Validation of Planing-Induced Microfracture for Determining Pipe Body Toughness

Xuejun Huang, Bryan Feigel, Victor Jablokov
Massachusetts Materials Technologies LLC

Pipeline Pigging and Integrity Management Conference

February 12-16, 2024

Organized by
Clarion Technical Conferences

https://doi.org/10.52202/072781-0043

https://doi.org/10.52202/072781-0043

Abstract

Material toughness is needed when analyzing the critical crack size that would fail at MAOP and when performing a fitness-for-service evaluation with cracks discovered during inspection. When toughness data is not available, gas transmission operators may be required to use conservative values or perform cut-outs for lab testing or other industry-accepted data, such as collected by nondestructive testing. This paper presents a new in-situ, minimally invasive method to provide pipe body toughness data via planing-induced microfracture. A microcrack is successfully introduced by a specially designed blade with a unique stretch passage feature. Validation has been performed on 33 vintage pipe samples with various toughness values to establish a correlation between the test data and material fracture toughness. This paper gives an overview of the planing-induced microfracture method, the lab test setup, and the procedure to obtain material fracture toughness from test data. The first instrument for field use called the Blade Toughness Meter (BTM) is being developed and tested for pipe body toughness, as a complement to the existing frictional sliding method to test for longitudinal seam toughness.

https://doi.org/10.52202/072781-0043

1. Introduction

Pipe toughness determination as part of nondestructive evaluation (NDE) has been sought for decades. When crack or crack-like flaws are detected during pipeline inspection, gas transmission operators may be required to determine the predicted failure pressure and the crack size that would fail at MAOP, where material toughness data is needed. When toughness data is not available, operators may have to use conservative values (for example, maximum Charpy V-Notch toughness values of 13.0 ft.-lbs for pipes with no history of reportable incidents per 49 CFR § 192.712) or perform cut-outs for lab testing. An innovative instrument using the planing-induced microfracture method is being developed at Massachusetts Materials Technologies LLC (MMT) to help operators obtain fracture toughness data of the pipe body in an in-situ, minimally invasive manner. This instrument aims to reduce the number of cutouts to obtain statistically significant and reliable fracture toughness data for pipeline integrity management.

1.1 Planing-Induced Microfracture

Developed in 2022, the idea of planing-induced microfracture is to introduce a sub-surface fracture surface and measure its features to correlate to the material fracture toughness. It involves using a specialized blade, featuring a central opening, to plane the surface of a material. As the blade moves across the surface, the area adjacent to the opening is left uncut. Material in this region flows through the opening and is subjected to tensile stress until it fractures. This opening is referred to as the "stretch passage," as the material passing through it experiences primarily tensile strain. When the material fractures, residual ligaments remain on the cut surface of the substrate and the opposite face of the separated chip. The characteristics of these ligaments, such as their height, are correlated with the material's fracture toughness as discussed later in this paper.

1.2 Novel Blade Design with Stretch Passage

MMT has been performing research to develop a fracture toughness testing instrument since 2018. Prior research focused on developing a novel machining method that used the concept of stretch passage to estimate the upper shelf Charpy impact energy and initiation fracture toughness J_c typically obtained from compact tension specimens [1, 2, 3]. The earlier research led to the emergence of a new concept in 2022. The new concept adopted the earlier stretch passage, but the blunt wedge was replaced by a blade where the cutting edge is at the intersection between a “dive” and “lift” surface (Figure 1). The lift surface reduces significantly bending in the stylus, allowing a sharpness similar to a knife blade without breaking. This design provides the benefits of less shear plastic deformation of material ahead of the stylus, and high states of material stress triaxiality which promotes fractures to occur and propagate within the stretch passage. Also, equal dive and lift angles create equal forces on the dive and lift surfaces which allows the stylus to maintain constant test depth. Lastly, the forces exerted on the stylus from testing are mainly compression, this allows the stylus to withstand testing of high strength and high toughness materials.

https://doi.org/10.52202/072781-0043

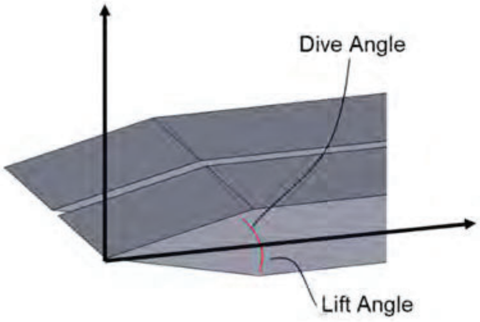
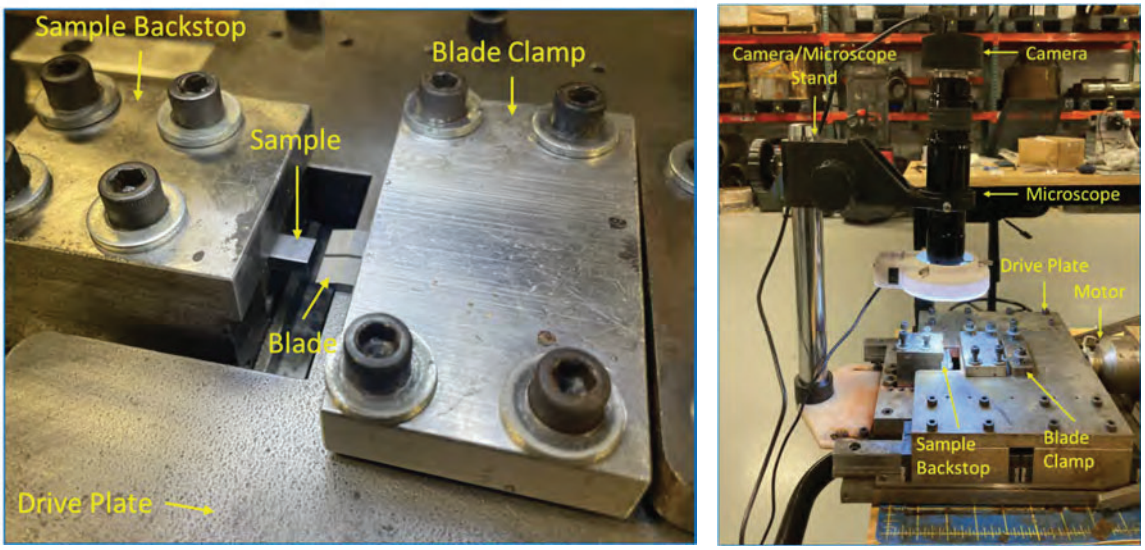


Figure 1. Blade stylus geometry.

2. Proof of Concept Testing

To accelerate the development process, initial validation testing was done on a simplified test apparatus that utilized the same blade geometry as the final instrument to "cut" or "split" the sample in halves as opposed to microplaning. Figure 2 shows the laboratory setup, which consists of a tungsten carbide blade configured to drive into the center of a prepared sample of pipeline steel. The tungsten carbide blade consisted of a 25-degree angle split evenly about the cutting edge, as well as a "stretch-passage" of 0.030" in width. The pipeline steel utilized in this study came from the same samples as utilized in a previous PRCI project PRCI NDE 2-9 [3]. These steel samples were machined from pipe cutouts to a dimension of 1/8" thickness, 1/4" width, and 0.3" length. The blade is clamped into position (right) and aligned to drive into the prepared sample (left) as shown in Figure 2 (a). The overview of the test setup is shown in Figure 2 (b).



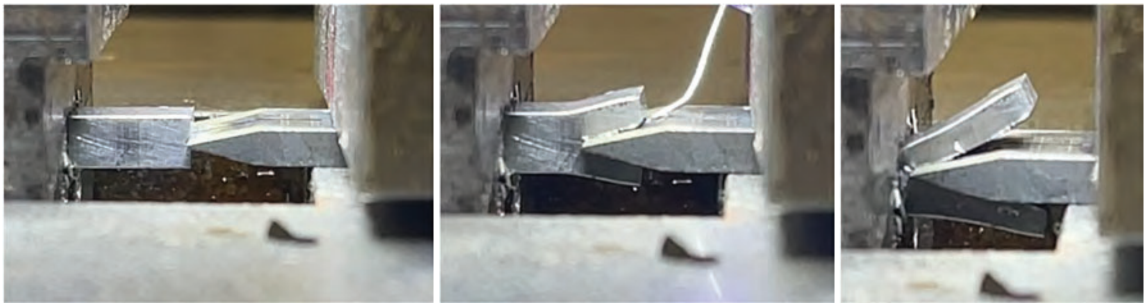
(a) (b)

Figure 2. (a) Zoomed-in lab test setup, (b) Overview image of lab test setup

An oversized NEMA 34 stepper motor attached to a GBPH-0901-NP planetary gearbox to the right of the clamped blade in Figure 2 (a) translates the blade into the sample material at a rate of 0.2

https://doi.org/10.52202/072781-0043

inches per minute. During the earliest portion of the test, the sample material inside the stretch passage of the blade is forced into tension, fails, and begins to propagate along the test path as a crack. Over a small amount of test length past this initiation point, the feature stabilizes into an advancing crack within the stretch passage of the blade. These developments from initiation to stabilization take place between the snapshots in Figure 3 (a), and Figure 3 (b). The blade will continue to translate through the sample until it has been fully separated (Figure 3 (c)). At this point measurements of the generated ligament are collected and processed.

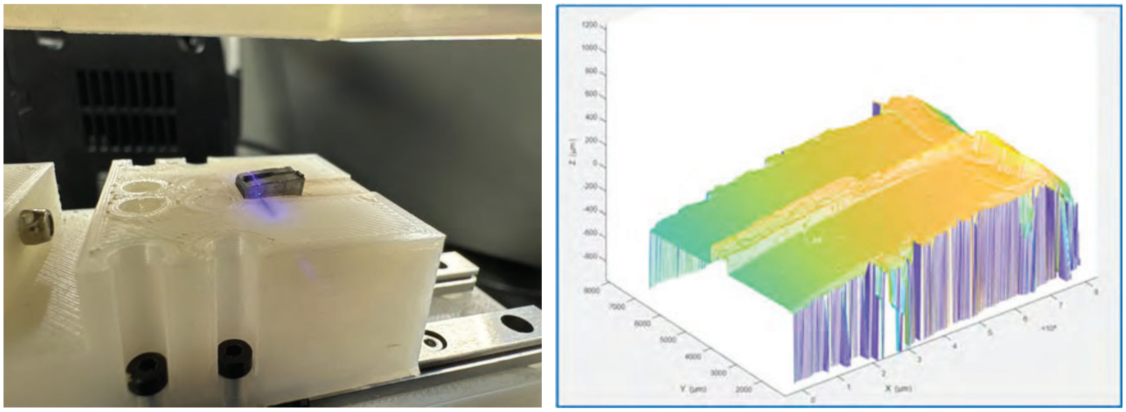


(a) (b) (c)

Figure 3. (a) Test start point (b) Test mid point (c) Test end point

3. Ligament Height Processing

The geometry of the stretched and broken region within the stretch passage, referred to as the "ligament", is a critical output of the BTM test. Once the split halves of the sample are imaged, they are scanned utilizing an LJ-X8020 Keyence line laser in a custom mount to capture the topography. The line laser setup can be seen in Figure 4 (a), while the output of the scan can be seen in Figure 4 (b).



(a) (b)

Figure 4. (a) In-process Keyence line laser scan, (b) Exported line laser scan output.

A key feature of the ligament geometry is its height. Extracting the ligament height from the line laser scan is done using a custom post-processing software. Two-dimensional ligament height data are first averaged within each scan to obtain a line profile of averaged ligament height vs. scan number, as shown in the red and blue lines for the two sides in Figure 5. The two side profiles are aligned and

https://doi.org/10.52202/072781-0043

added up to obtain the total ligament height profile (black line in Figure 5). Once the ligament height of each side is aligned with the other, many of the variations on each side can be canceled out and a smoother total ligament height profile can be observed. The initial region is typically an increased height corresponding to the initial tensile response leading up to the generation of the fracture. After this fracture begins to propagate, the height of the ligament stabilizes and reaches a region highlighted in yellow which is referred to as the 'steady-state region' (highlighted in yellow in Figure 5). Finally, as the test reaches the back of the sample the behavior becomes more erratic as edge effects come into play. A second average of the ligament height in the steady-state region is calculated.

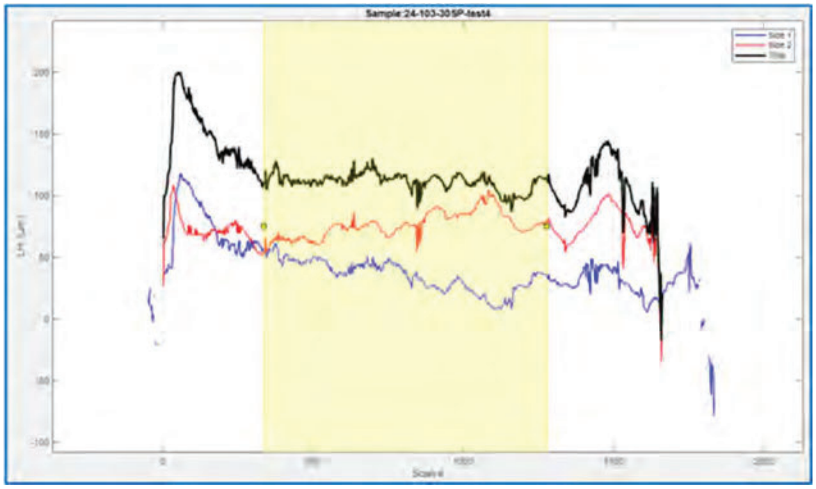


Figure 5. Averaged ligament height per scan of a BTM test

4. Fracture Toughness Correlation Model

Models are built to correlate the test data to material fracture toughness. One model leverages a simplified relationship by Oh [4] between the fracture toughness (K_{Ic}) and the toughness measured using the area under the tensile stress-strain curve up to the elongation at break (K_f):

$$\left(K_{Ic}/\sigma_y\right)^2 = \alpha\left(K_f/\sigma_y\right)^2$$

where σ_y is the yield stress of the material and α is a constant for a certain group of material (e.g. carbon steels). K_f can be estimated using the yield strength, ultimate tensile strength (σ_u), and elongation at break (ε_f) [4]:

$$K_f \approx \varepsilon_f\left[k\sigma_y + (1-k)\sigma_u\right]$$

Where k is a weighted coefficient to account for the nonlinearity of the stress-strain curve and $0 < k < 1$.

The yield and tensile strength of the material can be measured conveniently using the HSD non-destructive instrument by MMT [2] and thus are considered known properties. The central hypothesis is that the ligament height (LH) is linearly proportional to the elongation at break

https://doi.org/10.52202/072781-0043

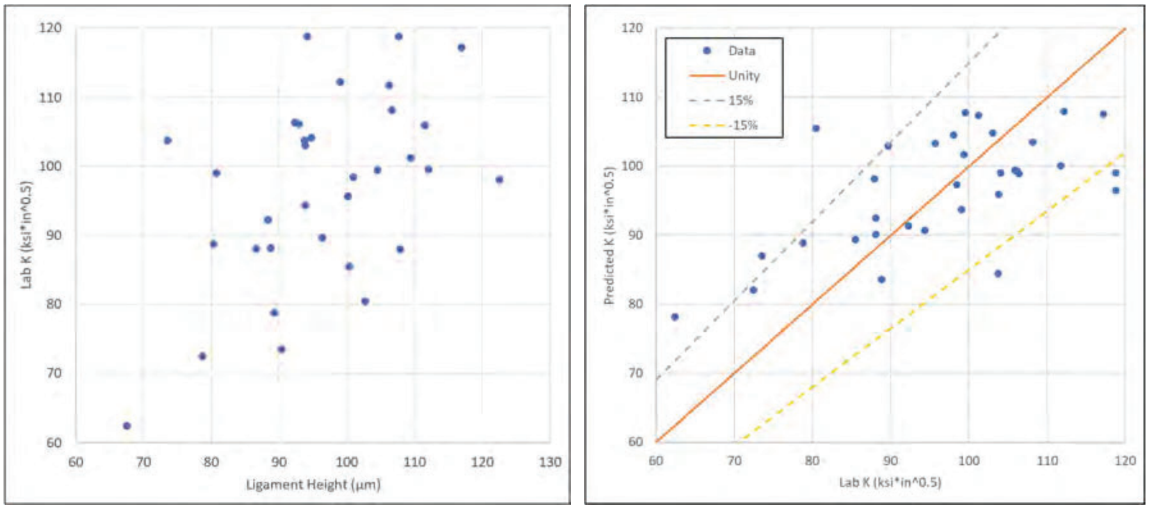
considering the material within the stretch passage is subjected to predominantly tensile stress and stretched to failure:

$$\varepsilon_f = a * LH + b$$

where a and b are fitted coefficients. Combining the equations above and with some modifications, we propose the following correlation between K_{Ic} and ligament height:

$$K_{Ic}/\sigma_y = C_1 * \left[k + (1-k)\sigma_u/\sigma_y\right] * LH + C_2/\sigma_y + C_3$$

where C_1, C_2, C_3 and k are fitted coefficients using test data. Figure 6 (a) shows the lab tested K_{Ic} vs. LH for all the test samples and Figure 6 (b) shows the predicted K_{Ic} using the proposed correlation vs. lab tested K_{Ic}. It is observed that for most data points, the predicted K_{Ic} values are within ±15% of the lab-tested values.



(a) (b)

Figure 6. (a) Lab-tested K_{Ic} value vs. ligament height, (b) Predicted K_{Ic} value vs. lab-tested K_{Ic} value

5. Field Instrument Development

5.1 The BTM Field Instrument

The first instrument that utilized the planing-induced microfracture method, called the Blade Toughness Meter (BTM), is currently being built by MMT. The BTM instrument (Figure 7) is a standalone device that allows the operator to attach to a live pipeline from 8 to 48 inches in diameter, prepare the surface to obtain 8 tests, and conduct two tests simultaneously. The BTM utilizes an adjustable "foot" which connects the frame of the tester to the pipe and adjusts for varying pipe diameter. The feet are then strapped to the pipe giving a secure connection preventing the tester from sliding on the pipe during testing. After the tester is secured to the pipe, the surface is prepared for testing by machining using a drill with a magnetic base (mag drill) equipped with a purpose-built end mill. The surface preparation and associated safety aspects are described in detail in the following section. The mag drill is attached to the BTM instrument with a pin assembly with 6 prescribed positions allowing the operator to machine 4 test specimens, each of which is tested twice, for a total of 8 tests. The mag drill machines 4 semi-rectangular test specimens, called "islands", to a depth of 0.030 inches. After all 4 islands are machined, each side of the islands is then tested with two independent test apparatuses. Each test apparatus consists of a movable drive mechanism that holds the test blade and is driven at a precise and constant speed via a stepper motor. Upon completion of the 8 tests, the mag drill is reinstalled with a "clean up end mill" which removes any sharp edges remaining from the initial surface machine and subsequent testing that could result in stress concentrations from the pipes' internal fluid pressure.

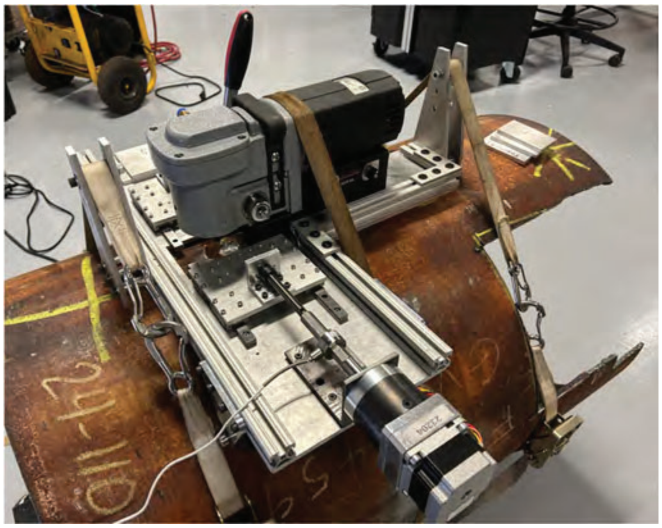
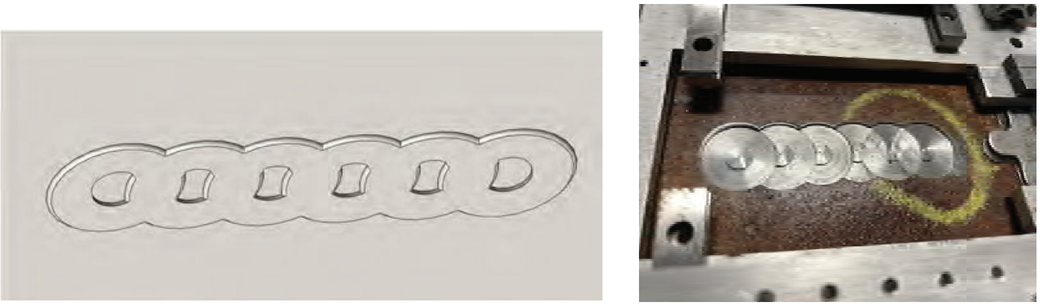


Figure 7. First-generation BTM field instrument

5.2 Surface Machining and Safety

The BTM surface machining process creates 4 test islands (Figure 8). Each island is 0.030" deep regardless of pipe diameter. The BTM is designed to test each side of the island creating 2 tests per island. The BTM blade contains a flat feature that rides along the untested surface between each island to ensure that the test cannot penetrate the pipe deeper than the 0.030" island depth.



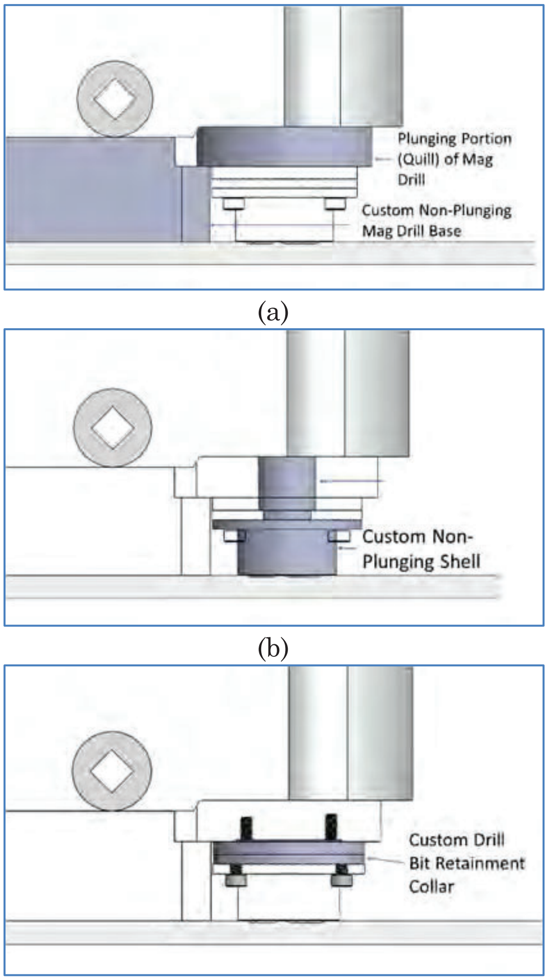
(a) (b)

Figure 8. BTM islands (a) CAD image, (b) photo on pipeline

The BTM surface machining process has 3 safety mechanisms (Figure 9) designed to make the machining process failsafe and have redundancy should the equipment malfunction, become

https://doi.org/10.52202/072781-0043

damaged, or the user makes an error. First, the drill chuck which controls the depth of the end mill has a physical limit stop preventing the drill from going past 0.030 inches of depth (Figure 9 (a)). Second, the end mill that creates the island is a custom non-plunging bit which has a circular flat 0.030 inches deep at the center of the bit, as well as an outer shell with a similar flat (Figure 9 (b)). This ensures that if the physical limit stop were to fail, it is not possible for the end mill to drill deeper than 0.030 inches because the OD of the pipe would contact this solid recessed feature. Additionally, if the mounting to the pipe surface were to fail resulting in the bit not being normal to the pipe surface, the outer shell will contact first and prevent over-drilling. Finally, we have created an installation plate that ensures that the drill bit is installed into the same position within the drill chuck to eliminate operator error when installing the end mill bit (Figure 9 (c)). An extra measure takes advantage of the max plunging depth of the mag drill dictated as supplied by the manufacturer. To take advantage of this manufacturer limitation the mag drill is attached to the BTM tester such that, should all the above-mentioned safety systems fail, the drill cannot physically move greater than 0.040 inches. Given that the thinnest pipe wall encountered in oil and gas is approximately 0.18 inches, this ensures that the end mill can never pierce the pipe.



(a)

(b)

(c)

Figure 9. Machining Safety Devices (a) Physical limit stop on mag drill on drill chuck, (b) drill bit island depth limiting within end mill, and (c) device to fix drill bit position with respect to drill chuck.

6. Conclusion and Future Work

A lab test setup implementing the planing-induced microfracture method was validated with 33 pipe samples. A physical model was built to correlate the ligament height measurement to the material fracture toughness K_{Ic}. Preliminary results show that most predicted K_{Ic} values fall within ±15% of the lab-tested values. The first instrument for field use is currently being developed to measure pipe body fracture toughness. We are planning to perform validation testing with a larger dataset using the instrument and incorporate a machine-learning model into the physical model to further improve the accuracy of fracture toughness predictions.

7. References

[1] Palkovic, Steven D., et al. "Calibration of a nondestructive toughness tester (NDTT) for measuring fracture toughness of pipeline steel." International Pipeline Conference. Vol. 51869. American Society of Mechanical Engineers, 2018.

[2] Palkovic, Steven, et al. "Nondestructive evaluation of metal strength, toughness, and ductility through frictional sliding." Pressure Vessels and Piping Conference. Vol. 58974. American Society of Mechanical Engineers, 2019.

[3] Palkovic, Steven, et al. “Fracture toughness via in-ditch nondestructive testing – validation.” PRCI Catalog No. PR-610-183867, 2020.

[4] Oh, Gyoko. "A simplified toughness estimation method based on standard tensile data." International Journal of Pressure Vessels and Piping 199 (2022): 104733.

https://doi.org/10.52202/072781-0043

https://doi.org/10.52202/072781-0043