In-Ditch Materials Verification Methods and Equipment for Steel Strength and Toughness

S.D. Palkovic[1,2], K. Taniguchi[1], and S.C. Bellemare[1,2]

[1]Massachusetts Materials Technologies, 810 Memorial Drive, St. 105, Cambridge, MA, 02139
[2]Massachusetts Institute of Technology, 77 Massachusetts Avenue, Cambridge, MA, 02139
Email: s.bellemare@byMMT.com; Telephone: (617)-502-5636

MATERIAL VERIFCATION FOR STRENGTH AND TOUGHNESS is an ongoing challenge for oil and gas transmission pipeline integrity. In this paper, we describe two portable and nondestructive technologies developed to provide this data without requiring the shutdown of operations. The Hardness Strength and Ductility (HSD) Tester probes the outer surface of a pipe to determine tensile properties. This technology has been validated for determining the steel grade and welded seam type of Electric-Resistance-Welded (ERW) pipeline materials. The HSD Tester provides a safer and cheaper alternative to hydrostatic testing for determining allowable operating pressures without the risk of additional fatigue cycles. We are also developing the Fracture Toughness Tester (FTT) which evaluates fracture resistance by generating local tension in a small volume of surface material. This will eliminate the need for expensive fracture toughness experiments and provides the first practical method for field measurements of toughness. The material verification data that these testing solutions provide will reduce uncertainty regarding the risk of catastrophic failures and help to prioritize inspections and repairs to extend the lifetime of existing pipelines.

1. Introduction

Data on steel pipeline strength and toughness supports integrity management programs to define maximum operating pressure, anomaly detection requirements, prioritize repairs, and extend service life. Technologies that measure material properties for assets in service have been developed over the past few years to support engineering critical assessment as alternatives to hydrostatic pressure testing, especially when material testing records are incomplete or cannot be matched with specific pipe joints. In-line tools have demonstrated ability to group large numbers of joints in populations having similar characteristics. Combining the high throughput capabilities of in-line tools with the precise strength and toughness measurements obtained from in-ditch technologies is an appealing concept for direct assessment programs.

Among in-ditch techniques for steel grade testing, most methods currently combine indentation hardness using Brinell or Instrumented Indentation Testing (IIT) with a combination of chemical or metallographic characterization. In general, increasing the number of parameters considered for a database of samples reduces the average error for property predictions. However, including additional parameters in machine learning leads to compounding measurement errors given varying equipment, test conditions, and personnel used to perform the testing. For example, a 2 to 5% experimental error for each physical measurement will lead to greater sensitivity of the predictive equations. Sensitivity analysis of predicting functions for material properties is therefore a powerful and necessary step for validating predictive methods [1, 2]. Additional difficulties associated with training an empirical model to a sample database include overfitting of parameters, sensitivity of individual measurements, and size of the sample set. Minimization of the predictive error over a large sample set may still yield unconservative outliers within the population.

Over the past 2 years, Massachusetts Materials Technologies (MMT) LLC has developed, implemented, and validated a mechanical-based method of precisely evaluating the hardness, strength and ductility (HSD) of steel materials. The test can be performed on any exposed surface that is quickly and easily prepared using sandpaper to remove the decarburization layer. The accuracy of the HSD Tester is achieved by a simple and robust method where frictional sliding contact is used to engage hard styluses that induce superficial grooves on the surface at targeted plastic strain levels. Measurements of the grooves are simultaneously collected using surface profilometry which are then used to predict mechanical properties. For certain applications, including the testing of vintage assets with a microstructure gradient through the thickness, HSD testing can be combined with chemistry or metallography for added confidence or redundancy.

This paper describes the progression and level of validation of the HSD tester technology. An additional, complementary, concept for the nondestructive evaluation of material fracture toughness is also introduced. Unlike prior methods which attempt to predict fracture toughness while inducing a ductile material response, our Fracture Toughness Tester (FTT) generates clear signatures of ductile fracture within a superficial surface layer of material. We discuss the fundamental concepts of our device, experimental validation on ductile metals, and future directions.

2. Hardness Strength and Ductility (HSD) Tester

2.1. Technology

The HSD Tester is a portable device that can perform measurements on an exposed pipe, fitting, or metal surface. The initial concept and fundamentals has been published through several academic journals [3-5], with more recent industry publications detailing advances in HSD technology for field applications [6-8]. Prior to testing, a 3x4 inch area of material to be tested is polished using a sandpaper-based standardized procedure which takes approximately 10 minutes. The HSD Tester is then mounted to the outer surface of the test specimen. The unit consists of an enclosure that protects internal measurement and mechanical components during field operation. This include avoiding the known effect that dust on the surface can have on the indenter surface versus pipe surface in any contact mechanic test, especially if the primary loading mode is indentation.

An overview of an HSD experiment is shown in Fig. 1. During an experiment, the HSD Tester travels around the circumference of the pipe or fitting and uses three styluses which engage with the sample material using a constant applied load. This results in three parallel grooves on the surface with a penetration depth of less than 0.001 inches allowing for the test to be considered as nondestructive. As the HSD Tester travels, a contact profilometer travels laterally behind the styluses to collect measurements of the 3 groove profiles. The ability to simultaneously collect and measure data during a test allows for immediate quality control. This includes internal checks of hardness measurements on each stylus as well as surface roughness from initial polishing. Each HSD test takes approximately 15 minutes to complete, but varies depending on the target amount of redundant test data per test.

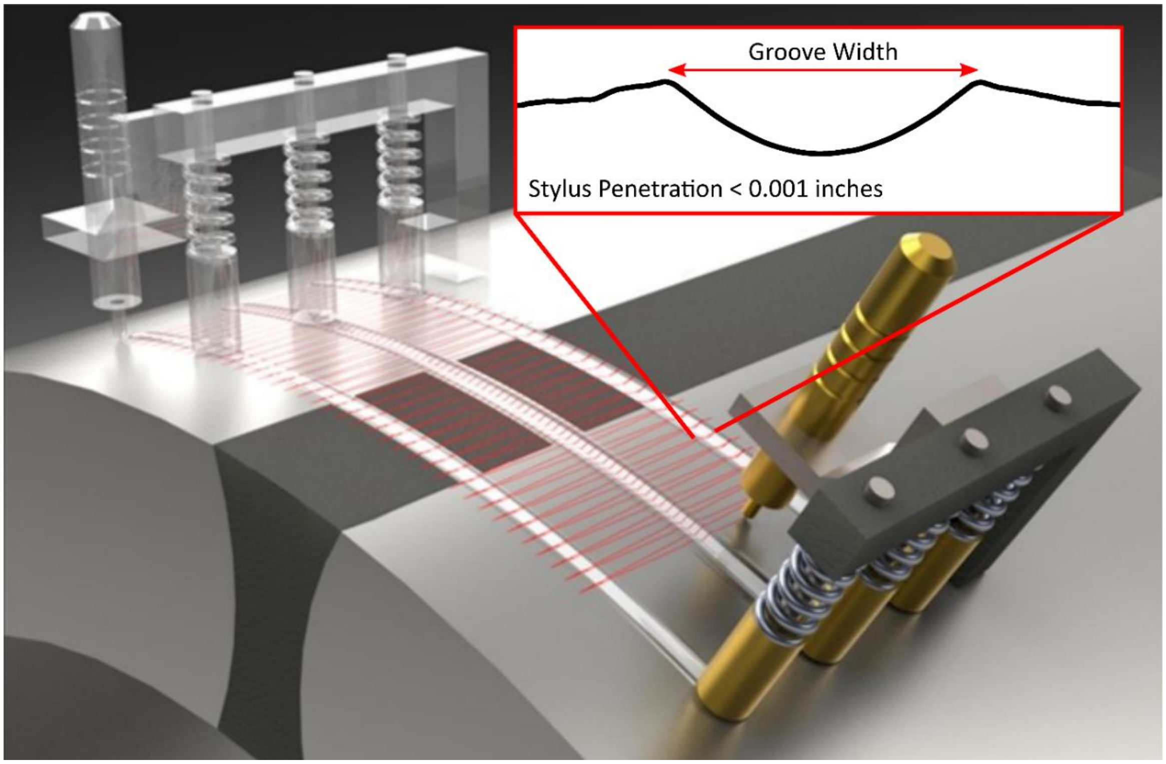

Fig. 1: Overview of the HSD tester operation across a longitudinal welded seam. Three independent styluses engage with the sample surface and generate permanent grooves that are subsequently measured using a contact profilometer that rasters behind the styluses.

Data collected from an HSD experiment is analyzed using predictive functions that are based on finite element analysis (FEA) simulations of frictional sliding processes. FEA simulations consider over 200 combinations of stylus geometries, contact conditions, and material properties to establish correlations between the dimensions of groove profiles obtained through frictional sliding and laboratory tensile tests. An overview of the concept used is described in Fig. 2. Each stylus has a geometry that is designed to probe at targeted plastic strain levels. Styluses with a larger radius and less penetration induce less overall strain in the material (see Stylus 1), whereas a smaller radius and greater penetration depth result in a higher strain magnitude (see Stylus 3). An effective stress-strain value that is representative of the measured material response can then be obtained for each stylus through principles of contact mechanics and our database of FEA simulations. A complete stress-strain curve is obtained by fitting through individual stylus measurement as shown in Fig. 2. An advantage of using multiple styluses is that it greatly reduces the sensitivity of tensile property predictions and enables the HSD tester to probe strain values of less than 2%, which cannot be achieved through indentation methods. A second advantage is that measured hardness values obtained through frictional sliding can be translated into tensile stress-strain material properties using a peer-reviewed and scientific approach utilizing dimensional analysis of finite element simulations [3-5]. Comparisons between HSD yield measurements and actual tensile test values are then used exclusively for validation, meaning there are no empirical corrections.

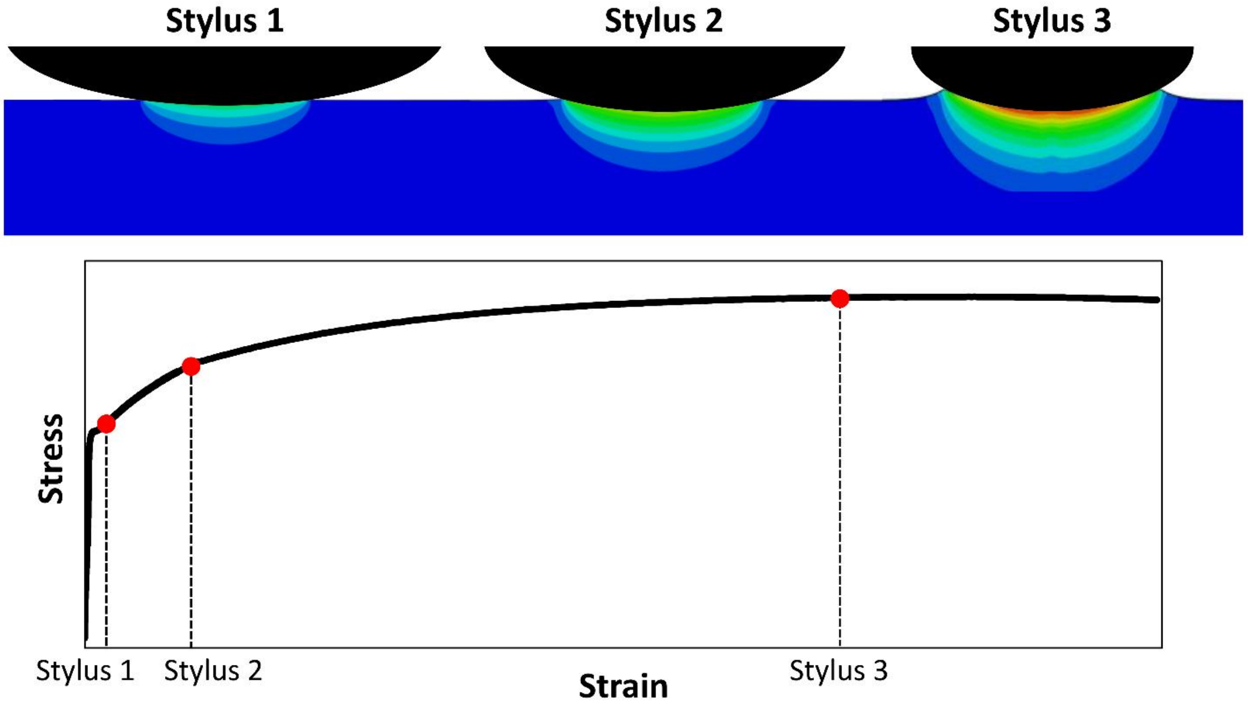

Fig. 2: Prediction method used by the HSD Tester to generate a tensile stress-strain curve. **(TOP)** The HSD Tester utilizes three styluses with different geometries that each generate a different material response as observed through finite element simulations of the plastic strain distributions beneath the stylus. **(BOTTOM)** A complete tensile stress-strain curve is fit to the stress-strain values associated with each stylus geometry.

2.2. Validation

The manufacturing of pipelines may induce gradients in material properties through the pipe wall thickness. For most electric resistance welded (ERW) pipes, a gradient exists due to the cold forming of a flat plate into a cylindrical tube. This means that material near the outer or inner diameter has experienced greater strain hardening than material near the pipe mid-wall, resulting in higher strength predictions for surface measurements measured through frictional sliding or indentation methods. This gradient in properties is reduced or eliminated for pipes that have experienced normalization through heat treatments or cold expansion after forming. Therefore, prediction of material properties with nondestructive contact mechanics is a two-step process for pipes involving,

1. obtaining an accurate surface measurement of material properties, and
2. determining whether the surface measurement needs to be corrected to account for gradients in material properties through the pipe wall thickness. These material gradients are averaged to provide a full equivalent to destructive tensile testing of full-wall specimens

To validate our methodology, we use both homogeneous and full-wall pipe specimens, and compare the HSD predictions of yield strength to the destructive tensile test results. Homogeneous samples have no gradients in properties through the thickness, allowing us to directly compare the accuracy of HSD measurements with tensile tests To obtain homogeneous samples of pipe materials we remove a tensile coupon from the mid-wall of the pipe sample where strain hardening has not influenced the strength properties. Our results for yield strength prediction for 15 different steel materials is shown in Table 1. The range error compares the average HSD tester to the range of tensile yield strength values obtained from two or more test samples per condition, taking account the variability of the standard measurement technique. The absolute value of the average error for homogeneous samples is approximately 3.3%.

Table 1: Validation of yield strength prediction for homogeneous materials. Pipe samples were obtained from the mid-wall (MW), and plate specimens are designated “flat”.

Sample	Type	Tensile Test 0.5% YS (ksi)			HSD Test 0.5% YS (ksi)			Range Error	Average Error
		Min.	**Max.**	**Avg.**	**Test 1**	**Test 2**	**Avg.**		
08T2	Midwall	34.4	40.3	37.0	38.3	35.8	37.0	0.0%	0.0%
F004	Flat	43.3	43.5	43.4	40.1	41.9	41.0	-5.3%	-5.6%
24T2	Midwall	43.4	44.5	44.0	45.8	46.7	46.2	3.9%	5.2%
12SLF	Midwall	43.3	47.7	45.5	46.0	45.9	46.0	0.0%	1.0%
14GRB	Midwall	42.8	51.7	47.3	50.7	48.0	49.4	0.0%	4.4%
12Y64	Midwall	49.4	50.5	50.3	51.8	50.3	51.1	1.1%	1.6%
18GRB-B	Midwall	50.6	53.7	52.2	51.5	52.0	51.8	0.0%	-0.8%
F001	Flat	53.5	54.0	53.8	53.8	55.5	54.6	1.1%	1.6%
16X42	Midwall	54.1	58.0	55.7	58.0	57.0	57.5	0.0%	3.2%
F015	Flat	56.1	56.9	56.5	59.8	58.5	59.1	3.9%	4.6%
10SHF	Midwall	64.1	66.0	65.0	60.8	63.0	61.9	-3.4%	-4.8%
16GRB	Midwall	69.8	70.2	70.0	72.1	69.9	71.0	1.1%	1.4%
16X52	Midwall	68.5	73.8	70.8	64.9	--	64.9	-5.3%	-8.4%
F005	Flat	70.6	72.7	71.7	68.9	71.3	70.1	-0.7%	-2.2%
T3011	Midwall	72.5	73.0	72.7	69.6	70.0	69.8	-3.7%	-4.0%

After validating the accuracy of surface measurements, we can test on the outer surface of pipe materials and apply a surface-to-bulk correction, if necessary. The bulk value is associated with what is obtained from a tensile test conducted on a full-wall thickness specimen. Our surface-to-bulk correction accounts for the strain hardening of bending a flat plate into a cylindrical tube [7]. Our results for yield strength prediction of 16 different steel materials and the corresponding full-wall thickness tensile tests are shown in Table 2. The absolute value of the average error for pipe samples is approximately 4.0%.

Table 2: Validation of yield strength prediction for pipe samples. HSD experiments were performed on the outer surface of pipe specimens.

Sample	**Tensile Test 0.5% YS (ksi)**			**HSD Test 0.5% YS (ksi)**			**Range Error**	**Avg. Error**
	Min	**Max**	**Avg.**	**Test 1**	**Test 2**	**Avg.**		
12SLF	43.3	47.7	45.5	47.2	47.6	47.4	0.0%	4.2%
14GRB	42.8	51.7	47.3	45.9	48.2	47.1	0.0%	-0.5%
22SLF	49.7	49.9	49.8	47.4	--	47.4	-4.5%	-4.8%
12Y64	49.4	50.5	50.3	48.3	49.0	48.7	-1.5%	-3.3%
16SLF	51.1	53.9	52.6	53.7	--	53.7	0.0%	2.2%
16X42	54.1	58.0	55.7	55.1	55.6	55.3	0.0%	-0.7%
08SHF-2	57.0	57.2	57.1	56.4	--	56.4	-1.0%	-1.2%
08SHF-1	64.2	64.9	64.6	68.9		68.9	6.2%	6.7%
16GRB	69.8	70.2	70.0	63.8	62.7	63.3	-9.4%	-9.6%
16X52	68.5	73.8	70.8	--	74.3	74.3	0.7%	5.0%
22SLF-2	49.1	49.1	49.1	53.3	51.2	52.3	6.4%	6.4%
16Y69-1	57.8	57.8	57.8	61.8	--	61.8	6.9%	6.9%
19Y72-1	63.1	63.1	63.1	64.1	--	64.1	1.7%	1.7%
20Y68-1	53.5	53.5	53.5	48.5	53.8	51.1	-4.4%	-4.4%
26Y52-1	58.5	58.5	58.5	54.3	56.8	55.5	-5.1%	-5.1%
20X42-1	58.8	58.8	58.8	57.6	62.4	60.0	2.0%	2.0%

For our work so far, the justification for applying a surface-to-bulk correction on ERW pipes is based on an additional test across the longitudinal welded seams. A unique capability of the HSD tester is to continuously measure the material response with sub-millimeter spatial resolution. This allows for the identification of low-frequency (LF) or high-frequency (HF) welding processes, as well as the identification of normalization or cold expansion during manufacturing. Fig. 3 shows weld profiles performed on a LF, HF, and HF normalized pipe sample. The HF pipe that is not normalized shows significant spikes in hardness associated with the heat-affected-zones, which are not visible for the normalized pipe. The LF process results in a much wider fusion pool compared to HF samples.

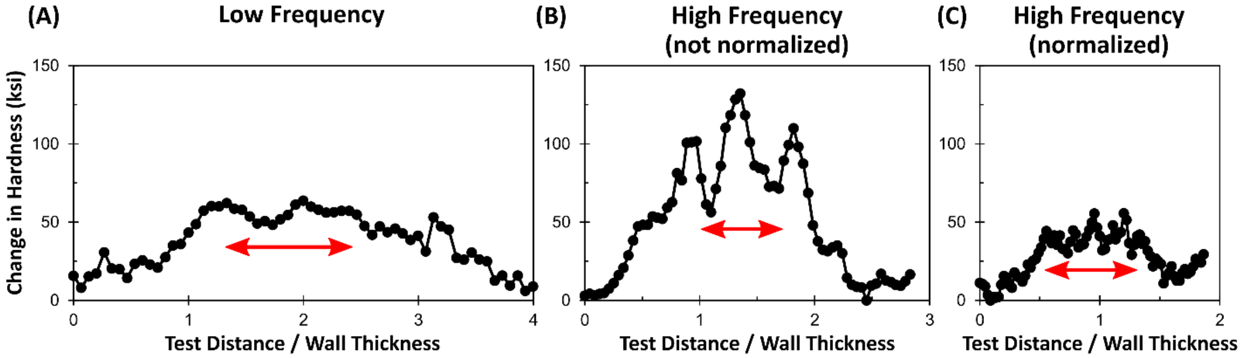

Fig. 3: Hardness profiles across the longitudinal seam for **(A)** low frequency (LF), **(B)** high frequency (HF), and **(C)** HF normalized. The relative size of the weld pool is shown by the red arrows.

2.3. Next Steps

Over the past year, we have tested more than a hundred pipes and fittings using our fourth generation HSD Tester. Our testing unit has undergone multiple design iterations that have greatly improved accuracy, reliability and ease-of-use. These changes include the addition of a third stylus, automation of stylus engagement loads and construction of a protective enclosure. We are currently working on our fifth-generation HSD tester. This unit features a re-design of stylus geometries to enable the testing of high strength steel (>100 ksi) and improve the accuracy of ultimate tensile strength predictions. We are also incorporating a fourth stylus that will used to directly probe for gradients in material properties and to add an additional method of redundancy and quality control.

In parallel, we are developing a method which includes chemistry and metallurgical data with our mechanics based strength prediction software. Unlike "black-box" algorithms which weight multiple measurement techniques using a single predictive equation, our implementation will be used to evaluate whether chemical or microstructure gradients exist through the wall thickness. We have found that these conditions exist for some assets manufactured prior to the 1960s, and these effects can be accounted for by determining whether there is a chemistry or microstructure gradient in additional to the forming-induced work hardening, or by applying a reduction factor to the yield strength value to provide a conservative lower bound when the material already exceeds minimum requirements by a sufficient margin. These steps will enable the HSD tester to be the most reliable and accurate nondestructive testing tool for field measurements.

3. Fracture Toughness Tester (FTT)

3.1. Technology

We are developing a Fracture Toughness Tester (FTT) that utilizes a contact mechanics based approach to generate fracture processes within a superficial layer of surface material in-situ. . Fracture toughness measurements are often needed in fitness for service to determine the maximum allowable flaw size or burst pressure of a pipeline. These properties traditionally require the use of large-scale laboratory experiments where a standardized sample of material is tested to failure, including expensive instrumented compact test (CT) or single-edge notched beam (SEB) specimens, as well as semi-empirical methods like Charpy impact testing. The FTT would greatly reduce the need for removing large material samples for destructive testing, and would allow for simple testing of directional dependence of fracture properties. Combined with the strength predictions from the HSD tester, the two technologies can provide valuable mechanical data to pipeline asset verification.

The fundamentals of the FTT are described in Fig. 4. The FTT uses a specially designed stylus to generate a loading condition that is primarily in tensile Mode-I. This is accomplished through a wedge-shaped geometry that includes a narrow opening, which we refer to as a stretch passage (Fig. 4A). During an experiment, material flows up the front-face of the wedge like a traditional machining tool, resulting in a chip that separates from the material. However, material within the stretch passage is not sheared by the sharp cutting edge of the stylus, but stretches as the surrounding material flows up the stylus (Fig. 4B). This results in the tensile fracture of material within the stretch passage, and the formation of a ligament that remains on the machined surface and preserves features of the fracture process, (Fig. 4C) including the amount of plastic deformation in tension that the steel was able to undertake before micro void formation and coalescence that are precursors to a ductile fracture.

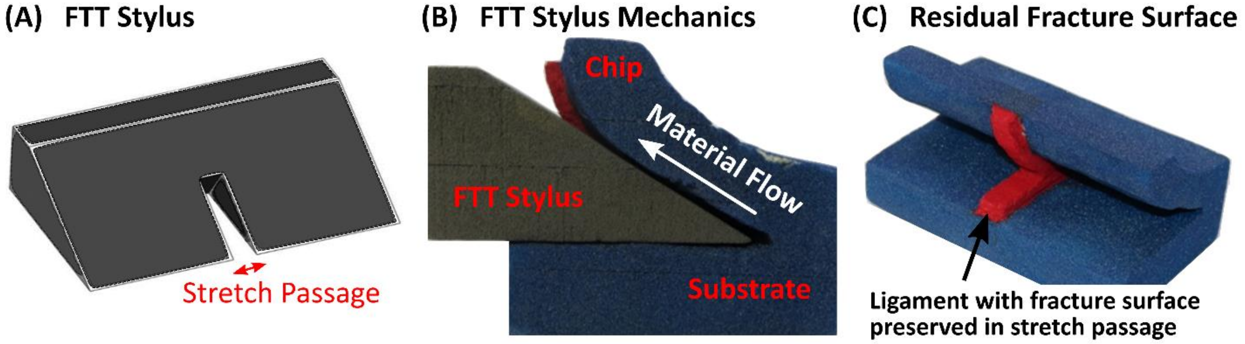

Fig. 4: An overview of the FTT stylus and operation. **(A)** The FTT stylus utilizes a stretch passage within an inclined wedge to generate tension and fracture during a contact mechanics test. **(B)** During a test material is forced to flow up the inclined wedge of the stylus, resulting in a chip that separates from the substrate through a machining process. However, material contained within the stretch passage is subjected to a tensile stretch that results in a Mode I opening fracture process. **(C)** When the stylus is removed, a fracture surface is preserved on a ligament remaining on the machined substrate surface as well as the opposing face of the chip that has separated from the substrate.

We have successfully completed FTT experiments on a 6061-T6 aluminum and 1020 steel material. The test results are shown in Fig. 5 for the steel sample. An SEM microscopy image of the fracture surface provides clear evidence of void growth and coalescence that are signatures of tensile fracture in ductile metals. Our initial experiments were conducted using a modified milling machine using a lathe tool with a machined stretch passage for the FTT stylus. MMT is seeking additional support of the R&D work to accelerate the FTT technology development.

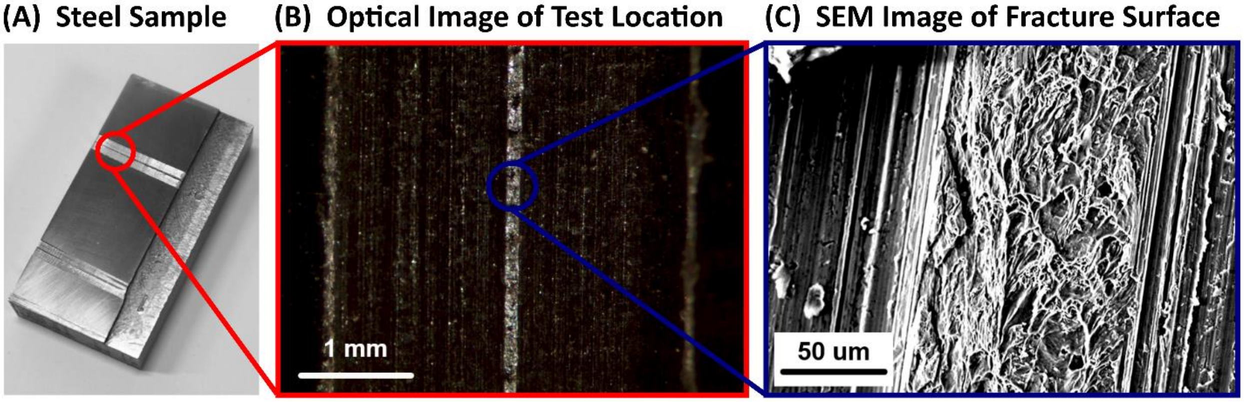

Fig. 5: Experimental proof-of-concept of the FTT. **(A)** A 1020 steel specimen was tested with a cut depth of 0.005 inches and stretch passage width of 0.002 inches. **(B)** An optical microscopy image of the cut surface showing the ligament preserved by the stretch passage. **(C)** An SEM image of the fracture surface that remains on the ligament shows indications of ductile fracture processes.

3.2. Simulation-Based Validation of the FTT

To complement the experiments completed with the FTT tester, we have developed a FEA simulation of ductile fracture using established analysis approaches. We utilize the software Abaqus with a Bao-Wiezbicki tensile and shear failure criterion that has been validated for a high strength aluminum alloy [9, 10]. These analyses implement continuum damage mechanics to simulate fracture. Our explicit FEA model captures the essential features that are observed through FTT experiments, as shown in Fig. 6. We observe a ligament that has a height which is strongly dependent on the yield strength, strain hardening exponent, and fracture toughness of the simulated material. This model will help us to better understand the mechanics of our device, benchmark stylus geometries, and potentially establish correlative functions. We are also able use FEA to assess the degree of triaxiality for material within the stretch passage. Fig. 7 shows that the stress state for a material that flows through the FTT stretch passage consists of significant triaxial tension. A larger magnitude of triaxial tension is consistent with transitions from plane stress to plane strain fracture conditions.

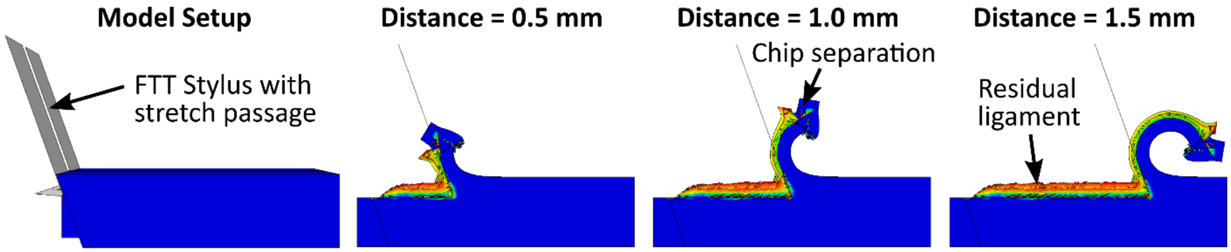

Fig. 6: Three-dimensional FEA model of fracture processes using a Bao-Wiezbicki damage model for a ductile aluminum alloy. Elements are colored by their scalar damage index. The height of the residual ligament remaining on the cut surface is dependent on the fracture and plastic properties of the material.

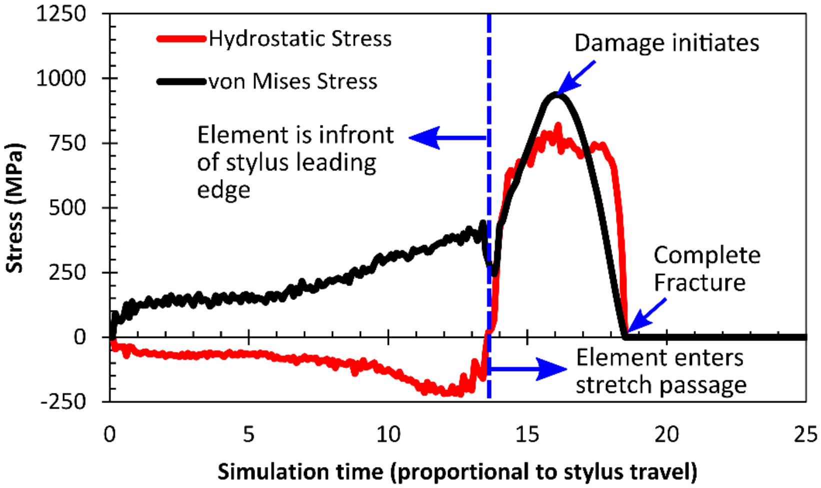

Fig. 7: Evolution of stress state for an element within the material ligament as predicted by FEA. The hydrostatic stress is associated with volumetric stress components, whereas the von Mises stress is a tensile equivalent of deviatoric stress components. The element transitions from a compressive to triaxial tensile stress state when it enters the stretch passage, until failure occurs.

4. Conclusions

The Hardness, Strength, and Ductility (HSD) Tester technology is a testing solution that is commercially available to provide mechanical testing solutions for steel pipe and fittings. The HSD Tester provides more information and greater accuracy than competing technologies because it utilizes multiple styluses at varying strain magnitudes including closer to the yield point than any alternate means, has higher spatial resolution for characterizing welded seams, and utilizes welded seam test results to determine whether a surface-to-bulk correction is required. Ongoing refinement to the testing unit and methodology, including the optional use of chemistry and metallographic testing, will allow for assessment of vintage assets that may have gradients in chemical composition or microstructure.

The Fracture Toughness Tester (FTT) technology is an innovative, nondestructive method for determining fracture toughness. We have successfully completed proof-of-concept testing, demonstrating that the FTT can induce ductile fracture on a superficial layer of material, and developed FEA simulations to understand and optimize the test method.

The successful development of innovative technologies often require industry support. One of the key issues for pipeline materials is the through-wall material variations of vintage assets, which is well known but has yet to be fully studied to quantify the effect and take the steps needed to fully address it. Without quantifying variations and establishing the bounds of the correction needed for gradients through the thickness, we believe it would be risky to rely on field NDE measurements on vintage assets using any testing method that is targeting an accuracy of plus or minus 10% versus tensile tests with vintage assets. Although many operational margins would be significantly greater than 10% of the maximum allowable service pressure, intrinsic variation between joints of the same line adds to the NDE measurement accuracy for a total interval of confidence. The continued engagement and support of industry participants is paramount to enabling the benefits of any technology innovation, including the HSD Tester and the FTT, and to solving key issues that face the industry. Many technologies are emerging for potential use with integrity management of pipelines in general. With continued partnership we hope to help enable engineering critical assessment (ECA) based on in-ditch NDE as a reliable and standardized method for pipeline assets.

Acknowledgements

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