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CALIBRATION OF A NONDESTRUCTIVE TOUGHNESS TESTER (NDTT) FOR MEASURING FRACTURE TOUGHNESS OF PIPELINE STEEL

Steven D. Palkovic
Massachusetts Materials Technologies
Waltham, MA, USA

Simon C. Bellemare
Massachusetts Materials Technologies
Waltham, MA, USA

Kamal K. Botros
NOVA Chemicals
Calgary, Alberta, Canada

Xiande (Derek) Chen
TransCanada PipeLine
Calgary, Alberta, Canada

Richard Kania
TransCanada PipeLine
Calgary, Alberta, Canada

ABSTRACT

In-ditch/in-service characterization of pipelines using nondestructive evaluation (NDE) can provide valuable data for confirming operating pressure and qualifying pipelines for transporting natural gas of different quality or gas mixture, as well as for determining repair criteria for integrity management programs. This is especially relevant for vintage pipelines that may not have material test reports (MTR) available, and for aging infrastructure that have been subjected to suspected or unknown integrity threats. However, measurement of material fracture toughness currently requires the removal of large samples for laboratory testing, such as compact tension (CT) fracture testing or Charpy impact testing. The present work introduces a new concept, the Nondestructive Toughness Tester (NDTT), that provides a NDE solution for measuring the fracture toughness of pipeline steel in a superficial layer of material (~0.005 inches). The NDTT uses a specially designed wedge-shaped stylus to generate a Mode I tensile loading that results in a ductile fracture response. NDTT tests are performed in multiple orientations on 8 different pipeline steel samples covering 3 different grades to compare the NDTT material response with the fracture toughness measurements from laboratory CT specimens. Analysis of these results indicate that the height of a fractured ligament that remains on the sample surface after NDTT testing exhibits a linear relationship with traditional CT J-integral measurements normalized by its yield strength. This type of behavior is analogous to the crack-tip-opening-displacement (CTOD) calculated through elastic-plastic fracture mechanics. Tests conducted on the pipe outer diameter and in the longitudinal direction near the pipe mid-wall indicate that the NDTT can measure differences in fracture toughness for different crack orientations. Furthermore, the results show that outer diameter tests provide a conservative estimate of the overall steel fracture toughness. These observations indicate that the NDTT is a viable method for assessing toughness properties of steel materials. Additional research is required to further refine the implementation of the NDTT concept and understand the relationship with laboratory test results on pipe cutouts, but the progress is already a significant step towards obtaining additional material toughness data for integrity management.

NOMENCLATURE

The following nomenclature is referenced within the text:

CT	compact tension
CTOD	crack-tip-opening-displacement
L-T	longitudinal-transverse test configuration
MTR	material test report
NDE	nondestructive evaluation
NDTT	Nondestructive Toughness Tester
OD	pipe diameter
SEB	single-edge notched bend
S-L	short-longitudinal test configuration
S-T	short-transverse test configuration
T-L	transverse-longitudinal configuration
WT	pipe wall thickness
δ_I	Mode I crack-tip-opening-displacement
δ_L	NDTT ligament height
J_I	Mode I J-integral
J_{IC}	Mode I initiation fracture toughness
n	work hardening exponent
σ_y	tensile yield strength
σ_u	ultimate tensile strength

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INTRODUCTION

Accurate measurement of material fracture toughness ensures reliable structures and infrastructure. For ductile metals, resistance curves that describe a material's fracture toughness as a function of crack growth can be obtained through instrumented compact test (CT) or single-edge notched bend (SEB) specimens. An alternative to fracture toughness experiments are Charpy impact tests which provides an index of toughness that can be used to comparatively rank materials. These methods all require test specimens that meet standardized sample sizes, which is often not practical or cost-effective for in-service pipelines and pressure vessels where a sufficient volume of material cannot be easily removed.

As an alternative to large-scale laboratory testing, researchers have used contact mechanics to perform nondestructive evaluation (NDE) of fracture toughness properties. Contact mechanics uses a hard stylus that engages with a softer substrate to probe material properties in a small volume of material interacting with the stylus. Connections between nondestructive tests and traditional laboratory measurements can then be obtained through correlations that are established through analytical, numerical, or empirical models. Indentation hardness testing with a sharp stylus is one method that has been used for relatively low toughness ceramics to generate radial cracks and calculate the critical stress intensity factor [1]. This method is not suitable for ductile materials like polymers and metals that do not exhibit cracks during indentation testing. For these higher fracture toughness materials, the changes in plastic flow stress from repeated indentation has been combined with critical strain [2] or continuum damage [3] concepts, but these methods do not actually generate a propagating Mode I tensile crack that is captured through a traditional laboratory CT or SEB specimen.

An alternative to indentation is frictional sliding, where the stylus engages with a substrate and slides along the surface. A ductile or fracture material response can be generated depending on the stylus geometry, depth-of-penetration, friction, and strain rates [4]. One approach by Akono et al. assumes a planar crack in-front of the stylus and applies linear elastic fracture mechanics (LEFM) for quasi-brittle material [5]. Others have used cutting with a wedge stylus to predict fracture toughness by separating the energy components required for fracture, plasticity and friction [6, 7]. A challenge with these existing frictional sliding methods is that the material response is subjected to complex and competing deformation processes [8], and the fracture surface cannot be easily characterized because it is machined by the displacement of the stylus.

This work presents the experimental calibration of the Nondestructive Fracture Toughness Tester (NDTT), a new approach to measuring fracture toughness of ductile materials. To the authors' knowledge, the NDTT is the first contact mechanics test to produce a predominately Mode I tensile loading mode through frictional sliding with a specially designed wedge-shaped stylus. Previous studies have used finite element analysis (FEA) to study the propagation of a crack induced by the stylus, and quantified significant triaxial tension that exists near the crack tip [9]. This work presents the results from the first experimental application of the NDTT on 8 different pipeline steel samples covering 3 different grades. The material response measured with the NDTT is compared with traditional destructive methods to assess the ability of the NDTT to provide an index of fracture toughness.

OVERVIEW OF THE NDTT

The principles of the NDTT stylus are shown in Fig. 1. The stylus is a cutting tool that includes a stretch passage which creates two blades separated by a narrow gap. As the stylus engages with a material through frictional sliding, a chip separates from the substrate due to the cutting action of the blades. However, material near the stretch passage is not machined, but is subjected to increasing tension as the chip flows up the inclined face of the tool. Eventually, this region of material fractures into a ligament that remains on both the cut surface of the substrate and the opposing face of the separated chip. The ligament remaining on the substrate is then preserved as the stylus continues to slide across the surface, allowing for subsequent analysis.

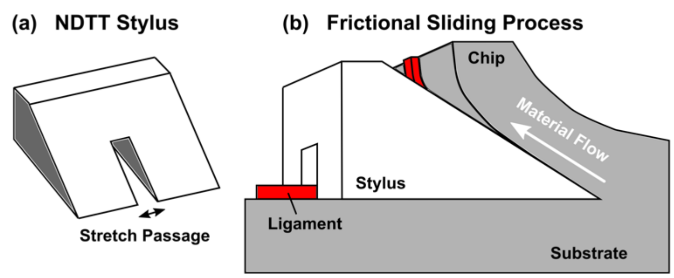

Fig. 1: (a) The NDTT stylus has a wedge-shaped geometry with a narrow stretch passage along the upstream face. **(b)** During a test, material within the stretch passage flows up the wedge and is stretched in tension until fracture, resulting in a ligament that remains on the specimen. Image adapted from [9].

The geometry of the ligament can be measured to obtain an indication of the magnitude of deformation prior to fracture. This is similar to the crack-tip-opening-displacement (CTOD) in a traditional laboratory destructive experiment. Therefore, it is expected that a larger ligament height is indicative of a greater CTOD and corresponding higher fracture toughness. This analogy is illustrated in Fig. 2, where significant crack blunting of a ductile material occurs just behind the front of the stylus at the crack tip. During an experiment, the ligament height can be measured along the length of the test using a contact, optical, or laser profilometer. This is a distinction from prior cutting techniques where fracture features are removed by the blade during the test. Scanning Electron Microscopy (SEM) of the sample after testing show the significant difference between the machined surface interacting with the stylus blades and the rough, dimpled surface observed on the fractured ligament.

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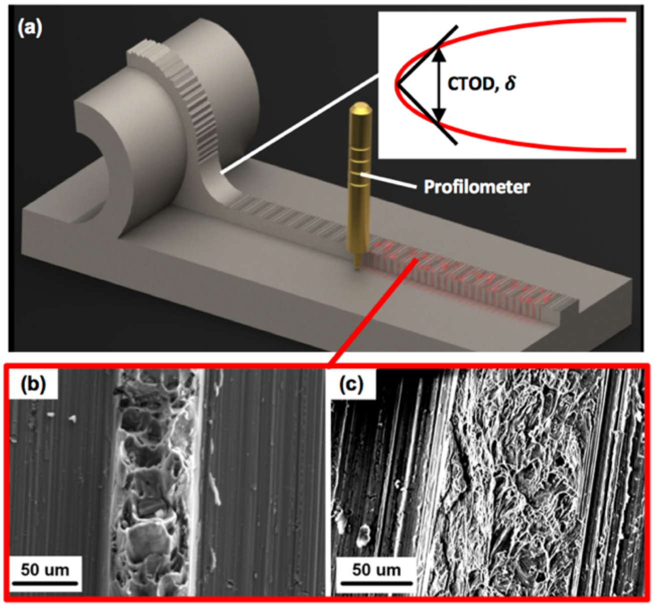

Fig. 2: (a) A contact profilometer measures the geometry of the fractured ligament that remains on the sample surface. Features of ductile fracture are observed with SEM images of the ligament for an **(b)** aluminum and **(c)** steel alloy. Microscopy images are adapted from [9].

The current NDTT is a desktop laboratory unit. An overview of the NDTT and a close-up of a test sample is shown in Fig. 3. The drive system is constructed from a steel hydraulic press frame, an electric ball screw linear actuator for sliding motion, a tool vice for modifying cutting depth and rake angle, and various stock components. The NDTT stylus is fixed to the frame and the sample is translated by the linear actuator. The simplicity of the stretch passage concept allows for straightforward fabrication of NDTT styluses. The current method is to bolt two tungsten carbide blanks together with a shim inserted between them to create a stretch passage of the desired width. The stylus rake angle is selected to balance the need for a continuous ductile chip while also reducing the magnitude of the applied cutting force. The electronics consist of a power supply, a power adjustment module, and a limit-stop for safety. Ligament heights are measured with a spring-loaded linear variable displacement transducer (LVDT) that rasters across the machined surface perpendicular to the cut length direction.

Table 1: Pipe type, year, grade, outer diameter (OD) and wall thickness (WT)

Sample ID	Seam Type	Year Installed	CSA Grade (MPa)	OD (mm)	WT (mm)
14-132	SAW	1972	448	1067	9.6
14-141	SAW	1981	448	914	13.2
15-132	ERW	---	359	406	6.0
14-134	SAW	1972	448	1067	9.6
15-176	SAW	1978	483	1067	9.9
15-177	SAW	1976	483	914	8.2
16-132	SAW	1965	359	762	9.5
17-020	SAW	1958	359	762	9.5

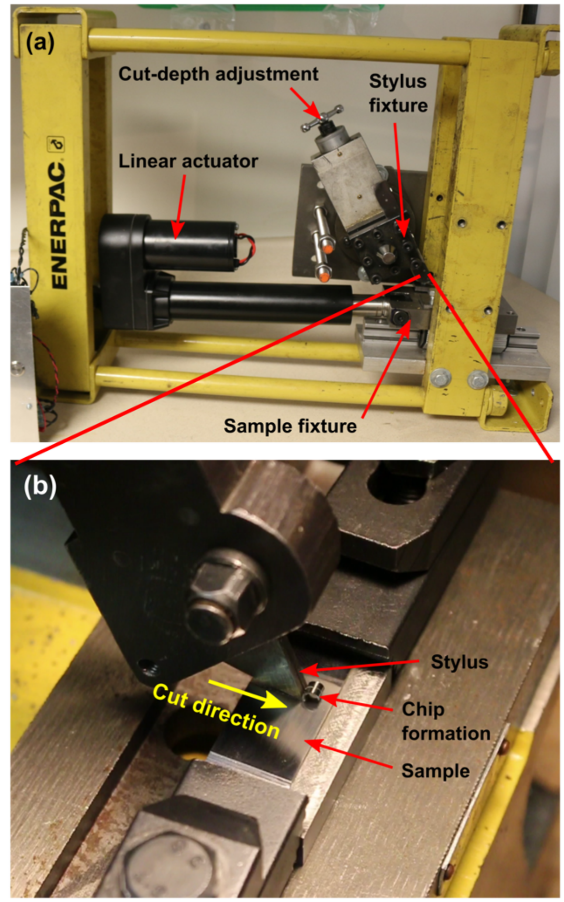

Fig. 3: (a) Overview of the NDTT desktop unit. **(b)** Samples are sectioned from the pipe wall and fixture by the NDTT to test in the desired orientation.

MATERIALS & EXPERIMENTAL PROCEDURE

This study considers 8 different steel pipes of varying grade, seam type, and vintage. Details of each pipe are provided in Table 1. The experimental program consists of traditional destructive laboratory tests which are used to compare with NDTT experiments on the same pipe sample. Destructive methods consist of tensile tests for uniaxial strength properties and compact tension (CT) specimens for evaluating fracture toughness. For each sample, transverse tensile coupons were removed from the pipe wall, cold-flattened, and then machined following standard procedures. CT specimens were removed from the full-thickness pipe wall, pre-cracked in the longitudinal direction and tested at ambient conditions. The crack length was monitored during fracture toughness testing using both compliance and optical methods. J-resistance curves and the initiation toughness was determined according to ASTM E1820.

NDTT experiments on each sample were conducted in four orientations to assess the influence of different crack configurations on the material response. Figure 4 provides an overview of the nomenclature for short (S), transverse (T) and longitudinal (L) directions. Each sample was tested twice in the T-L, L-T, S-T and S-L orientation. The T-L configuration is in the same orientation as destructive CT tests. NDTT specimens

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were sectioned from the pipe body into smaller samples to facilitate sample holding with the NDTT unit. Samples were milled flat on the appropriate test surface and wet polished to 120 grit. The rake angle was set to 20 degrees from vertical with a stylus penetration depth of approximately 125 µm (0.005 inches). A stretch passage width of 50 µm (0.002 inches) was used to ensure that multiple metallographic grains would be included on the fractured ligament for most pipeline steels. Duplicate NDTT tests of 3.2 mm (0.125 inches) in length were performed for each direction, for a total of 8 tests per sample.

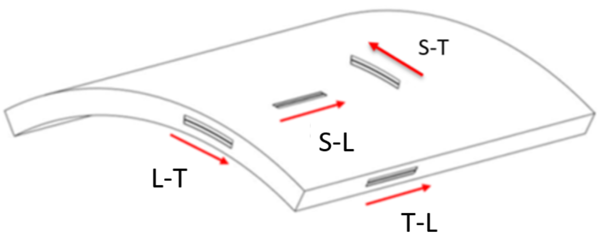

Fig. 4: Overview of nomenclature for NDTT test configurations on pipes.

RESULTS AND DISCUSSION

Destructive experiments

Laboratory tensile tests were used to determine the 0.2% offset yield strength (σ_y) and ultimate tensile strength (σ_u), whereas fracture toughness CT specimens provided the initiation fracture toughness (J_{IC}). The average values from three tensile coupons and four to five CT specimens is provided in Table 2. The sample fracture toughness showed a wider range of values compared to plastic strength properties for these pipeline steels.

Table 2: Destructive tensile and fracture toughness properties of pipe samples

Pipe ID	σ_y MPa (ksi)	σ_u MPa (ksi)	J_{IC} kJ/m^2 (lbf-in/in^2)
14-132	516 (74.8)	632 (91.6)	162 (925)
14-141	489 (70.9)	592 (85.8)	87 (497)
15-132	411 (59.6)	576 (83.5)	45 (255)
14-134	545 (79.0)	680 (98.6)	129 (733)
15-176	548 (79.5)	681 (98.7)	162 (923)
15-177	564 (81.8)	614 (89.0)	73 (415)
16-132	399 (57.9)	578 (83.8)	55 (315)
17-020	373 (54.1)	508 (73.7)	68 (386)

NDTT experiments

The overall average and standard deviation of up to 50 ligament height (δ_L) measurements with the NDTT for each pipe sample and orientation are provided in Table 3. The standard deviation reflects variation in local properties of the material, which can be significant for the small volume of material within the stretch passage that can approach the size of only a few grains within the steel microstructure. Additional sources of variability include the laboratory equipment due to (1) challenges related to holding and aligning samples for different cut directions, and (2) durability of the NDTT stylus for repeated tests on high strength and toughness pipeline steel. These hardware challenges can be alleviated through future improvements of the NDTT technology by increasing rigidity of the loading frame and sample fixture, and optimizing the material, geometry, and fabrication of NDTT styluses.

Table 3: NDTT ligament height (δ_L) for different test orientations

Pipe ID	T-L (µm)	S-L (µm)	S-T (µm)	L-T (µm)
14-132	169 (25)	132 (21)	128 (39)	123 (16)
14-141	146 (6)	96 (2)	92 (54)	82 (5)
15-132	115 (30)	67 (19)	84 (18)	69 (10)
14-134	147 (31)	100 (37)	88 (31)	135 (31)
15-176	158 (33)	124 (34)	84 (27)	85 (11)
15-177	121 (11)	78 (15)	50 (13)	60 (10)
16-132	119 (26)	81 (4)	67 (29)	99 (7)
17-020	133 (8)	98 (9)	65 (23)	98 (10)

The average and (standard deviation) from 6.4 mm of total test length

Correlation between destructive and NDTT results

A general relationship between the CTOD and fracture toughness is given by,

$$\delta_I = \frac{J_I}{m\sigma_y} \quad (1)$$

where δ_I is the Mode I CTOD, J_I is the Mode I J-integral, σ_y is a representative yield strength, and m is a constant that depends on the sample geometry and strain hardening behavior of the material [10]. The ability of δ_L from the NDTT to represent the traditional CTOD can be assessed by comparing its correlation with J_{IC}/σ_y from destructive laboratory experiments, as shown in Fig. 5. Note that NDTT data from S-T and S-L orientations are for cracks propagating on the same plane parallel to the outer surface of the pipe wall, which would be the two orientations for testing of pipe in service. The NDTT measurements show a fairly strong linear relationship with J_{IC}/σ_y in agreement with Eq. (1). An empirical estimate of $m \approx 4$ can be obtained by averaging the slope of the four different crack planes for all 8 pipeline steel samples. This value would change if an effective flow stress based on both the yield and ultimate tensile strength was used to account for strain hardening behavior.

The NDTT ligament height also varies for different crack planes on the same pipe sample, as shown by the changing y-intercept for the linear regression fits in Fig. 5. Previous studies reported in the literature has suggested that T-L cracks are the limiting fracture mode for pipeline steel [11]. However, traditional laboratory tests are unable to test the delamination-type failure on the outer diameter of the pipe that the NDTT measured as the lowest fracture toughness (S-L and S-T). As mentioned earlier, these two orientations are those that would be implemented during in-ditch testing on in-service pipelines. The present findings suggest that these two orientations provide a conservative estimate of the pipeline steel fracture toughness (compare Fig. 5a to 5b and 5c).

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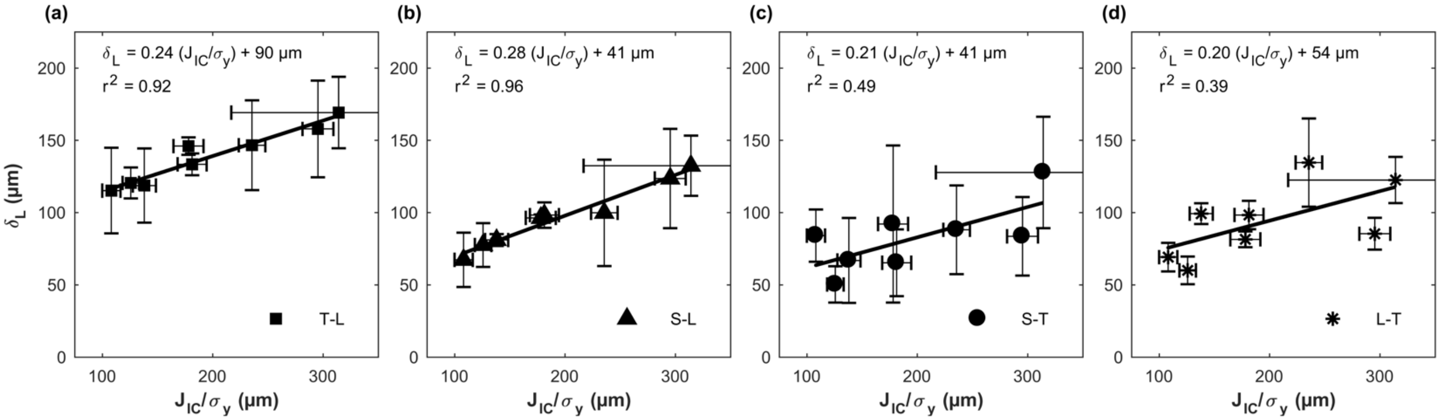

Fig. 5: Correlation between NDTT ligament height δ_L and J_{IC}/σ_y from destructive testing. A linear regression fit is shown for each NDTT test configuration.

Future Research and Development Directions

In the future, further study is needed to understand the role of plasticity and constraint near the crack tip on δ_L, and the resulting linear relationship with the destructive J_{IC}/σ_y. An estimate of the theoretical size of the fully developed fracture process zone r_p is given by,

$$r_p = \frac{J_{IC}E}{2\pi\sigma_y{}^2} \tag{2}$$

where E is the Young's modulus. For the samples tested, r_p ranges from approximately 7 to 20 mm, which is significantly larger than our cut depth of 0.125 mm and stretch passage width of 0.1 mm. This indicates that the fracture process zone captured through the NDTT is not fully developed compared to standard laboratory testing. We can study these effects experimentally by varying the cut-depth and stretch passage width, or numerically with finite element analysis. Finite element analysis is a powerful approach because it will allow us to establish the crack driving force (J-integral) as a function of elastic-plastic material inputs, crack tip position, and applied cutting force. Numerical analysis is likely required to advance beyond the empirical relationships shown here.

The principles applied by the NDTT are transferable to many different material systems and applications. Experiments on polymers or plastic pipe could examine the ability of the NDTT to measure the fracture toughness of other ductile material systems.

Other unique applications include studies on the effect of strain rate by increasing the sliding velocity, or the influence of temperature on the measured response. These two parameters could potentially be used to identify ductile-to-brittle transitions. Future correlations could also be established with Charpy values.

The current NDTT is a laboratory unit, but the hardware could be incorporated within a portable loading frame to enable nondestructive in-ditch and in-service assessments of fracture toughness. This would provide valuable data where material test records (MTR) are not available, and as inputs for pipeline integrity management programs.

CONCLUSIONS

This study has used experiments on pipeline steel to calibrate the NDTT, a new instrument for nondestructive measurements of the fracture toughness of ductile materials. The NDTT material response for multiple crack configurations was compared with traditional laboratory destructive tests. From these results, the following conclusions are made:

- The NDTT ligament height shows a linear correlation (or slope) with J_{IC}/σ_y from destructive tests. This agrees with fracture mechanics theory for the CTOD. A higher slope is associated with additional constraint near the crack tip (e.g. plane stress v. plane strain) and greater magnitudes of strain hardening.
- The NDTT is capable of measuring different fracture toughness values for cracks propagating along different planes. NDTT tests performed on the outer surface of the pipe (S-L and S-T) would be implemented for testing of in-service pipelines. These configurations show the lowest ligament height and therefore lowest fracture toughness, suggesting that they would provide a conservative measurement of toughness.
- Additional experimental and numerical studies will provide further understanding of the differences between the constraint, plasticity, and stress field at the crack tip for NDTT and traditional laboratory experiments.
- These results suggest that the NDTT is a viable tool for characterizing fracture toughness in a superficial layer of ductile metals. Additional work is recommended to further the development of the NDTT hardware and methodology so that the NDTT can become a viable field instrument. This may include the consideration of steel surface chemistry such as sulfur content within the fracture mechanics correlations.

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