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Crack tip opening angle optical measurement methods in five pipeline steels

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Abstract

Crack tip opening angle (CTOA) is becoming one of the more widely accepted properties for characterizing fully plastic fracture. In fact, it has been recognized as a measure of the resistance of a material to fracture in cases where there is a large degree of stable-tearing crack extension during the fracture process.

Our current pipeline research uses the CTOA concept as an alternative or an addition to the fracture energy characterizations provided by the Charpy V-notch (CVN) and drop weight tear test (DWTT). A test technique for direct measurement of CTOA was developed by use of a modified double cantilever beam (MDCB) specimen. A digital camera and image analysis software were used to record the progression of the crack tip and to estimate CTOA. In this report, different optical measurement methods are compared, three using the crack edges adjacent to the crack tip (defined in the ISO draft standard and ASTM standard) and one using the specimen surface grid lines. Differences in CTOA resulting from the various measurement methods are evaluated. The CTOAs for five different grades of gas pipeline steel are reported, and the effect of microstructure on CTOA is discussed.
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Keywords: Crack tip opening angle; Optical angle measurement methods; Pipeline steels; Modified double cantilever beam CTOA test set-up

1. Introduction

The increasing demand for natural gas as an alternative energy source implies continued growth of gas pipeline installations and the qualification of the actual pipeline network. A difficult problem to be solved for the economic and safe operation of high pressure gas pipelines is the control of ductile fracture propagation [1]. As a result, the accurate prediction of the resistance to fracture and ductile fracture arrest in pressurized gas pipelines are important issues.

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It has become clear that extrapolating the existing experimental absorbed fracture energy relations (based on Charpy V-notch (CVN) and drop weight tear test (DWTT) tests), to assess the fracture resistance of higher strength grades of modern pipeline steels, introduces significant errors [2–5]. Correction factors have been developed [1,4,5] for high strength steels; however, these correction factors do not reflect the fracture mechanisms characteristic for these new higher strength steels.

In parallel to the CVN and DWTT based fracture strategies, pipeline designers have worked on developing new measures of fracture control. Among these, crack tip opening angle (CTOA) is becoming one of the more widely accepted properties for characterizing fully plastic fracture [6,7], especially for running ductile cracks in pipes [2,7–13]. The main advantages of CTOA are that it can be directly measured from the crack opening profile and can also be related to the geometry of the fracturing pipe. Furthermore, in cases where there is a large degree of stable-tearing crack extension during the fracture process, CTOA has been recognized as a measure of the resistance of a material to fracture [6,9]. This type of steady-state fracture resistance takes place when the CTOA in a material reaches a critical value. This suggests that a steady-state CTOA could be considered to be a material property and used as either an addition or an alternative to the absorbed fracture energy for the assessment of the toughness of pipeline steels. In addition, the CTOA criterion can be implemented easily in finite element models of the propagating fracture process [6,9,13,14].

The literature contains a number of different specimen geometries for studying ductile crack propagation using the CTOA criterion, such as middle tension specimens, M(T) [6,15,16], compact tension specimens, C(T) [6,15,16], DWTT specimens (with methodologies based on one [1,8–10] or two specimens [17]), 3-Point Bending specimens, 3-PB [7,12], and Modified Double Cantilever Beam specimens, MDCB [3,13]. Our initial effort concentrates on quasi-static test methods using the MDCB specimen type.

The MDCB specimen [3,13,18–20], is very promising for CTOA measurement in pipeline steel. The specimen is convenient for CTOA measurement and it allows an extended region for steady-state crack growth. The design also allows for the development of a fairly large plastic region at the crack tip. This is a move in the right direction to simulate the very large plastic zones surrounding running cracks on pipelines (up to 2.5 pipe diameters ahead of the crack tip and about 0.3 diameters on each side of the crack line [10]). Another good feature of the specimen is that it can be cut directly from pipe with no subsequent flattening, which avoids possible inaccuracies due to pre-straining the material.

There are a number of methods used to measure the CTOA for quasi-static tests using MDCB specimens. Some are direct methods using moiré interferometry [21], or optics of various types [3,15,16,18–20,22–24], and others are indirect methods using approaches such as microtopography [15,25,26], finite element analyses [15,16], or determination using the crack opening displacement δ_5 [15,16]. Both direct and indirect methods are included in the ISO draft standard [15] and ASTM standard [16] for CTOA testing. A direct optical assessment method using digital image measurement was chosen for this study, which has reportedly produced good results for quasi-static CTOA tests [3,13,18–20].

2. CTOA experiments and set up

2.1. Materials properties

Five pipeline steels, including steel that had been in service on used pipelines, were tested. Table 1 summarizes the pipe dimensions.

Table 1
Designation of the tested steels

Steel #	1	2	3	4	5
Designation	N/A	X52	Grade B	N/A	N/A
O. D. (inch)	20	20	22	20	22
O. D. (m)	0.51	0.51	0.56	0.51	0.56
Thickness (mm)	9.7	8.0	7.4	7.9	7.8
Remarks	Unused	Used	Used	Used	Used