3-mm thick DWTT specimens to compare results from earlier results of 3-mm thick MDCB specimens, modified DWTT (M-DWTT) specimens were machined with the width reduced to 31 mm from the 76 mm of the standard DWTT specimen to avoid buckling; it was found that the standard 3-mm thick DWTT could not be satisfactorily tested even with an anti-buckling fixture. Figure 5 shows a 8-mm thick DWTT and a modified 3-mm thick DWTT specimen after quasi-static CTOA testing.

Figure 5. Tested 8-mm thick DWTT (bottom) and 3-mm thick M-DWTT (top) specimens.

THICKNESS

For MDCB specimens, thicknesses of 3 mm and 8 mm were used. For DWTT specimens, thicknesses of 3 mm, 8 mm, and full pipe thickness were used.

Early tests of MDCB specimens were conducted using 3-mm thick specimens [7] because thick (10-mm) MDCB specimens tended to deviate into the loading arm immediately after crack initiation from the fatigue precrack, a phenomenon explained by the T-stress in earlier work [6]. Later, it was found [11] that CTOA values from the 3-mm thick MDCB specimen were lower than those from the 8-mm thick specimen; the 8-mm thick specimen was considered more representative of pipe.

The DWTT specimen is usually full-thickness to eliminate any effects of thickness on CTOA. In this work, 3-mm specimens for N6 and N7 steels and 8-mm specimens for N10, N11 and C2 steels were also prepared and tested to directly compare results with MDCB specimens. A piece of C2 steel with thickness of 13.7 mm was flattened for preparing 8-mm gage-section MDCB and DWTT specimens. This allowed both types of specimens to sample the same material and have the same thickness. Some 8-mm DWTT specimens (N10 and N11 steels) were straightened using the wing-back technique and therefore no deformation was applied to the test section. The wing-back technique follows the straightening technique as used for fracture toughness testing of welds [15].

Loading Rate

Quasi-static tests for MDCB specimens were carried out using a servo-hydraulic machine at loading rates of 2 x 10^{-5} to 5 x 10^{-5} m/s. Dynamic tests were performed using a spring-loaded apparatus [9] at loading rate up to 14 m/s. Crack propagation velocities for dynamic testing were up to ~29 m/s. Quasi-static tests for DWTT specimens were done at a loading rate of 5 x 10^{-5} m/s using a servohydraulic machine. Impact tests were done at 5.1 m/s using a drop-weight tower. Crack propagation velocities at impact were between 12-18 m/s depending on steel toughness.

CTOA Measurement Method

For MDCB specimens, surface optical image (referred to as O) method according to ASTM E2472-06 [16] or improved procedures [8] were used to measure surface CTOA during testing. The recommended technique [16] is to take 3 to 5 four-point measurements of CTOA within the range of 0.5 to 1.5 mm behind the current crack tip; the CTOA is then taken as the average of these measurements. Surface images were taken using a digital camera for the static tests and a high-speed camera for the dynamic tests (Figure 6 [7]). The scatter of individual CTOA measurements in the steady-state stage can be large [17,18].

For DWTT specimens, both surface optical image (O) and simplified single specimen method (S-SSM) [4] were used to obtain CTOA. For the optical method, the CTOA measurement distance was chosen to be half the thickness of the steel plates to get beyond the transient effects at initiation [13]. This is different from the recommendation in ASTM E2472 which is mainly based on experience in thin sheet materials. For DWTT specimens, values measured using 1 mm distance were slightly higher than those using distances between 3 and 8 mm [13]. The quality of high-speed camera images is lower than that of images taken from quasi-static tests. The images taken from the current high-speed camera usually do not allow CTOA measured within 1.5 mm behind the crack tip. Also, a high-speed camera may catch only a few pictures in the steady-state region and inhibit adequate averaging. The optical measurement method provides direct comparison with other indirect measurement techniques but at present may not be suitable as a practical mill test owing to the requirement for additional equipment, and time to analyze images.

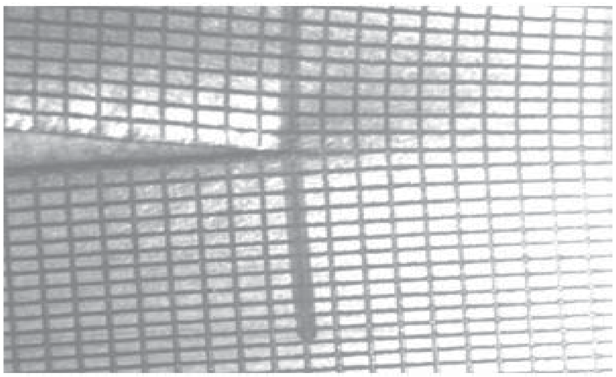


Figure 6. A digital image from MDCB specimen surface of C2 steel tested quasi-statically.

In the simplified single specimen method (S-SSM), CTOA is deduced from the load vs. deflection relation obtained during instrumented DWTT testing; this procedure has advantages both technically and economically [4,19]. The instrumentation system can be the same as used for instrumented Charpy testing. A typical load vs. deflection curve during impact testing is shown in Figure 7 where P_{max} is the maximum load and y_{max} is the deflection at maximum load. Crack propagation resistance (i.e., critical CTOA) is measured after maximum load (P_{max}) in the steady-state region. To apply the S-SSM, the steps are (i) A reference point is chosen, taken for convenience to be the maximum load (P_{max} and y_{max}), (ii) The load (P) vs. deflection (y) data after P_{max} is plotted as $Ln(P/P_{max})$ vs. $(y- y_{max})/S$ (S = 254 mm). The slope (ξ) of Ln (P/P_{max}) vs. $(y- y_{max})/S$ is determined in the steady-state region. For the standard DWTT specimen (i.e., W = 76 mm and a = 10 mm), the steady-state region corresponds to $Ln(P/P_{max})$ values between -0.51 and -1.21 [19], and (iii) $CTOA_c$ is then calculated according to the following equation:

$$CTOA_c = \frac{8r^*}{\xi} \cdot \frac{180}{\pi} \qquad (1)$$

where r* is the rotation factor taken as 0.57 and 0.54 for typical high-strength and low-strength pipe steels respectively [19] and ξ is defined above. The steady-stage region (i.e., constant CTOA region) for DWTT specimens occurs usually between ratios of crack length to width (a/W) of 0.32 to 0.53 and therefore, the load ratio (i.e., $Ln(P/P_{max})$ given above can be calculated from the limit load equation (i.e., $P \propto b^2$) [4,19]. The S-SSM CTOA method may be executed automatically in commercially available ordinary office software.

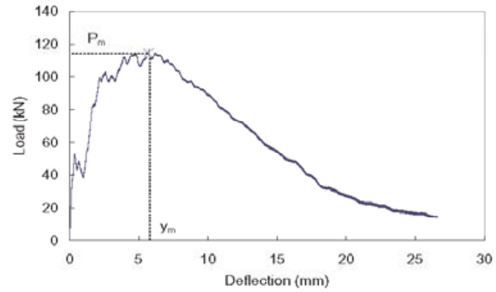


Figure 7. Load vs. deflection curve of DWTT specimen of N10 steel (specimen thickness = 8 mm) tested at impact rate.

In addition to the usual surface CTOA measurements, some quasi-static CTOA tests were interrupted to examine CTOA near the mid-thickness of specimens and to reveal crack front tunnelling using steels without splitting during testing. CTOA near mid-thickness was done on sections cut using electric discharge machining (EDM). Crack front tunnelling was revealed on specimen fracture surfaces broken in liquid nitrogen after heat-tinting treatment (350°C, 30 min., air cool).

RESULTS AND DISCUSSION

The report of data includes information of the key parameters mentioned above as well as fracture mode, i.e. slant (S) or flat (F). Note that full-scale burst tests showed slant fracture and it has recently been reported that dimple size distributions in pipeline burst fracture were similar to those in DWTT specimens [20].

Critical CTOA (CTOAc) measured using MDCB, DWTT and M-DWTT specimens are summarized in Table 4 along with thickness, fracture mode and measurement method in square brackets. The significance of results in Table 4 is discussed next.

CTOA OF MDCB SPECIMENS

MDCB specimens exhibited slant fracture at quasi-static (in most cases) and impact loading rates. The C2 specimen in Figure 8 shows slant fracture, running from right to left. The triangular shaped crack front markings are typical, and in this case, tunneling depths range from about 2 mm to near the thickness of the specimen. This test was interrupted at about 80 mm of crack growth and the heat tinted crack tip (far left) shows asymmetric local tunneling in the center region of the specimen's thickness. Crack Tunnelling was predicted in 3D CAFE modelling [21]. The effects of tunnelling on CTOA for MDCB specimens are still under investigation.

Figure 8. Fracture surface of an 8 mm thick MDCB specimen of C2 steel tested quasi-statically.

Effects of loading rate from quasi-static to dynamic for MDCB specimens can be examined in steels N6, N9, N10, N11 and C2. The thickness of the specimens was 8 mm and CTOA was determined using the optical method from surface images. Optical surface $CTOA_c$ were essentially the same at static and dynamic testing rates for N6, N9, N10 and N11 steels, with the exception of the C2 steel which had a lower CTOA at the dynamic rate (Figure 9).

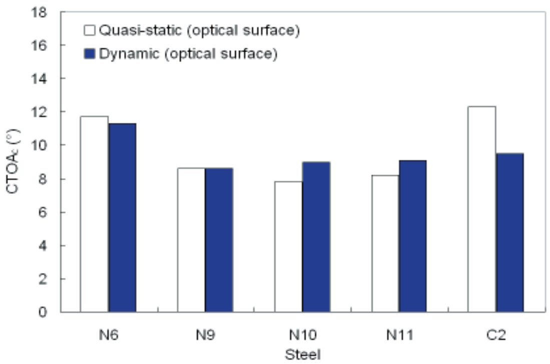


Figure 9. Effect of loading rate on optical surface CTOAc of 8-mm thick MDCB specimen.

CTOA OF DWTT SPECIMENS

DWTT specimens showed slant fracture at impact loading rate; however, at quasi-static rate the fractures were generally flat and only some high-strength steels (i.e., N10 and N11) showed slant fracture. Interrupted quasi-static CTOA tests were performed for C4 (full-thickness), N10 and N11 (8 mm thick) DWTT specimens. Both DWTT specimens of C2, N10 and N11 did not show splitting on fracture surfaces and this allowed further cutting the specimens to examine CTOA at mid-section without interference of splitting. The C4 specimen showed flat fracture. The C2 specimen was interrupted in the steady-state region at surface crack length of 38.5 mm (the surface crack lengths were 37 mm on one side and 40 mm on another side) and the crack length near mid-thickness was about 50.5 mm (i.e., the extent of tunnelling is about the thickness of the specimen). (Note: optical measurements are usually done on one side but can be different on two sides if crack propagation on the two sides is different.) The fracture surface of the interrupted C2 specimen is shown in Figure 10; no chevron marks were evident. A deep triangular crack-tip shape is well exhibited by the heat-tinting treatment. Note that the interrupted specimens were cut parallel to the large specimen surfaces using EDM to reveal CTOA on sections before opening for crack tunnelling examination. The N10 and N11 specimens showed slant fracture and also deep triangular crack-tip shapes (about as deep as the specimen thickness as shown in Figure 11). The N11 specimen showed V-shape slant fracture and clear chevron marks with the chevron pointing to the crack propagation direction. The chevron marks indicate the instantaneous crack front position during fracture.

For the interrupted C4 specimen, two surface CTOA values were 20° [Figure 12(a)] and 18° (i.e., average surface CTOA of 19°) while the CTOA value in the mid-thickness section was only ~10° [Figure 12(b)]. This is the first experimental report to the authors' knowledge that surface CTOA values can be much higher than those in the interior section. This difference is associated with the deep crack front tunnelling (Figure 10). Similar observations for the N11 specimen are shown in Figure 13 (surface CTOA: ~13° and interior CTOA: ~7°).

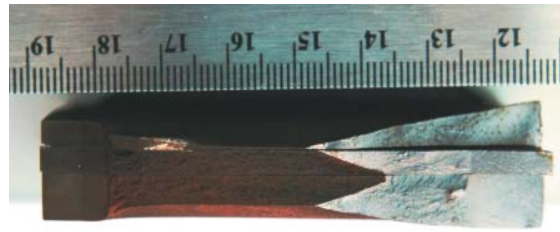


Figure 10. Fracture surface of the interrupted C2 DWTspecimen (14.4 mm thick).

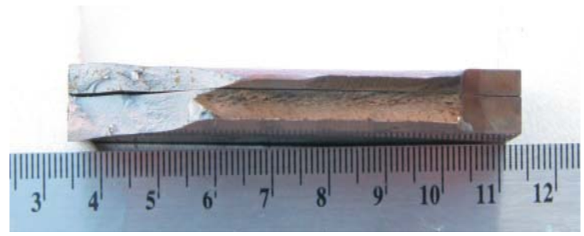
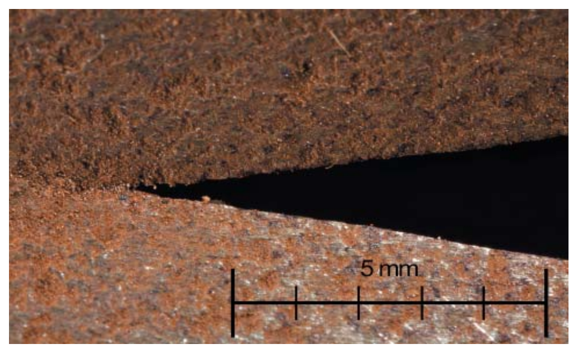
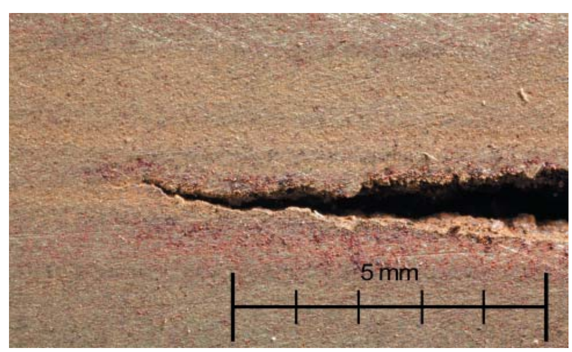


Figure 11. Fracture surface of the interrupted N11 DWTT specimen (8 mm thick).



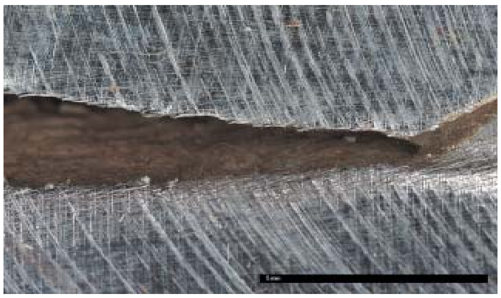
(a) Image from surface



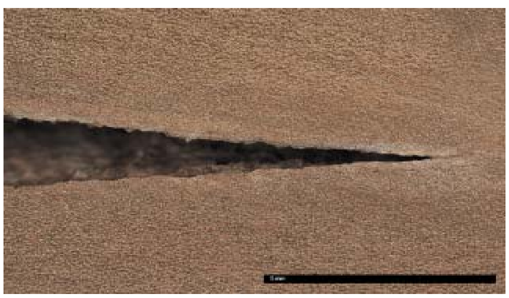
(b) Image from the mid-thickness section

Figure 12. Surface and interior CTOA of the interrupted C4 DWTT specimen.

For DWTT specimens tested quasi-statically, $CTOA_c$ values measured optically at the surface were significantly higher than those from the S-SSM (i.e., N10, N11, C2 and C4 results in Table 4) and measured at mid-thickness (C2 and N11 specimens as discussed above). This observation was predicted from FEA calculations of DWTT specimens [22]. $CTOA_c$ measured using different methods for tests at quasi-static rate are compared in Figure 14 including optical $CTOA_c$ at mid-section for C4 and N11 specimens which are in good agreement with S-SSM $CTOA_c$.



(a) Image from surface



(b) Image from the mid-thickness section

Figure 13. Surface and interior CTOA of the interrupted N11 DWTT specimen (scale mark in pictures are 5 mm).

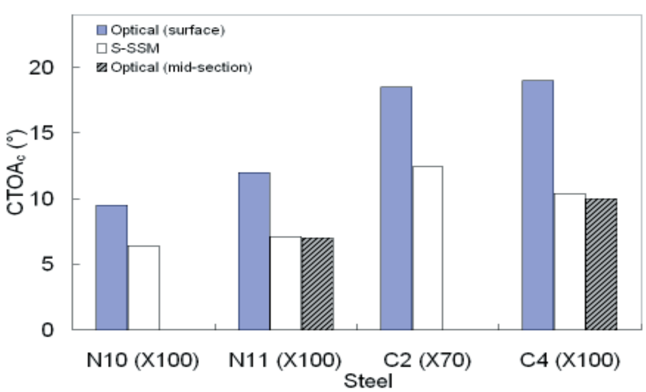


Figure 14. $CTOA_c$ for quasi-static DWTT testing by different measurement methods (8 mm thick or full-thickness).

For DWTT specimens exhibiting slant fracture in impact and thin modified DWTT specimens (3 mm thick), $CTOA_c$ results from S-SSM were in agreement with surface values within the scatter of the optical image method for impact testing. The impact specimens (i.e., N5-N11, C2 and C4 in Table 4) are expected to have limited crack tunnelling, which is also the case for the M-DWTT specimens (N6 and N7 at quasi-static and impact rates) because their thickness is only 3 mm. For specimens with significant crack tip tunnelling such as quasi-static-tested DWTT, surface $CTOA_c$ values correspond to upper-bound values. Based on the results shown in this work, S-SSM delivers a $CTOA_c$ value averaged through the thickness and the CTOAc values from S-SSM were close to those measured near mid-thickness. Therefore, S-SSM is recommended to give a more representative CTOA value for the DWTT specimen; hence, $CTOA_c$ values from S-SSM are used for comparisons in the remainder of this work.

The effect of rate (loading velocities: quasi-static to 5.1 m/s; crack velocities: quasi-static to ~18 m/s) on $CTOA_c$ from the S-SSM is negligible for 8-mm thick (N10, N1 and C2) and full-thickness specimens (C4), as shown in Figure 16. However, for 3-mm thick modified DWTT specimens, which is not considered representative of high-strength pipe, increase of loading rate increased $CTOA_c$. This is in agreement with the results of DWTT specimens of low-strength pipe steel [13].

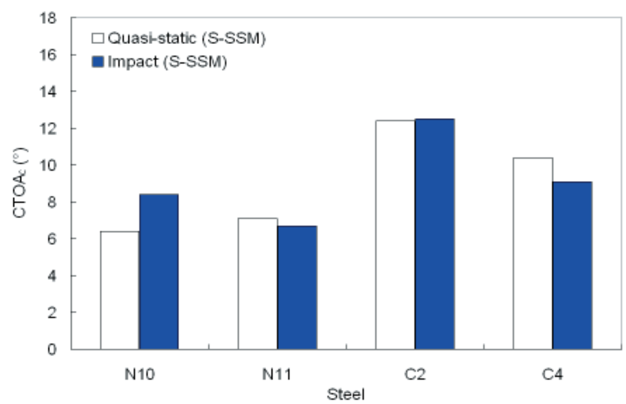


Figure 15. Effect of loading rate on $CTOA_c$ of 8-mm thick and full-thickness DWTT specimen.

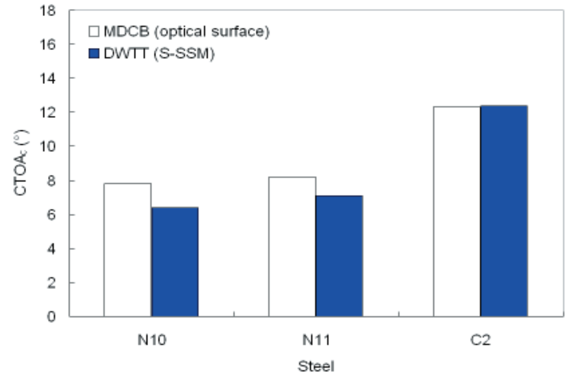
COMPARISON OF MDCB AND DWTT SPECIMENS

Direct comparison of $CTOA_c$ can be made from N10, N11 and C2 steels in Table 4 because both geometries used specimens machined to 8 mm thickness in the test section. $CTOA_c$ values from surface measurement of MDCB specimens were comparable to those derived from S-SSM of DWTT specimens. Note that For C2 steel, MDCB specimens showed slant fracture while DWTT specimens showed flat fracture at quasi-static rate. Figure 16 shows comparison of $CTOA_c$ of MDCB and DWTT specimens.

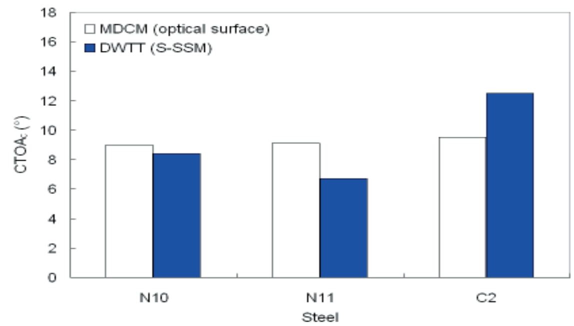
Comparison of 3-mm MDCB specimens and M-DWTT specimens can be made for N6 and N7 steels. M-DWTT specimens showed higher CTOAc than those from MDCB specimens. This may be due to an effect of ligament size on CTOA, i.e., decreasing CTOA with increasing ligament for DWTT specimens [13]. Also, note that 3-mm thick MDCB specimens tended to have lower CTOA compared to thicker specimens (e.g., 8 mm thick) [11].

For steels N1 to N5, MDCB specimens were tested at quasi-static rate using 3-mm thick specimens. Owing to the limited amount of materials, tests of DWTT specimens were done only on full-thickness and at impact rate. For N1 steel (9.7 mm thick), DWTT specimens twisted during impact testing showing that anti-buckling fixtures may be necessary for DWTT specimens with thickness less than 10 mm. For steel N3 and N4, 3-mm MDCB specimens tested at quasi-static rate showed ductile fracture while full-thickness DWTT specimens were tested at impact rate and exhibited cleavage fracture. For mill tests, CTOA testing should be at impact rate to best simulate service conditions.

Advantages and disadvantages of MDCB and DWTT specimens are compared in Table 5. DWTT specimens may be suitable for a mill test owing to simplicity of machining, testing and data analysis. However, further validation of the transferability from small-scale mill tests to full-scale burst tests needs to be done.



(a) Quasi-static rate



(b) Dynamic rate

Figure 16. Comparison of CTOAc of 8-mm thick MDCB and DWTT specimens.

Table 4. Average CTOA$_c$ [thickness in mm, fracture mode: slant (S) or flat (F), measurement method: Optical (O) or S-SSM].

Steel	Quasi-static			Impact		
	MDCB	DWTT	M-DWTT	MDCB	DWTT	M-DWTT
N1	11.7 [3,S,O]	–	–	–	Twisted [9.7,S,O]	–
N2	9.1 [3,S,O]	–	–	–	<5 [8.1,F,O] (cleavage)	–
N3	9.8 [3,S,O]	–	–	–	<3 [7.4,F,O] (cleavage)	–
N4	10.4 [3,S,O]	–	–	–	8.4 [7.9,S,S-SSM]	–
N5	9.2 [3,S,O]	–	–	–	7.0 [7.8,S,O] 7.8 [7.8,S,S-SSM]	–
N6	11.7 [8,S,O]	–	16.0 [3,F/S,O] 17.0	11.3 [8,S,O]	20** [26.3,S,O] 18.6 [26.3,S,S-SSM]	20 [3,S,O]
N7	9.9 [3,S,O]	–	[3,F/S,S-SSM] 14.0 [3,F/S,O]	–	Stopped the hammer[31.5,S,O]	20.0 [3,S,O]
N9	11.6 [8,S,O] 8.6 [8,S,O]	–	14.9 [3,F/S,S-SSM]	8.6 [8,S,O]	12.0 [20.6,S,O] 10.6 [20.6,S,S-SSM]	21.4 [3,S,S-SSM]
N10	7.8 [8,S,O]	9.5 [8,S,O] 6.4 [8,S,S-SSM]	–	9.0 [8,S,O]	12 [8,S,O] 8.4 [8,S,S-SSM]	–
N11	8.2 [8,S,O]	12.0 [8,S,O] 7.1 [8,S,S-SSM]	–	9.1 [8,S,O]	10 [8,S,O] 6.7 [8,S,S-SSM]	–
C2	12.3 [8,S,O]	18.5 [8,F,O] 12.4 [8,F,S-SSM]	–	9.5 [8,S,O]	11.0 [13.7,S,O] 12.5 [13.7,S,S-SSM]	–
C4		19 [14.6,F,O] 10.4 [14.6,F,S-SSM]			11.1 [14.6,S,O] 9.1 [14.6,S,S-SSM]	

* No tests were performed.
** Absorbed energies of full-thickness DWTT specimens were close to machine capacity.

Table 5. Comparison of MDCB and DWTT specimens for mill testing.

Factor	MDCB	DWTT
Specimen Machining	More complex & higher cost	Relatively simple & lower cost
Specimen Thickness	Limited to 80 % of pipe wall thickness to avoid flattening	Tested as full thickness, which requires slight flattening. Thin specimens may buckle.
Specimen Ligament size	No limitation	Limited to specimen width
Test Machine	Uniaxial tensile, specially designed impact fixture	Universal test machine, Instrumented Impact machine
Loading Conditions	More like in-situ loading	3-point bend
Data Collection	Surface CTOA, crack propagation rate, and load-deflection data measured	Surface CTOA, crack propagation rate and load-deflection data measured
Data Analysis	More time consuming	Using S-SMM, faster and more robust

Main observations in the work are summarized below:

- At dynamic loading rates, both MDCB and DWTT specimens fail in slant fracture modes.
- At quasi-static test rates, mixed mode and flat fracture modes can occur with both MDCB and DWTT specimen configurations.
- The effect of loading rate on CTOA was found to be negligible within the range of rates used in this work.
- Crack front tunneling in these high-strength steel pipeline specimens typically ranged from about 25 to 100 % of the specimen thickness, and the crack front typically has a triangular shape.
- For DWTT specimens that failed in a flat fracture mode, CTOA values measured optically at the surface were significantly higher than those measured at mid-thickness, and the CTOA measured at mid-thickness in the specimens agreed well with the CTOA calculated from the S-SSM.
- For DWTT specimens that failed in a slant fracture mode, CTOA results from S-SSM and surface measurement were similar.
- CTOA values measured using the S-SSM for DWTT and surface measurement for MDCD specimens agree reasonably well.

CONCLUSIONS

The results from two very different methods of determining CTOA have been compared, and found to yield similar CTOA values for a range of pipeline steels and testing rates. The tests are complementary, but their differences suggest strengths and usefulness in different ways. DWTT specimens are suitable for a mill test, owing to its relatively simple specimen design (which lowers machining cost) and test machine configuration. In addition, determination of CTOA by using the S-SSM for DWTT specimen with this impact test makes data analyses straightforward and robust for a mill test. However, the applicability of the results for predicting full-scale burst test performance remains to be validated. MDCB specimens, with loading conditions more like in-situ loading, long ligament specimen design, and non-deformed test material, are more suitable as a laboratory test for model input to study physical phenomena for the resistance to crack growth. In this way, MDCB testing can support the validation of the DWTT test as a mill test for the prediction of full scale test results.

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