Introduction of a Portable Field Instrument for In-Ditch Pipe Body Toughness Determination

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Abstract

The toughness of pipeline materials, particularly in fracture toughness, is important for assessing the fitness-for-service of pipelines. With the advent of ultra-high resolution inline inspection (ILI) tools, the demand for fracture toughness data has risen. Current approaches to obtain fracture toughness include performing cutouts and destructive testing, leveraging existing databases, and nondestructive evaluation (NDE). A previous PPIM paper (Huang, et al., 2024) [1] demonstrated an innovative NDE method called planing-induced microfracture and validated the method for estimating fracture toughness using a lab prototype that splits a sample into two halves. Based on this successful validation, a portable field tool, Blade Toughness Meter (BTM), has been developed. The field instrument is a significant advance as it directly attaches to a pipe to perform surface preparation and surface testing in-situ. The instrument first creates raised testing surfaces by machining called "islands" on the pipe surface and then planes these islands with specially designed blades with a central opening. A true microcrack forms within the central opening, and fractured ligaments left on the chip and substrate are scanned. This paper focuses on describing the material response during the test as it relates to the fracture toughness property. The fracture surfaces examined using a scanning electron microscope (SEM) show increasing ductility features as toughness increases. The laser scanning data from these fracture surfaces show direct correlation to toughness. With these recent findings, the analytics to provide toughness results are being developed and blind-tested.

Introduction

As pipeline safety gains increasing attention, operators are turning to advanced inline inspection (ILI) tools to identify and characterize defects in their pipelines. Recent ILI technology, such as electromagnetic acoustic transducer (EMAT), has significantly improved in resolution, enabling the detection of smaller cracks, down to sizes as small as 40 mm in length and 2 mm in depth [2]. However, the identification of these cracks presents a critical challenge to operators: what actions should be taken to address them? The application of modern fracture mechanics, including fitness-for-service (FFS) evaluation, offers a systematic approach to assessing the risks associated with these inspected cracks. These analyses, however, are highly dependent on the availability of accurate material properties.

Fracture toughness, a fundamental property reflecting a material's resistance to crack propagation, is essential for evaluating pipeline integrity. Developing effective and reliable methods for measuring fracture toughness has become a pressing issue within the industry. This challenge was highlighted during the PHMSA Research & Development Forum held in October 2023 [3], where industry experts emphasized the critical need for standardized testing protocols and innovative techniques to ensure precise assessments. Addressing this issue is vital not only for enhancing pipeline safety but also for optimizing maintenance strategies and ensuring regulatory compliance in an increasingly safety-conscious industry.

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A previous PPIM paper [1] introduced an innovative, non-invasive method known as planing-induced microfracture for measuring material fracture toughness. Significant progress has been made in developing the first field-deployable instrument, the Blade Toughness Meter (BTM), which applies this method to measure pipe fracture toughness directly in situ. This paper presents the level of correlation between key features of the material response and the fracture toughness through microscopic observation as well as laser profilometry of the fractured ligaments.

BTM Field Instrument and Testing

The BTM field instrument is developed based on the method of planing-induced microfracture [1], which introduces a sub-surface microcrack into a specimen by utilizing a specially designed blade with a central opening referred to as a stretch passage. As the blade cuts across the surface, the material that flows into the stretch passage is subjected to tensile stress created between the formed chip and substrate until it fractures. The formed crack can be identified by examining a cross-section within the stretch passage [4]. Characteristics of the residual ligaments on the fractured surface of the substrate and the opposite face of the separated chip can be used to correlate with the material's fracture toughness.

A photo of the current BTM field instrument is shown in Figure 1. The field instrument works similarly to the prototype, as described in [1], and is summarized here, along with recent improvements. The BTM field instrument performs two primary operations. The first is surface preparation, while the second is the ‘planing’ operation that generates the measured material response. Surface preparation is executed using a mag-drill configured on a platform and attached to a fixed frame. The platform is designed to translate between six different positions. At each location, a custom non-plunging drill bit is utilized to machine a circular ‘island’ of material. Improvements to the platform mechanism, including a quick-locking mechanism, improved rigidity, and a pin-locating mechanism have all been incorporated into the latest iteration of the instrument. The combined effect of these improvements when compared to prior iterations is a more consistently shaped and located island feature, which is produced in a shorter amount of time. Following the creation of the ‘island’ features, the mag-drill is removed from the frame by unfastening four captive screws. The planing operation is then performed by driving two tungsten-carbide blades with different stretch passage widths (0.015” and 0.020”) into opposite sides of the ‘island’ feature. Figure 2 shows the cutting operation, and the chip formed after a BTM test. Actuation of the blades is accomplished through stepper motors driving a sled and linear rail assembly. Each sled assembly is equipped with a tool post and blade holder for the tungsten-carbide blade. In the latest iteration of the tool, the sled assembly as well as the overall frame has been reworked to improve rigidity of the system.

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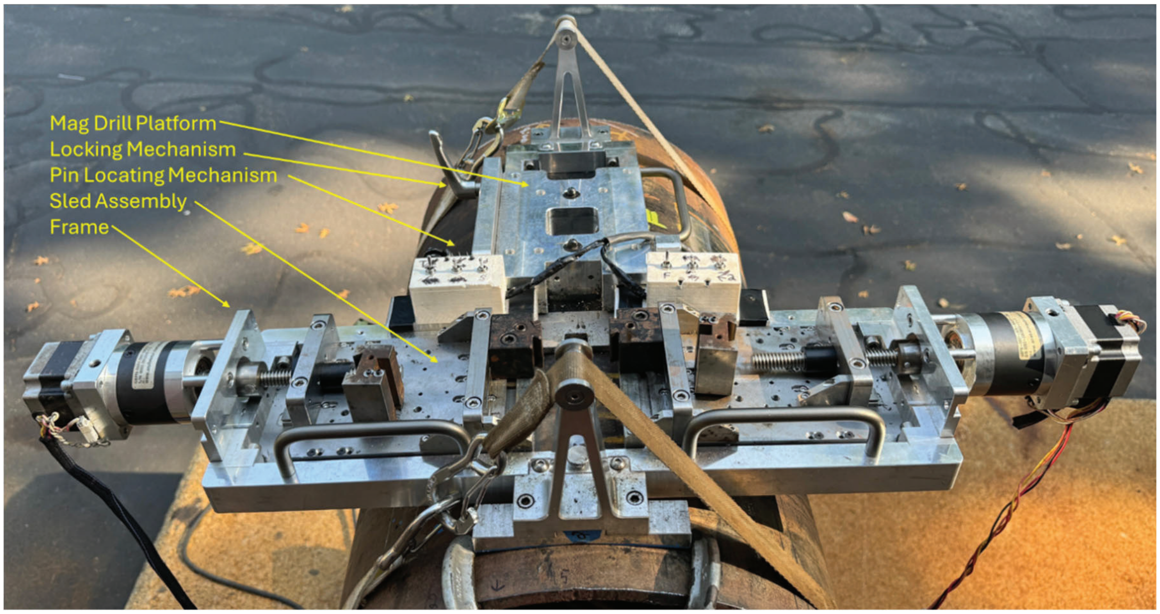

Figure 1. The BTM field instrument.

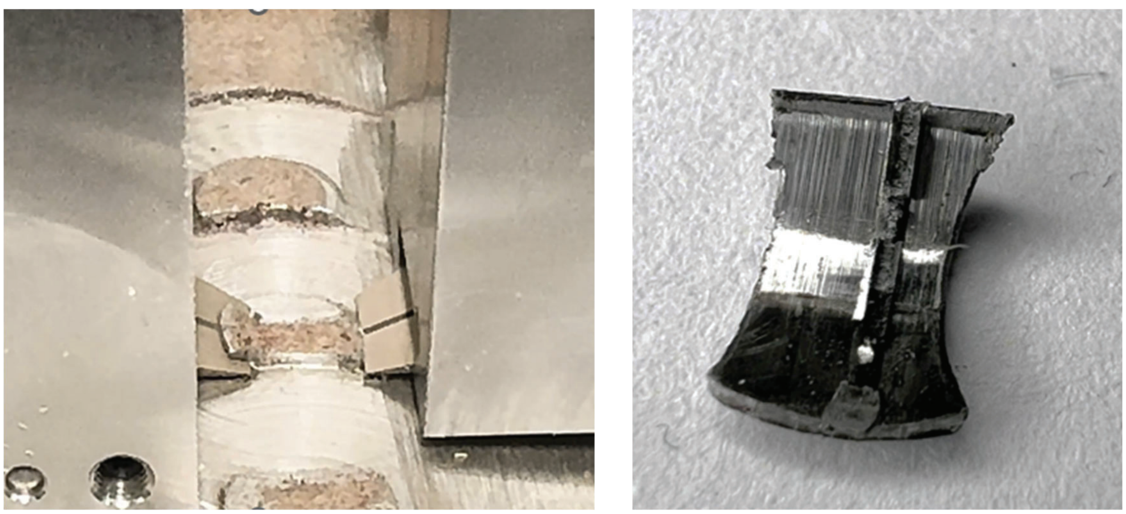

Figure 2. Left: a Zoom-in of the BTM blade cutting into a test island. Right: chip formed after a BTM test.

The field instrument has been used in a joint industry program (JIP) to test pipes with fracture toughness in order to evaluate its performance. So far, over 60 specimens have been BTM tested, and 37 of them have fracture toughness data obtained from destructive lab testing following ASTM E1820. Data from two different labs are combined and used for this paper. Data from a third lab is being re-examined. When multiple K tests are performed for a sample, the minimum value of all tests is used. Features of the resulting ligaments from these test specimens are analyzed, and their correlations to lab fracture toughness are examined in the following section. Correlation is quantified using the R^2 value from linear regression. The results are from tests using a stretch passage width of 0.020”.

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Features of the Ligament and their Correlations to Fracture Toughness

Combined Ligament Height

After the chip and substrate ligaments are scanned, the profiles on the two sides are aligned and combined [1]. The average ligament height along the cut path within the region where the height is relatively stable (called the stable region) is calculated and plotted against lab K values in Figure 3. Combined ligament height showed a strong correlation with a position slope. It is postulated that the combined ligament height correlates with the ductility of the sample [1], thus it shows a correlation to toughness.

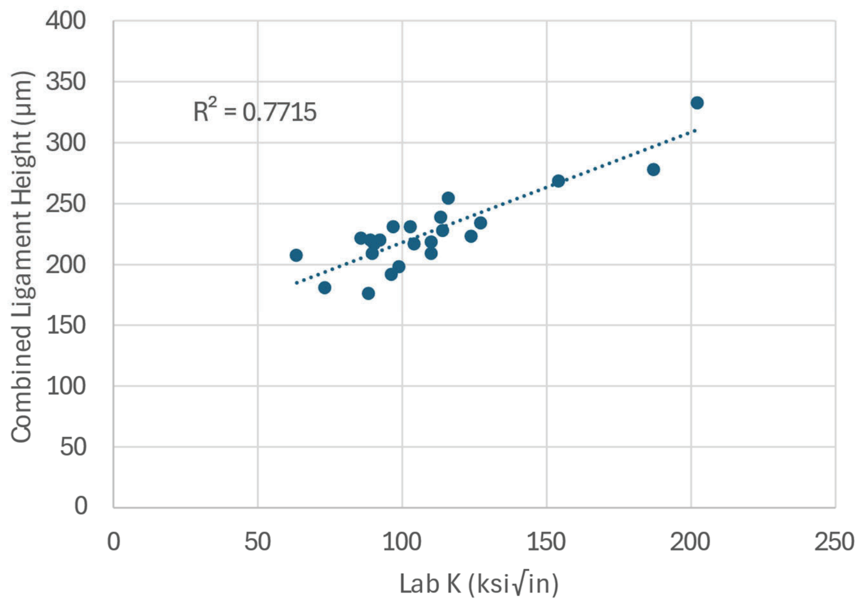

Figure 3. Correlation between Combined Ligament Height (y-axis) and Lab K (x-axis).

Roughness

The relationship between fracture surface roughness and a material's fracture toughness has been studied in the literature (e.g., Ref [5]). This correlation arises from the fundamental mechanisms of ductile fracture, which involve the nucleation, growth, and coalescence of microvoids. These microvoids typically form at sites associated with second-phase particles embedded within the steel matrix. As the voids expand and connect, they create a characteristic fracture surface topography whose roughness reflects the spatial distribution, size, and concentration of these secondary inclusions. Consequently, examining the roughness of the fracture surface provides insight into the underlying microstructural features of the material and offers a valuable means of inferring its fracture toughness [5].

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There are different methods of quantifying surface roughness, which leads to different correlations [6]. Here, we use a common measurement of roughness, the arithmetic average roughness (R_a), which is calculated as:

$$R_a = \frac{1}{l}\int_0^l |z(x)|dx$$

where l is the length of the profile, $z(x)$ is the profile height deviation from the mean line. Figure 4 shows the strong correlation between R_a along the centerline of the chip ligament vs. lab K. The negative slope indicates that for lower toughness samples, the crack propagation follows a more zig-zag pattern, thus leaving a rougher ligament profile along the cut path.

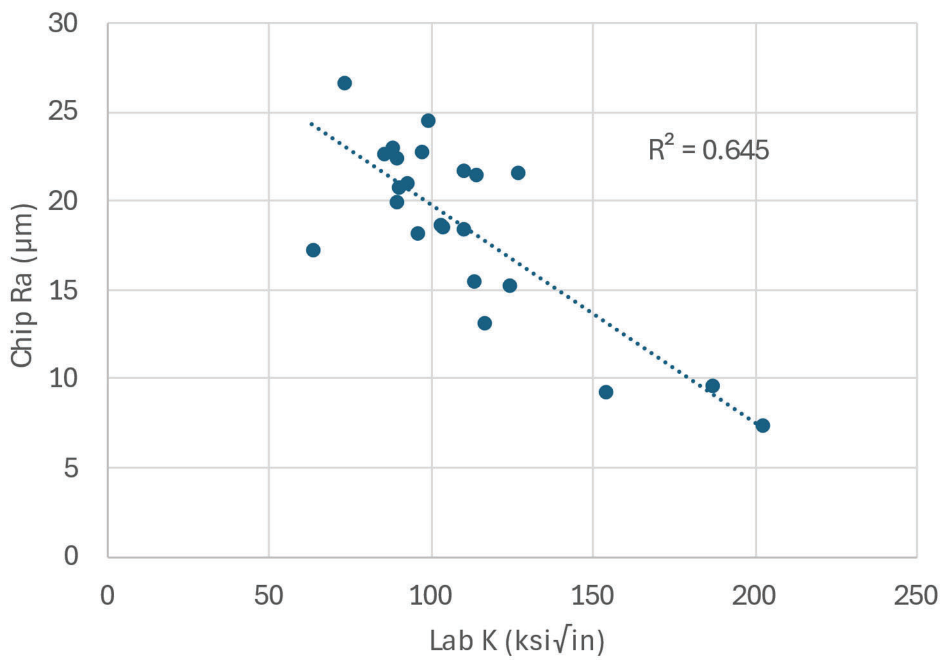

Figure 4. Correlation between R_a (y-axis) and Lab K (x-axis).

Flat Width from Cup Profile

In most cases, the cross-section of the fracture ligaments on the substrate and chip exhibits a cup and cone fracture, as normally seen in ductile fracture in tensile specimens. The width of the flat portion at the bottom of the cup profile (Figure 5) is postulated to correlate to the fracture toughness of the sample. The result is shown in Figure 6. The mechanism is further discussed in the following section with the SEM images.

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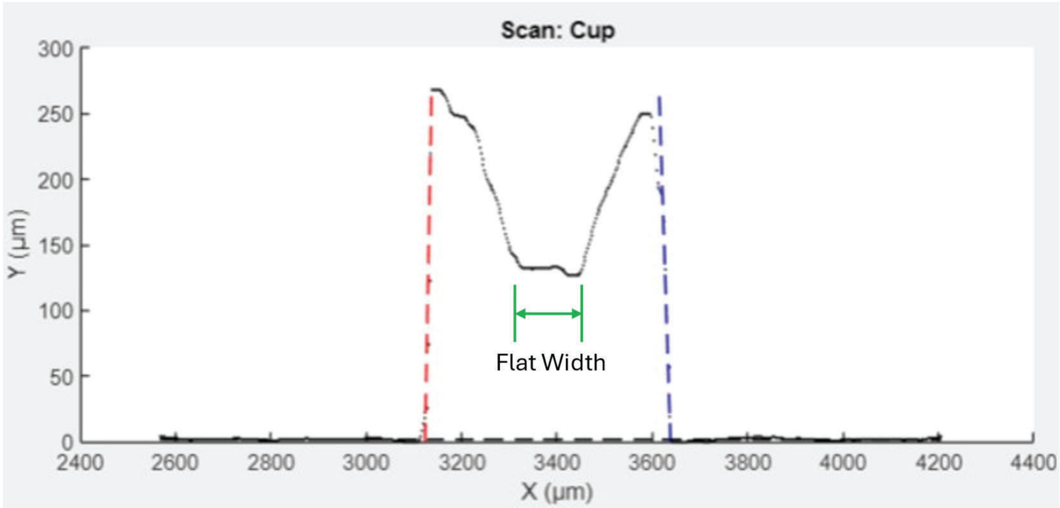


Figure 5. An example of a cup ligament profile and the flat width.

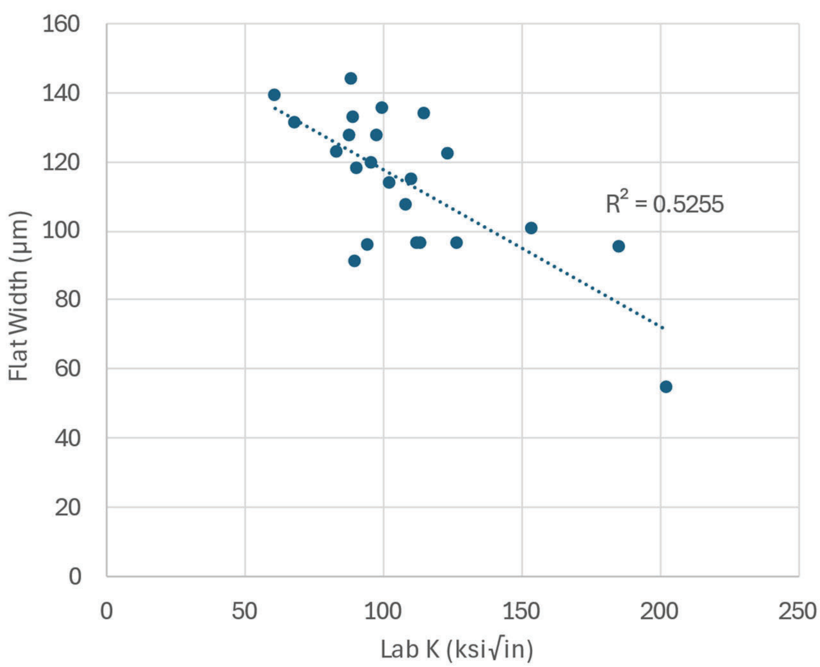


Figure 6. Correlation between Flat Width (x-axis) and Lab K (y-axis).

Ligament under Scanning Electron Microscope (SEM)

The shape of the ligament and fracture surface on the formed chips from BTM testing were examined using a JEOL JSM-6610LV scanning electron microscope at 20 kV. Figure 7 shows a set of low magnification (100X) SEM images for low, medium-low, and medium samples. The low magnification enables the observation of the overall shape of the ligament. From these images, it can be seen that the flat width of ligament profile decreases as the fracture toughness of the sample increases. This trend holds for both stretch passage widths of 0.015” and 0.020” used in the BTM testing and agrees with the correlation shown in Figure 6. The reason for this diminishing flat width may be explained in a way similar to the thickness effect in fracture toughness testing with a compact tension (CT) specimen. It is widely known that as the thickness of a compact tension (CT) specimen increases, the measured fracture toughness tends to decrease [7]. This reduction in apparent toughness likely relates to a slight change in the stress state at the crack front from a predominantly plane stress condition, where the material can yield more freely, to a more constrained condition in the direction of plane strain, where through-thickness constraint increases and the material’s ability to absorb energy before fracturing is diminished. As the toughness of the sample increases, the plane stress condition will become more dominant at the crack front, resulting in a more significant shear portion and a smaller flat portion, which is in line with the SEM observations.

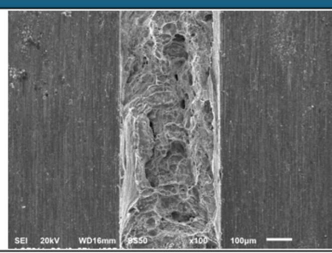
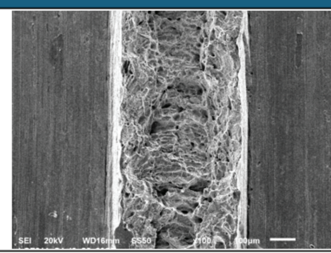
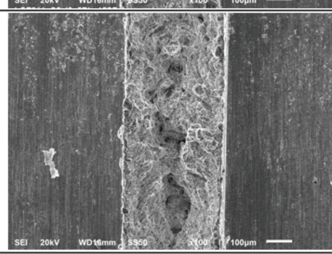
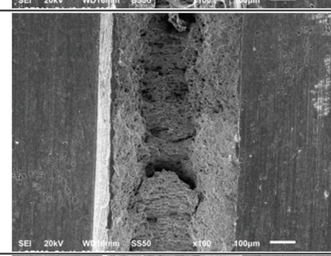
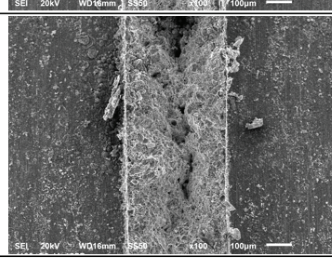
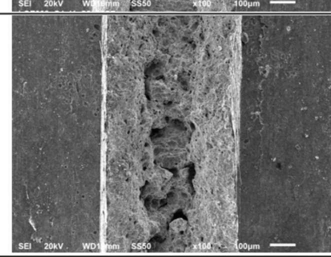
	SP Width = 0.015”	SP Width = 0.020”
Low toughness sample		
Medium-Low toughness sample		
Medium toughness sample		

Figure 7. Change of flat portion for samples with different toughness.

Fracture surfaces of the ligament are examined at a higher magnification (1000X) near the initiation of the test. The fracture surfaces, in general, display a mix of cleavage and ductile fracture characteristics, where they have regions that resemble the flat planes of cleavage fracture, as well as areas that show dimpling or microvoid coalescence typical of ductile fracture. In general, specimens with higher toughness tend to exhibit a greater proportion of ductile fracture features, as demonstrated in Figure 8.

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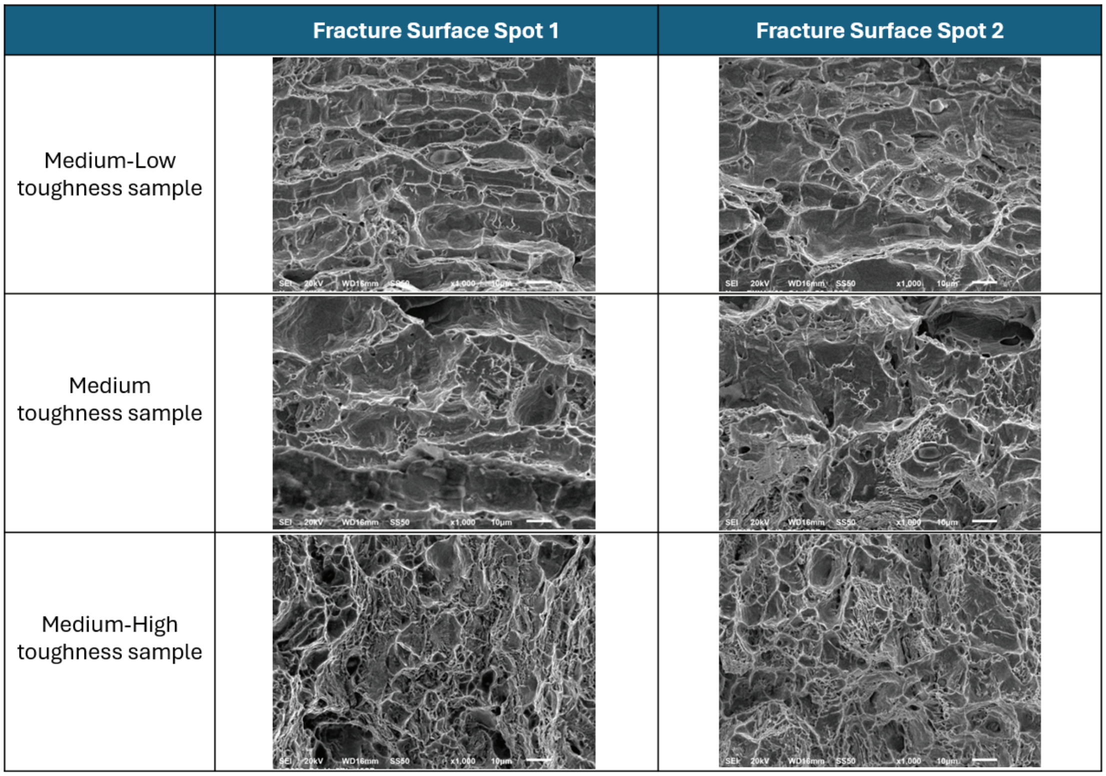

Figure 8. Change of fracture surface for samples with different toughness.

Conclusions

This paper presents preliminary test results using the new BTM field instrument. It examines the ligament features from test specimens for their correlations to fracture toughness, including ligament height, roughness, and the width of the flat fracture region at the center of the central opening of the stretch passage. Overall, these ligament features show good correlations to fracture toughness measured from destructive testing. Using SEM images of the chip ligaments, the trend of a decreasing flat width with increasing toughness is confirmed. Fracture surfaces at high magnification also reveal a trend of increasing ductility features with increasing toughness.

The level of correlation with these parameters, along with other parameters and physical modeling, is sufficient to develop prediction models. Prediction models using machine learning algorithms are currently being built and validated within the JIP program as more samples are being tested and added to the database.

References

[1] Huang, Xuejun, et al. “Validation of Planing-Induced Microfracture for Determining Pipe Body Toughness.” 36th International Pipeline Pigging and Integrity Management Conference (PPIM 2024), Clarion Technical Conferences, 2024, pp. 759–770.

[2] Parlak, Berke Ogulcan, and Huseyin Ayhan Yavasoglu. "A comprehensive analysis of in-line inspection tools and technologies for steel oil and gas pipelines." Sustainability 15.3 (2023): 2783.

[3] Pipeline Safety Research and Development (R&D) Forum 2023 Final Meeting Report, https://primis-meetings.phmsa.dot.gov/archive/MtgHome.mtg@mtg=166.html

[4] Huang, Xuejun, et al. " In-Situ Determination of Pipe Body Fracture Toughness Using Planing-Induced Microfracture Method." International Pipeline Conference. American Society of Mechanical Engineers, 2024.

[5] Barak, Yali, Ankit Srivastava, and Shmuel Osovski. "Correlating fracture toughness and fracture surface roughness via correlation length scale." International Journal of Fracture 219 (2019): 19-30.

[6] Charkaluk, E., M. Bigerelle, and A. Iost. "Fractals and fracture." Engineering Fracture Mechanics 61.1 (1998): 119-139.

[7] Anderson, Ted L., and Ted L. Anderson. Fracture mechanics: fundamentals and applications. CRC press, 2005.

https://doi.org/10.52202/078572-0066