Proceedings of IPC2008
7th International Pipeline Conference
September 29-October 3, 2008, Calgary, Alberta, Canada

IPC2008-64369

CTOA MEASUREMENTS OF WELDS IN X100 PIPELINE STEEL*

Elizabeth Drexler
NIST
Boulder, CO, USA

Philippe Darcis**
NIST
Boulder, CO, USA

Christopher McCowan
NIST
Boulder, CO, USA

J. Matthew Treinen
NIST
Boulder, CO, USA

Avigdor Shtechman***
NIST
Boulder, CO, USA

Rony Reuven
NIST
Boulder, CO, USA

Thomas Siewert
NIST
Boulder, CO, USA

Robert Smith
DoT Office of Pipeline Safety
Washington, DC, USA

James Merritt
DoT Office of Pipeline Safety
Washington, DC, USA

J. David McColskey
NIST
Boulder, CO, USA

ABSTRACT

A suite of tests characterizing X100 pipeline steels was initiated at the National Institute of Standards and Technology (NIST) in Boulder. Part of the test matrix included testing the toughness of the base metal, welds, and heat-affected zones (HAZ) by use of modified double cantilever beam specimens for crack tip opening angle (CTOA) testing. The thickness of the test section was either 3 mm or 8 mm. Girth welds perpendicular to the growing crack, and seam welds and their HAZ parallel with the crack, were tested with a crosshead displacement rate of 0.02 mm/s (with the exception of one girth weld specimen for each thickness, which were tested at 0.002 mm/s). Analysis of the data revealed some general differences among the weld specimens. The tests where the crack ran perpendicular to the girth weld demonstrated changes in CTOA and crack growth rate as the crack moved through the base metal, HAZ, and weld material. We observed the values for CTOA increasing and the crack propagation slowing as the crack moved through the weld and approached the fusion line. The stress field appeared to be strongly influenced by the thin HAZ, the fusion line, and the tougher base material. Consequently, the CTOA of the HAZ associated with the girth weld was larger than that of the seam-weld HAZ. It was not possible to obtain CTOA data for the seam weld, with the crack parallel within the weld, because the crack immediately diverted out of the stronger weld material into the weaker HAZ. CTOA values from both girth welds and seam-weld HAZ were smaller than those of the base material. The 8 mm thick specimens consistently produced larger CTOA values than their 3 mm counterparts, introducing the possibility that there may be limitations to CTOA as a material property. Further tests are needed to determine whether a threshold thickness exists below which the constraints and stress field are sufficiently changed to affect the CTOA value.

*Contribution of the National Institute of Standards and Technology, an agency of the US government; not subject to copyright in the USA.
** current address: Tenaris, Via Xalapa, Veracruz, Mexico
***current address: NRCN, P.O. Box 9001, Beer-Sheva, Israel

INTRODUCTION

CTOA (crack tip opening angle) is gaining acceptance in the pipeline community as a material property for pipeline design [1,2]. The double cantilever beam specimen has been used to study fracture toughness in metals since the 1960s [3,4]. We have adopted the design for the modified double cantilever beam (MDCB) specimen advocated by Hashemi et al.[5,6] and Shterenlikht et al. [7]. Advantages of this specimen design include a long ligament arm for stable crack growth, and higher constraints, approaching those seen in the pipeline material in service. This design has been used successfully to generate values for the resistance to crack extension for pipeline base metals, such as X52, X80, and X100 [8,7,5, respectively]

There is a need for characterization of weld performance of X100 base metal. Beyond the challenge of obtaining a weld with good integrity, there is the challenge of understanding how the weld will behave if a running crack should be initiated [9,10]. CTOA measurements can add to this understanding by providing the same design criteria, resistance to crack extension, as is seen with the base metal. Seam welds, girth welds, and their associated heat-affected zones (HAZ) are each of concern, separately and in concert. This work seeks to determine whether it is possible to obtain valid CTOA measurements using the MDCB, and to quantify the resistance to crack extension for each of these areas of concern.

MATERIAL AND MEASUREMENTS

Weld material and the associated HAZ from X100 experimental pipelines were tested with MDCB specimens to obtain CTOA data. The chemistry for the X100 pipeline sections is found in Table 1. The sections had a diameter of 1.32 m (52 in), and were 20.6 mm (0.81 in) thick. The girth welds were made manually with shielded metal arc, and the seam welds were processed automatically. The tensile properties of the base metal, girth weld, and seam-weld HAZ are shown in Table 2. Figure 1 shows the microhardness profile across the seam (a) and girth (b) welds.

CTOA specimens were made in three different categories and two different thicknesses (Figure 2). One tests the girth weld, a second the seam weld, and the third the HAZ associated with the seam weld. To generate flat specimens from the curved pipe, the MDCB specimens were ground flat and parallel to avoid flattening. The specimens were machined with the crack aligned with the axis of the pipe. With this configuration, cracks ran perpendicular to girth welds, and parallel to the seam welds

Table 1. Bulk chemistry of X100 material

C	Mn	P	S	Si	Ni	Cu	Mo
0.07	1.90	0.008	0.0005	0.10	0.50	0.30	0.15

Table 2. Tensile properties of X100

Orientation	$\sigma_{0.2}$ (MPa)	σ_{UTS} (MPa)	$\sigma_{0.2}/\sigma_{UTS}$	e_u (%)	e_f (%)	e_u/e_f
Base Metal (Trans)	798	827	0.97	4.1	19.3	0.21
Base Metal (Long)	732	806	0.91	4.6	20.3	0.23
Global Girth Weld	730	835	0.87	7.7	15.0	0.51
Seam weld HAZ	693	642	0.93	4.1	12.1	0.34

and HAZ, which were centered in the test section of those specimens. The test sections were machined to thicknesses of 3 mm and 8 mm, and were acid etched and neutralized to make the weld and HAZ visible. Finally, a laser was used to place a 1 mm × 1 mm, or 1 mm × 0.5 mm grid on the test section. The grid, with its heavier lines marking 10 mm increments, can be seen on any image of the test section (see for example, Figs. 4–6).

CTOA tests were conducted as previously reported [8,11], but are described here briefly. A chevron notch 60 mm long was machined for crack initiation, to which an additional 5 mm to10 mm of fatigue precrack was added. The specimen was bolted to rigid gripping plates and then mounted in the servo-hydraulic testing machine having a 250 kN (55 kip) capacity via a pair of hardened pins. The gripping plates had flattened holes to minimize friction during fatigue precracking. The tests were run in displacement mode at a crosshead velocity of 0.002 mm/s for girth weld specimens of each thickness, and 0.02 mm/s for the remaining specimens. Images were captured with a high-resolution camera.

ANALYSIS

Analysis was conducted with the use of commercially available image analysis software, augmented with customized macros. The collected images were screened to meet minimum standards, such as having adequate focus and 1 mm of straight

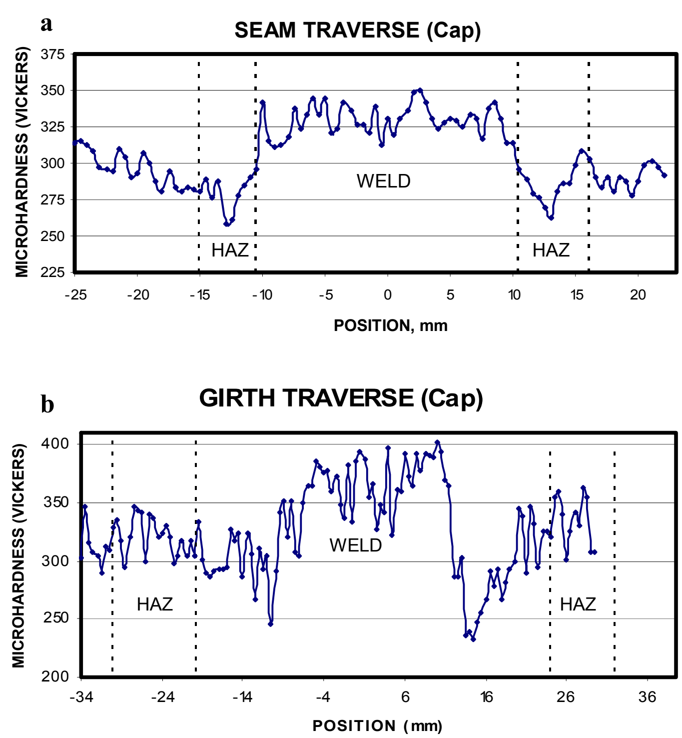

Figure 1. Vickers hardness measurements across the cap of a seam weld (a), and a girth weld (b).

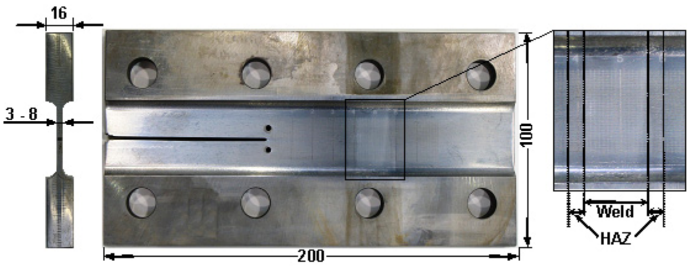

Figure 2. Image of the MDCB specimen showing the orientation and location of the girth weld in a typical specimen. (Dimensions in mm.)

crack tip. Crack growth in weld material was more erratic, in general, than in base metal, so other criteria, such as the crack tip being reasonably horizontal and the deformation zone being symmetrical about the crack tip, were sometimes ignored in order to get more data.

The analysis was also modified slightly from that reported by Darcis, et al. [8,11]. Figure 3 shows a crack in HAZ material. This image shows a common problem encountered in these specimens associated with welds and HAZ; the adjacent material has deformed to such an extent that the grid that was etched onto the test section has been obliterated. For the data reported here, the values for CTOA will be determined from the intersection of the linear fit of 100 points that define each edge of the crack. The edge is located by an operator using a spline-fit tool in image-analysis software. An example of a crack, advancing from the left, whose edges have been identified by use of the spline-fit tool, is shown as green fill in Figure 3. The area around the crack is highly deformed except for the region in advance of the crack tip, which is undeformed and is seen mirroring the crack tip to the right.

RESULTS

Five girth weld specimens were tested. Two were 3 mm thick and three were 8 mm thick. One of each thickness was tested at a crosshead velocity of 0.002 mm/s and the remaining three were tested at 0.02 mm/s. Each HAZ ranged from 2.5 mm to 4 mm across, and the girth weld was 9 mm to 16 mm. Since

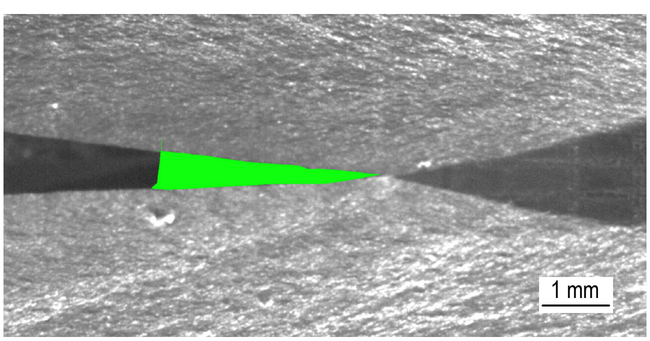

Figure 3. Image showing how the CTOA was determined for these weld specimens.

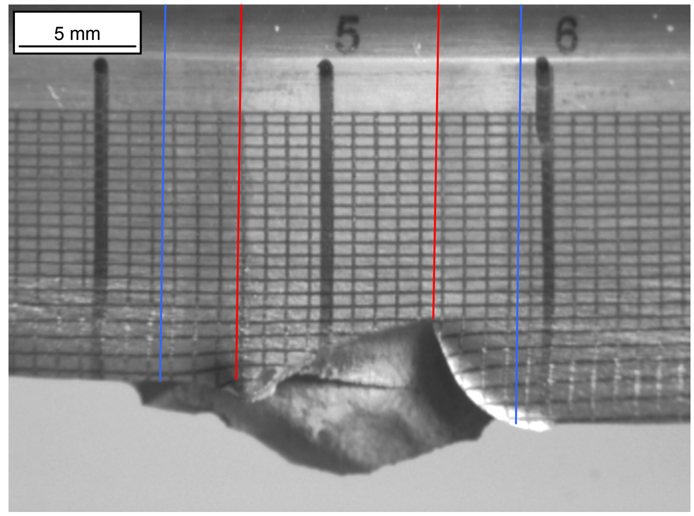

Figure 4. An example of the fracture through a girth weld. The approximate location of the fusion line is denoted by the red lines, and the blue lines indicate the approximate location of the interface between the base metal and the HAZ. The crack jumped through the first HAZ to the left.

the crack ran perpendicular to the weld, we expected to obtain CTOA data on the HAZ at two locations from each specimen. However, the crack jumped through the first HAZ into the weld material in all of the 0.02 mm/s tests. Figure 4 is an example of a test in which the crack jumped through the first HAZ; the weld and HAZ are visible on the face of the specimen. A prominent shear lip is also present in the weld fracture surface.

Three primary results were observed from these tests. (1.) Although one might have assumed little resistance to crack growth in the HAZ from the crack jumping through the first HAZ, the second HAZ generated a larger CTOA than the weld. (2.) CTOA is proposed as a material property and *not* dependent on size; however, the CTOA of the weld material was significantly smaller in the 3 mm specimens, as compared with the 8 mm specimens (using a Student's T-test, probability $p<0.0001$). Table 3 shows the mean and standard deviation of all the CTOA values from each specimen (1–5) following 2.5× the gage thickness (t) of crack growth, and for all the specimens for the given t. (3.) In every case, as the crack approached the fusion line exiting the weld, the crack growth slowed or stopped, the crack tip blunted, and the CTOA increased. This increase was as little as 59 % of the mean value for the CTOA within the weld to as much as 213 %. The increase in CTOA was also associated with a plateau or abrupt decrease in slope in the load-displacement curve for the test (Figure 5).

Also of interest, the rate of the test may have had a small effect on the values for CTOA, as in three out of four instances the slower tests resulted in smaller CTOA values, but within the standard deviation. However, in the companion paper to this

Table 3. Data on the mean value of CTOA from each specimen and for all specimens for the given thickness

	Girth Weld				Seam HAZ		Seam Weld/HAZ	
	HAZ		Weld					
	Mean	SD	Mean	SD	Mean	SD	Mean	SD
3 mm	10.61	1.70	3.00	1.07	3.96	1.08	3.80	1.61
1	10.74	1.07	2.72	0.79	4.18	1.33	4.87	1.60
2	9.90	2.80	4.92	NA	3.79	0.85	3.01	1.08
8 mm	10.73	2.59	6.75	1.73	6.96	1.27	6.11	1.44
3	8.30	2.38	5.46	1.35	7.17	1.29	6.54	1.22
4	13.12	1.09	7.57	1.48	6.48	1.11	5.70	1.54
5	11.16	1.93	7.41	1.64				

* SD = standard deviation

one [12], we found that rate had little effect on CTOA values for the base metal.

Four specimens, two of each thickness, were tested with the HAZ from a seam weld centered in the test section. The size of the HAZ in these specimens appeared to be larger than those from the girth welds, 5 mm to 6 mm across. As with the girth welds, we found significant differences in the CTOA ($p<0.0001$), depending on the thickness of the test section (see Table 3).

Four specimens were also tested to determine the CTOA for the seam welds, two of each thickness. Invariably, and although we were able to grow a fatigue precrack in the weld, upon crack growth during the test, the crack diverted into the HAZ. Figure 6 shows an example of this. The crack was essentially vertical until it reached the HAZ. Values for the CTOA of the HAZ from these specimens were similar to those obtained from the specimens made with HAZ in the test section (Table 3).

DISCUSSION

(1.) Of particular interest is the question of why the HAZ displayed both less and more resistance to crack growth, depending on whether it was approaching or leaving the girth weld, respectively. The HAZ is often considered the weak link in the joining process, as welds are usually overmatched in strength. Increased strength, however, is often associated with lower toughness. The crack jumping through the first HAZ corresponds to expected low tearing resistance. Conversely, the larger values for the CTOA from the second HAZ from the girth welds would indicate a tougher material and needs further scrutiny to understand this contradiction. But before we pursue that discussion, it is worth noting that the CTOA values for the HAZ associated with seam welds are much lower than those associated with girth welds. If, for example, we compare values for the 8 mm thick specimens, we see that the mean value for CTOA from the girth-weld HAZ is 10.73°, whereas it is 6.96° from the seam-weld HAZ. This value is much lower, and in

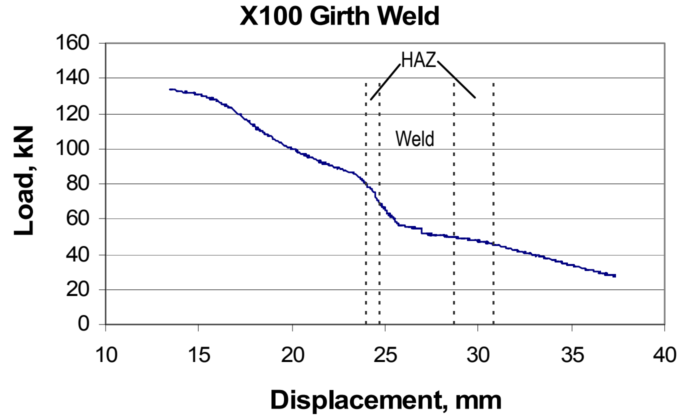

Figure 5. Typical load vs crosshead displacement plot across a girth weld. Note the load plateau in the weld, as the crack approaches the HAZ.

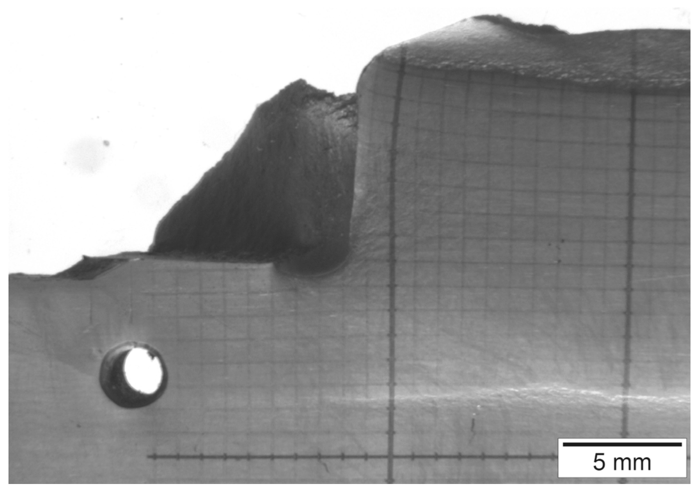

Figure 6. Image showing how the crack deviated from the seam weld into the HAZ.

fact less than the ~9° value for the same X100 base metal [12], as one would expect for the "weak link."

The welding process is certainly different in the seam weld and girth weld, but other factors may be affecting these values. As mentioned in the Results, the thickness of the girth weld HAZ is only 2.5 mm to 4 mm wide. As the crack approaches the interface perpendicularly, the surrounding material changes the stress field at the crack tip, and the deformation bands are well ahead of the crack tip. Figure 7 shows a crack approaching the second HAZ. The deformation appears to be bypassing the HAZ and is concentrating in the base metal. The combination of the tougher base material and the fusion line contributes to buildup of dislocations and back stress at the interface, artifice-ally increasing the CTOA of the HAZ. It appears that with this

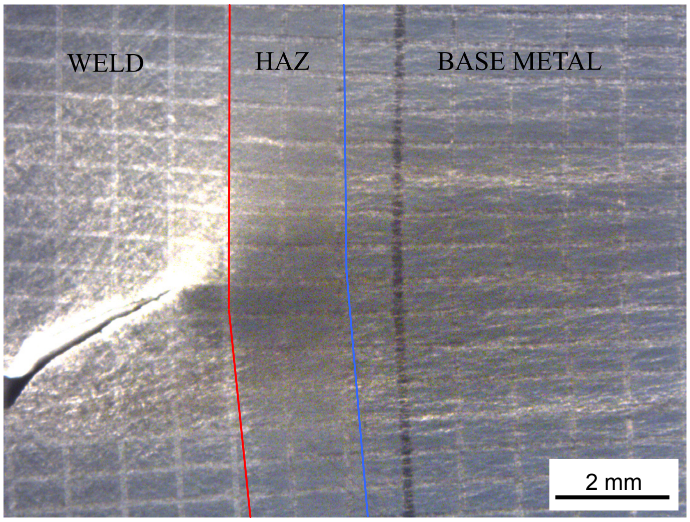

Figure 7. Image of a crack growing in a girth weld, approaching the fusion line. Notice the deformation in the weld and base metal, and the relative smoothness in the HAZ. The approximate locations of the fusion line and the HAZ/base metal interface are indicated by the red and blue lines, respectively.

test configuration, the HAZ is too narrow to accurately test its resistance to crack extension.

The HAZ that was centered in the test section and associated with seam welds had a very different geometry. The HAZ itself was wider and the crack was oriented parallel to its length. The stress field above and below the crack may be constrained by the base material and the weld, but the crack was able to grow without impediment. The behavior observed in the attempt to measure the CTOA of seam welds supports the premise that the HAZ is the most susceptible to crack growth. Mean values of ~3.9° for the 3 mm specimens and ~6.5° for the 8 mm specimens also confirm that the HAZ exhibits less tearing resistance than the base material.

(2.) Hashemi et al. [5] and Shterenlikht et al. [7] tested MDCB specimens with gauge thicknesses of 8, 10, and 12 mm, and 4, 8, and 10 mm, respectively. Neither group found that the thickness influenced the value for CTOA. This led them to conclude that CTOA is a material property. We found that the values for the CTOA from the girth weld and the seam-weld HAZ were significantly smaller for the 3 mm specimens than from the 8 mm specimens. Only the value for CTOA from the girth-weld HAZ showed no significant difference. But, as discussed previously, the stress field was complicated by the narrow HAZ being approached perpendicularly, leading to doubts as to the validity of those CTOA values.

Although not reported here, we have found that, similarly, base metal tests on 3 mm and 8 mm specimens also resulted in smaller CTOA values from the thinner specimens. These results would imply that there is a threshold thickness below which the constraints change sufficiently to affect the CTOA. This issue merits further investigation.

(3.) Steady-state crack growth is not meaningful in the context of a crack growing perpendicularly to the weld. We observe many contradictions to steady state, such as the CTOA increases, the crack growth rate slows, load vs. displacement changes slope, the crack path deviates, and the deformation field does not exhibit the expected decreasing gradient with respect to distance from the crack tip in the vicinity of the girth weld and its associated interfaces. Although not steady state, the behavior associated with the crack growth is quantifiable for these test conditions and has the potential to be useful in the modeling of crack propagation and growth in pipelines and their girth welds.

Although potentially encouraging for in-service conditions, the crack tip blunting that was observed as the crack leaves the weld material, test was conducted at such slow rates that the blunting observed is unlikely to be sufficient to absorb much of the energy of a running crack at the velocities observed in full-scale tests.

CONCLUSIONS

The test technique described here has limitations when applied to a narrow HAZ with the crack is running perpendicular to the interface. Likewise, it may not possible to obtain reliable CTOA data from weld material with the crack running parallel to the length of the weld, as the crack diverts into the weaker HAZ. However, obtaining reliable data is possible if the specimen is designed so that for the weld, the crack runs perpendicular to the weld, and for the HAZ, the crack runs parallel with the HAZ. The girth weld exhibits a lesser degree of resistance to crack growth, with a mean CTOA of ~6°, and the seam-weld HAZ demonstrates even less tearing resistance, with a CTOA of ~5°. Specimens with thinner test sections have smaller CTOA values. This observation runs contrary to the usual understanding of the plane-strain/plane-stress behavior, and merits further investigation.

ACKNOWLEDGMENTS

The authors thank the US Department of Transportation for financial support, and Ryan Johns, Marc Dvorak, and Ross Rentz for their assistance.

REFERENCES

[1] Horsley, D. J., 2003, “Background to the use of CTOA for prediction of dynamic ductile fracture arrest in pipelines,” Eng. Fract.Mech., 70, pp. 547–552.

[2] Rudland, D. L., Wilkowski, G. M., Feng, Z., Wang, Y. –Y., Horsley, D., and Glover, A., 2003, “Experimental investigation of CTOA in linepipe steels,” Eng. Fract. Mech., 70, pp. 567–577.

[3] Hoagland, R. G.,, 1967, “On Use of Double Cantilever Beam Specimen for Determining Plane Strain Fracture Toughness of Metals,” J. Basic Eng., 89, pp. 525–532.

[4] Hahn, G. T., Sarrate, M., and Rosenfie, A. R., 1971, "Plastic Zones in Fe-3Si Steel Double-Cantilever-Beam Specimens," 7, pp. 435–446.
[5] Hashemi, S. H., Howard, I. C., Yates, J. R., Andrews, R. M., and Edwards, A. M., 2004, "Experimental study of the thickness and fatigue precracking influence on the CTOA toughness values of high grade gas pipeline steel," Proc. Int. Pipeline Conf., IPC04-0681.
[6] 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. Int. Pipeline Conf., IPC04-0610.
[7] Shterenlikht, A, Hashemi, S. H., Howard, I. C., Yates, J. R., Andrews, R. M., 2004, "A specimen for studying the resistance to ductile crack propagation in pipes," Eng. Frac. Mech., 71, pp. 1997–2013.
[8] Darcis, P. P., McCowan, C. N., Windhoff, H., McColskey, J. D., and Siewert, T. A., 2008, "Crack tip opening angle optical measurement methods in five pipeline steels," Eng. Frac. Mech., 75, pp. 2453–2468.
[9] Liu, M., Wang, Y. –Y., and Horsley, D., "Significance of HAZ softening on strain concentration and crack driving force in pipeline girth welds," Proc. 24th Int. Conf. Offshore Mech. Arctic. Eng., pp. 385–393.
[10] Hudson, M., Di Vito, L., Demofonti, G., Aristotile, R., Andrews, R., and Slater, S., 2004, "X100 – girth welding, joint properties and defect tolerance," Welding Engineering Research Center, Cranfield University, http://www.msm.cam.ac.uk/phase-trans/2005/LINK/176.pdf
[11] Darcis, P. P, Kohn, G, Bussiba, A., McColskey, J. D., McCowan, C. N., Fields, R., Smith, R., and Merritt, J., 2006, "Crack tip opening angle: measurement and modeling of fracture resistance in low and high strength pipeline steels," Proc. Int. Pipeline Conf., IPC2006-10172.
[12] Reuven, R., Drexler, E., McCowan, C., 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.