A portable NDT device for mechanical properties of pipelines during integrity digs

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THERE IS A PRONOUNCED NEED for the development of new in situ mechanical testing techniques for oil and gas pipelines. As PHMSA's Integrity Management Program (IVP) for undocumented pipes moves towards implementation, a tool for rapid, accurate field measurements of mechanical properties becomes critical. The technology for mechanical testing of materials has changed very little since the 1950s, when commercially available universal tensile testing machines and hardness testers became ubiquitous. These techniques still dominate because they are inexpensive, easy to operate, and reliable. However, they are limited in their utility in the field, especially during integrity digs. Tensile testing can only be carried out in a laboratory, and in the case of pipelines requires a shutdown of operations for sample removal and subsequent repairs. Hardness testing is portable, but does not present stress-strain tensile data required for design and exhibits high variability when predicting strength properties. Hardness testing also suffers in that it is a point measurement, lacking in spatial resolution. Instrumented indentation techniques based on hardness testing, such as automated ball indentation (ABI), require testing at several locations to produce a single result. There is a need for portable nondestructive predictions of the true mechanical properties: strength and ductility.

In this paper we present the Hardness, Strength, and Ductility (HSD) Tester; a new tool for accurately determining the mechanical properties of pipelines in the field, through a non-destructive measurement on the surface of the pipe. The HSD Tester is based on a contact mechanics technique known as frictional sliding. The HSD Tester creates approximately 30 micron deep grooves in the outer diameter of a pipe by sliding two styluses, with known geometries, across the surface at a fixed load. The response of the material, specifically the profile of the shallow groove that remains after a test, is directly related to the mechanical properties of the material being tested. Any any point along the groove, the HSD Tester can generate hardness data and the full uniaxial stress-strain curve for the material, including yield strength, ultimate tensile strength, and strain hardening exponent. The HSD Tester is able to provide the same data and accuracy as typical uniaxial tensile testing, but through a non-destructive and portable testing method.

Due to stresses from pipeline manufacturing, the surface measurements obtained through contact mechanics differs from the averaged bulk response measured through tensile tests performed according to API 5L. In our previous publications [1, 2], we have outlined the development of our method for correlating the bulk pipeline properties to surface measurements made with the HSD Tester. The data in these prior studies was gathered with a prototype utilizing a single stylus geometry. It is well known in the field of contact mechanics that using two different stylus (or indenter) geometries greatly enhances the accuracy of the measurement by comparing the material response under varying contact conditions [3]. This paper introduces our work to date using two stylus geometries: a 145 degree cone and a 14 mm diameter sphere. These geometries induce different amounts of strain in the tested material at a given load, and allow us to more accurately measure the stress-strain behavior of pipeline materials. Our experimental data includes two-stylus surface measurements of annealed 4130 steel, base metal of an HF ERW pipe, and base metal of an LF ERW pipe. Additionally, we tested three LF ERW pipes of various diameters and wall thicknesses. These samples were measured by creating grooves across the full wall thickness of mounted and polished sections of pipe material, in an effort to measure the change in mechanical properties across the wall thickness as a function of strain hardening from manufacturing.

Background of HSD Tester technology

The HSD Tester is a portable, non-destructive apparatus capable of generating a uniaxial stress-strain curve for metals through frictional sliding tests along a material surface. The device is intended for in-field condition assessment, grade verification, and measurements of gradients in properties across seam and girth welds. Our current instrument is seen in Figure 1, configured to test the welded seam of a low-frequency electric resistance welded (LF-ERW) pipe. To perform a test, two styluses, one spherical and one conical, are i) guided to remain perpendicular to the surface of the pipe using our self-aligning HSD core, ii) engage with the sample surface through a constant applied load, and iii) travel across the pipe surface at a constant velocity applied by our drive system to generate a permanent groove. The HSD Tester self-aligns with the curved test surface using a patent-pending apparatus and method. The device also simultaneously measures and characterizes the resulting groove profiles during a frictional sliding test via contact profilometry. A representative groove can be seen in Figure 2, which is 30 microns deep in a high strength steel. This penetration depth, according to ASME B31G [4], would produce a strength reduction of 0.1% allowing the HSD Tester to be considered non-destructive.

Figure 3 shows test data obtained from the HSD Tester with a single conical stylus across a butt-welded joint of low alloy 4130 steel [1, 2]. Here, the HSD Tester clearly identifies and characterizes the transitions from base metal, heat-affected-zone (HAZ) and filler metal. The advantage of fictional sliding is that a stress-strain curve can be generated for any measurement along the groove. As a result, this technique does not suffer the resolution limitations and spacing requirements associated with indentation methods. In the petroleum industry, these qualities make the HSD Tester ideal for pipeline grade verification, weld testing, and operator integrity management programs.

The two plots in Figure 3, hardness and pile-up ratio, are the data outputs from the HSD Tester. These outputs are used to calculate the entire stress-strain curve for a material, according to previously published methods [5]. Hardness is a function of the width of the groove left by the stylus, and pile-up ratio (an indicator of ductility) is the ratio of the depth of the groove to the height of the "peaks" at the edges of the groove, as seen in Figure 2. On their own, these plots show a distinct increase in hardness, and decrease in ductility, through the HAZ. Using these data, the HSD Tester measured the yield strength of the 4130 base metal to be 52 KSI [1]. In traditional tensile testing of the same material, we found yield strengths to be 51 KSI (at 0.1% offset) and 53 KSI (at 0.2% offset). The HSD Tester measured the strain hardening exponent (n) to be 0.17, while tensile testing produced an n value of 0.16. The difference in yield strength and strain hardening exponent values produced by the HSD Tester and tensile testing, in this case, are within the range of error for traditional laboratory tensile testing.

Surface measurements for bulk mechanical properties

The HSD Tester is able to produce bulk mechanical data for pipeline materials by combining the data gathered from grooves made on the surface of the pipe with Finite Element Analysis (FEA) of pipeline forming and manufacturing processes. As validation, we performed a study of a 12.75 inch OD, 0.25 inch wall thickness low frequency (LF) electric resistance welded (ERW) pipe provided to us by PRCI, sample UIN 583.B. Using a single stylus, the HSD Tester measured the yield strength at the surface of the pipe to be 59 KSI. Combined with FEA analysis, the HSD Tester predicted a bulk yield strength of 46.5 KSI for the full pipe wall. Traditional tensile testing produced a yield strength of 46 KSI for the LF-ERW material [2].

FEA allows for insight into how manufacturing effects a pipe's mechanical properties. In our study of this LF-ERW pipe, we found that hardness varied across the thickness the pipe wall. According to the trend seen in Figure 4, hardness increases towards the OD and ID of the pipe, and is at a minimum at the mid-wall. While there could be various reasons for changes in hardness through the wall – including grain size effects or elemental segregation – we found that the behavior was dominated by strain hardening. In all LF-ERW pipes we have had the opportunity to observe, we find that hardness changes across the wall thickness of pipes are due predominantly to cold forming, and not variations in grain size or chemistry. In the LF ERW process, flat steel plate is formed into a pipe by cold bending the material in incremental steps until a cylinder is formed. The seam is then welded. This cold bending strain hardens the material, which is maximized at the OD and ID of the pipe wall, and minimized at the mid-point of the wall.

In Figure 5, the magnitude of plastic strain due to manufacturing and forming of the 12.75 inch OD, 0.25 inch wall thickness pipe, is plotted by color. The dark blue areas near the neutral axis are not plastically strained; meaning this material remains within the elastic limit of deformation of steel and no strain hardening would occur in this zone. The lighter blue through green areas show increasing strain. Here, strain increases nonlinearly from the mid-wall outwards to both the OD and ID, where the strain will reach maximums at both outer surfaces. This means that strain hardening effects would increase towards the OD and ID, and that these surfaces would be significantly harder, with a higher yield, than the "blue" core, which is approximately 0.075" thick in this case. By measuring the tensile properties of samples milled from this 0.075" non-strain-hardened core, and using this as an input to our FEA model, we were able to plot how yield strengths will change across the wall thickness of this particular size pipe. These calculated yields strengths are seen in Figure 6.

The power of the FEA model developed to create Figure 6 is that it allows for the prediction of mechanical properties at any point across the thickness of a pipe wall, given knowledge of the properties at any other particular point. If one knows the properties at the core, you can accurately predict the properties at the surface, or at any location from OD to ID. Likewise, by measuring the properties at the surface with the HSD Tester, we can then predict the properties through the entire wall thickness. This is how we are able to produce bulk properties of the full thickness pipe wall with a 30 micron deep surface measurement. In our experience, the yield strength at the mid-wall of the pipe dominates the tensile behavior, and the bulk yield strength and mid-wall yield strength are approximately the same. This relationship will be further established in the future through a combination of FEA models and tensile experiment validation.

Fundamentals of the dual stylus technique

To date, the HSD Tester and frictional sliding method has been proven to predict mechanical properties with excellent accuracy. The results in Figure 7 are from prior tests on copper, brass, nickel, aluminum and steel materials reported in prior publications [1, 5], and shows the correlation with traditional laboratory tensile tests. Despite this performance, we have recently configured our HSD Tester to perform dual stylus experiments [2]. This change in hardware will allow us to further reduce our experimental sensitivity and improve the accuracy of predictions in field environments. This is because the use of two styluses with dissimilar geometries allows us to generate the desired material response by modifying the representative strain through principles of contact mechanics.

The concept of representative stress and strain has been used for over 50 years, and is an indication of the overall local deformation induced in a material during an experiment [6]. The representative strain is a function of the stylus geometry and loading condition. For a conical stylus, a smaller included angle induces a greater magnitude of representative strain. For a spherical stylus, the representative strain changes along with the depth of penetration based on the local angle of attack formed by the spherical surface and undeformed material. These concepts are demonstrated in Figure 8A, where the plastic strain distribution from finite element analysis (FEA) simulations of a conical and spherical stylus are shown. For the same material and contact conditions, the conical stylus with a larger attack angle will experience a significantly higher representative strain, as reflected by the greater magnitude of equivalent plastic strain (PEEQ) and wider PEEQ distribution for a similar contact depth. We can use these concepts to our advantage when making predictions with our HSD Tester.

Figure 8B shows a schematic of a uniaxial stress-strain curve for a typical metal or alloy. Our original single stylus approach with a conical tip utilized one representative stress value to determine predictive functions that accurately describe the entire stress-strain behavior [5,7,8]. By using two styluses with dissimilar geometry, we can measure the material response at two representative strains, near the ultimate tensile strength (high strain) and near the initial yield behavior (low strain). This additional information allows for a more accurate fitting of the stress-strain curve and improved prediction of mechanical properties. A similar approach was utilized for instrumented indentation and resulted in a decrease in sensitivity of up to 80% when compared to the single stylus approach [3]. The sensitivity of the current frictional sliding prediction equations is already more than 5x lower than the dual stylus technique for instrumented indentation due to the larger value of representative strain induced in the material [3, 5]. This will be further improved through our dual stylus technique.

Results from the two-stylus HSD Tester

We have recently tested our system in an attempt to validate the improvements provided by developing a two-stylus system. In all tests we utilize a 14 mm spherical stylus, and a 145 degree conical stylus, as described in Figure 8A. The data presented here reflect the current state of our data analysis. Full analysis, including prediction of bulk yield strengths, ultimate tensile strengths, and strain hardening exponents, and error will be presented in a future publication. For these experiments, we conducted surface measurements of the base metals of the previously discussed normalized 4130 plate, a 12.75” OD, 0.25” wall thickness LF ERW pipe, and a normalized ASTM HF ERW pipe of 10.75” OD and 0.375” wall thickness. We also performed measurements across mounted and polished sections of the full wall thickness of three LF ERW pipes, to measure the change in properties across the wall. These include: Sample 1 with a 16” OD, 0.264” wall; Sample 2 with a 16” OD and a 0.267” wall; and Sample 3 with 8.625” OD and a 0.222” wall thickness.

Surface measurements of 4130, LF ERW pipe, and HF ERW pipe

The current surface measurement data for the two-stylus HSD Tester on 4130, LF ERW pipe, and HF ERW pipe are tabulated in Table 1.

	4130	LF ERW	HF ERW
Tensile yield strength (KSI)	53	61*	64
HSD yield strength (KSI)	55	56	-
Tensile ultimate strength (KSI)	78	69*	78
Tensile (n)	0.14	0.09	0.12
Hardness: sphere (MPa)	1505	1445	1432
Hardness: cone (MPa)	2120	1728	1811
Hardness delta (MPa)	615	283	379

Table 1: Comparison of data produced via tensile testing and the two-stylus HSD Tester. Hardness values were produced with the HSD cone and sphere styluses. * denotes tensile properties at the surface of the pipe that were predicted from FEA modeling with inputs from tensile testing.

As seen in table 1, the predicted yield strength of the normalized 4130 plate, with the two-stylus HSD Tester, is 55 KSI. This represents a 3.7% error from the laboratory tensile yield strength of 53 KSI. Tensile testing also resulted in an ultimate tensile strength (UTS) of 78 KSI, and a strain hardening exponent (n) of 0.14. This means that of the three samples tested, the 4130 has the greatest degree of strain hardening. Although we have not yet run the full analysis of the HSD Tester data to predict UTS and n using our methods, the hardness data generated by the cone and sphere styluses follow the general trend of the 4130 strain hardening. The sphere, at very low strain values, produces a hardness of 1505 MPa, while the ~33% strain cone shows significant strain hardening at 2120 MPa.

For the LF ERW pipe surface, we predicted a surface yield of 61 KSI, as previously described. [2] The two-stylus HSD Tester produced a measurement of 56 KSI, which is approximately 8% error. This LF ERW material is the least strain-hardening of the three test samples, with an n value of 0.09, and an increase from 61 to 69 KSI from yield strength to UTS. Like in the 4130 case, this trend is reflected in the hardness data gathered from the sphere and cone styluses. The low strain sphere stylus measures a hardness of 1445 MPa, while the high-strain cone produces a hardness of 1728 MPa. The delta for these values marks the lowest change in hardness of the three samples, as would be expected for the sample with the lowest n.

The HF ERW sample has not yet been analyzed enough to produce a yield strength from the HSD Tester. The hardness data gathered via HSD again matches the expectations set by the strain hardening exhibited in tensile testing. Among the 3 samples tested, the HF ERW material was second in terms of strain hardening with an n of 0.12. Accordingly, the difference between the cone and sphere hardness data was the second greatest, with a delta of 379 MPa.

Data from full wall thickness measurements of three LF ERW pipes

Three samples of LF ERW pipe were subjected to HSD testing across their wall thicknesses. As seen in Figure 9, this process involves removing a circumferential sample from the pipe wall. The sample is then mounted on edge, so the full wall thickness is exposed, and then polished. The HSD Tester was then used to perform a frictional sliding test across the wall. Because of the transition within the mounts from a relatively soft thermoset resin and the hard metal, we were unable to measure across the entire OD to ID span. Grooves were produced as close to the edges as possible. Here, we present hardness values measured by the cone and sphere styluses on pipe cross sections.

Figures 10, 11, and 12 display the hardness data gathered from the spherical and conical tips of the HSD Testers, when run across the wall thickness of the pipe samples. Sample 1 is a 16” OD pipe with a 0.264” wall; Sample 2 is a 16” OD pipe with a 0.267” wall; and Sample 3 is 8.625” OD pipe with a 0.222” wall. All are LF ERW. As was the case with the 4130, LF, and HF ERW samples previously discussed, the lower strain sphere stylus exhibits lower hardness in all three cases, while the higher strain cone stylus shows higher hardness values. Also in all three cases, we see the lowest values of hardness at roughly the midwall of the pipe, and slight increases in hardness from the mid-wall towards the edges. This is particularly evident when looking at the trends from the midwall towards the inner diameter (ie towards the right of the graphs). This mirrors the behavior illustrated in Figure 4, where strain hardening from cold forming during the manufacture of the pipe creates increasing hardness and yield strengths from the center to the OD and ID.

The data analysis of these measurements has not been completed, so we do not yet have predictions for yield strength, ultimate tensile strength, and strain hardening. However, we can make some early conclusions by looking at the hardness data qualitatively. The delta between the cone and sphere hardness values is greatest for Sample 1 (Figure 10), and roughly equal for Samples 2 and 3 (Figures 11 and 12). This would suggest that Samples 2 and 3 are of equal strain hardening exponent n, and that Sample 1 exhibits significantly higher strain hardening behavior. The magnitudes of the hardness data suggest that Sample 1 is of higher yield than Sample 2, due to the fact that the pipe sizes are roughly the same and Sample 1 has higher hardness. Sample 2 and Sample 3 have roughly equal hardness values, but Sample 3 is a much smaller OD. Therefore, we expect strain hardening from cold forming of the pipe to have a greater effect on the surface hardness of Sample 3. Given equal hardness values, and greater strain hardening effects, Sample 3 would be expected to have the lowest bulk yield strength of the three though wall samples.

Conclusions

The HSD Tester and the frictional sliding technique are appropriate for use in pipeline integrity management programs. Our previous work has shown that the HSD Tester is a portable NDT device capable of quantifying the through-wall mechanical properties of a pipeline in situ, by relating bulk properties to a surface measurement. Although at this time our analysis of the data presented in this paper is incomplete, we feel that two-stylus measurements have shown promising results. The yield strengths predicted by the HSD Tester for normalized 4130 and base metal of an LF ERW pipe are in good agreement with bulk laboratory tensile results. The initial hardness data gathered on 4130, LF ERW, and HF ERW samples with the spherical and conical styluses correlate well with the tensile strain hardening results (n), suggesting that our HSD UTS and n predictions will be similarly accurate. The hardness data measured on three LF ERW wall cross-sections follow the trends expected from strain hardening due to cold forming, as they are softest at the mid-wall and harden towards the OD and ID. These data also reinforce the utility of two styluses that create different amounts of strain. With additional analysis, we hope to demonstrate that the HSD Tester properties for these samples match the laboratory tensile results. Although much work remains to be done, we are confident that the dual stylus HSD Tester will increase our accuracy and ability to predict bulk pipeline properties from a surface measurement. This will make the HSD Tester a unique and invaluable tool for integrity management and implementation of IVP.

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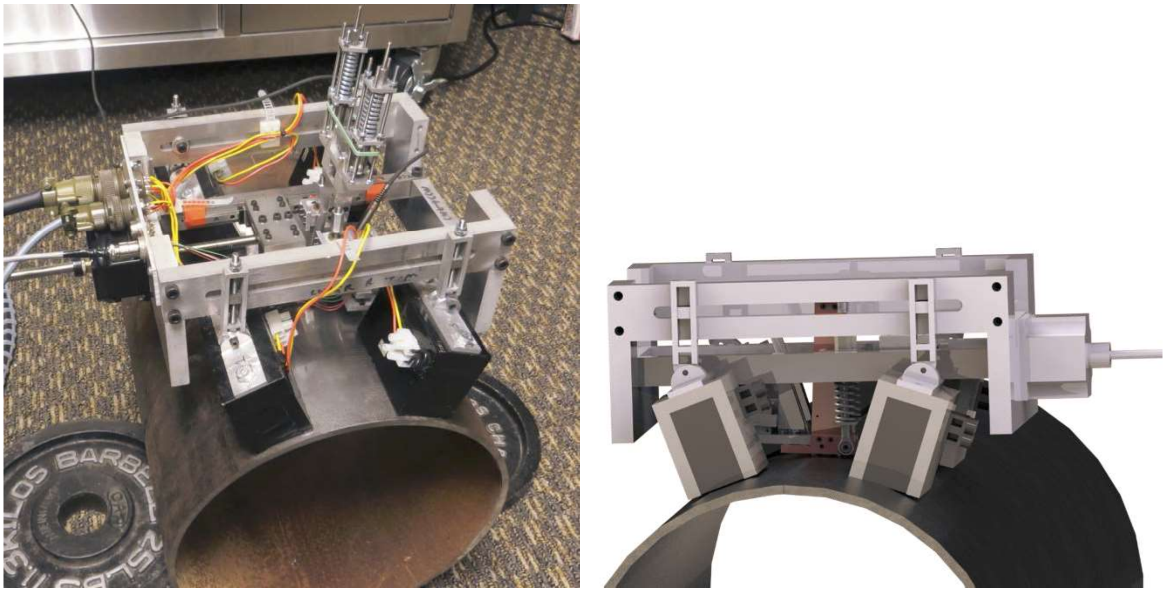

Fig.1. The HSD Tester, left, attached via magnetic bases to an ERW pipe. On the right is a CAD rendering of the HSD Tester.

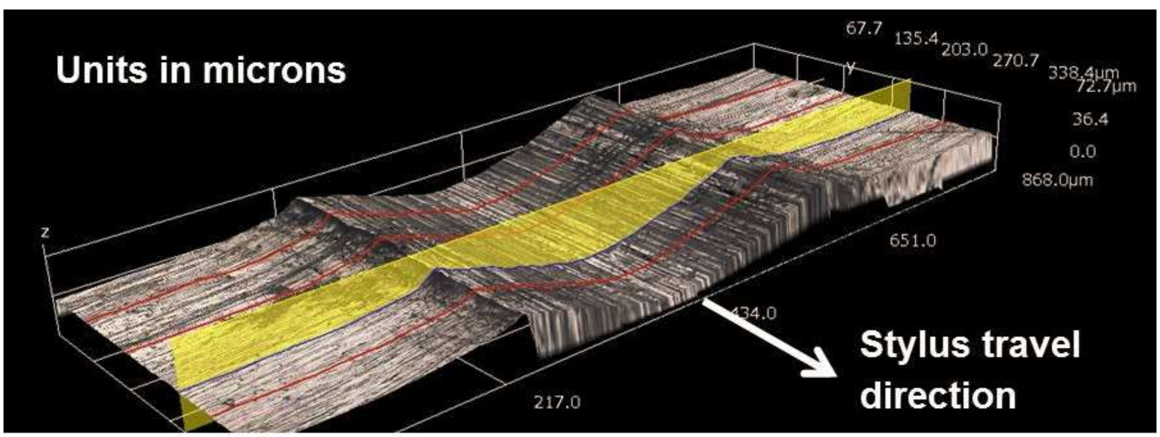

Fig.2. 3D digital microscopy image showing deformation induced in a high-strength steel.

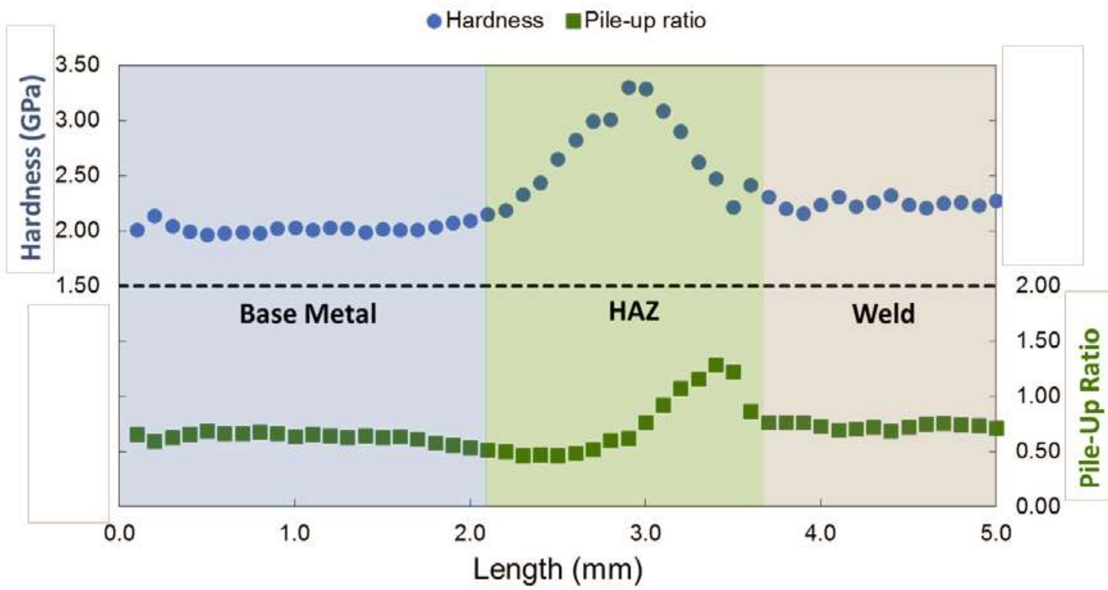

Fig.3. Data produced with the HSD Tester on a butt-welded joint in low alloy 4130 steel.

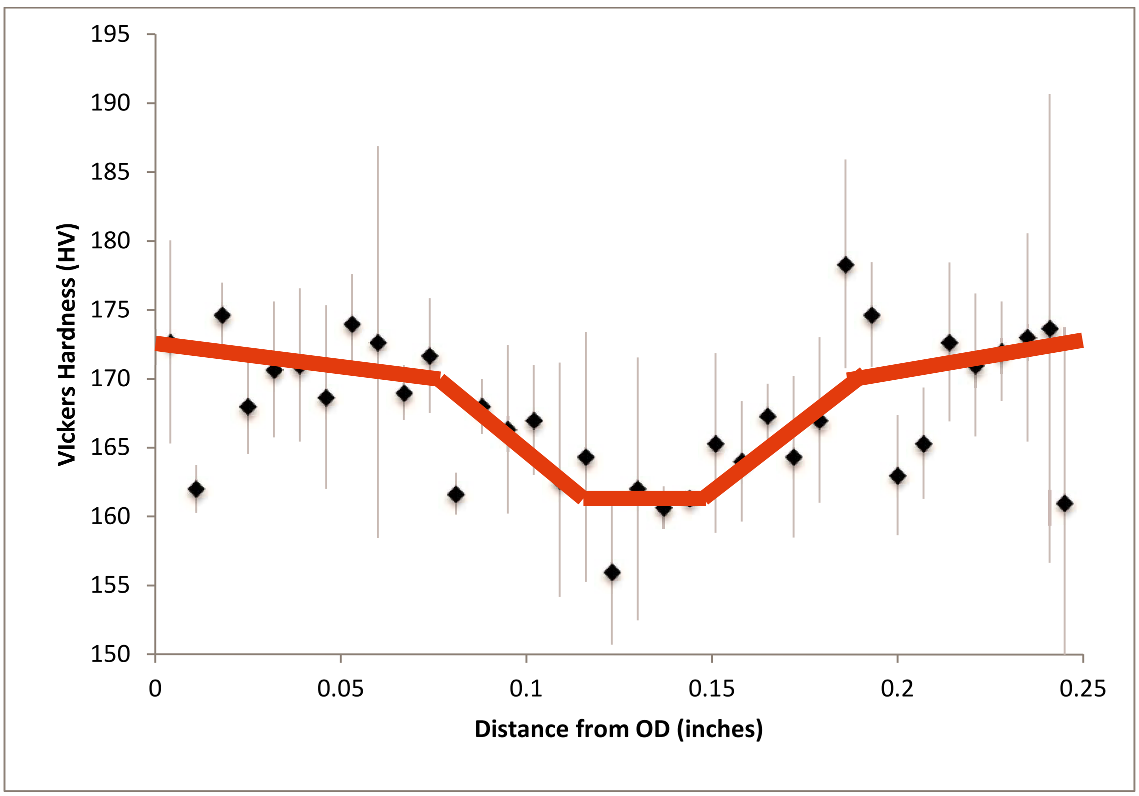

Fig.4. Hardness values across pipe wall thickness. Vertical lines are error bars of one standard deviation. Red lines are hardness value trends for OD, mid-wall, and ID.

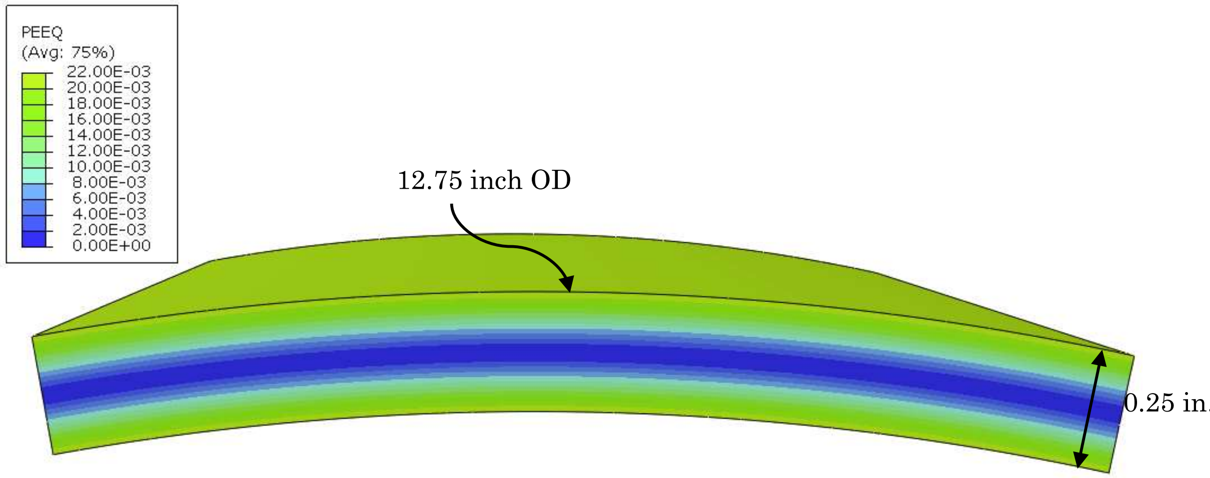

Fig.5. Contour plot of equivalent plastic strain (PEEQ) through the thickness of the formed pipe geometry.

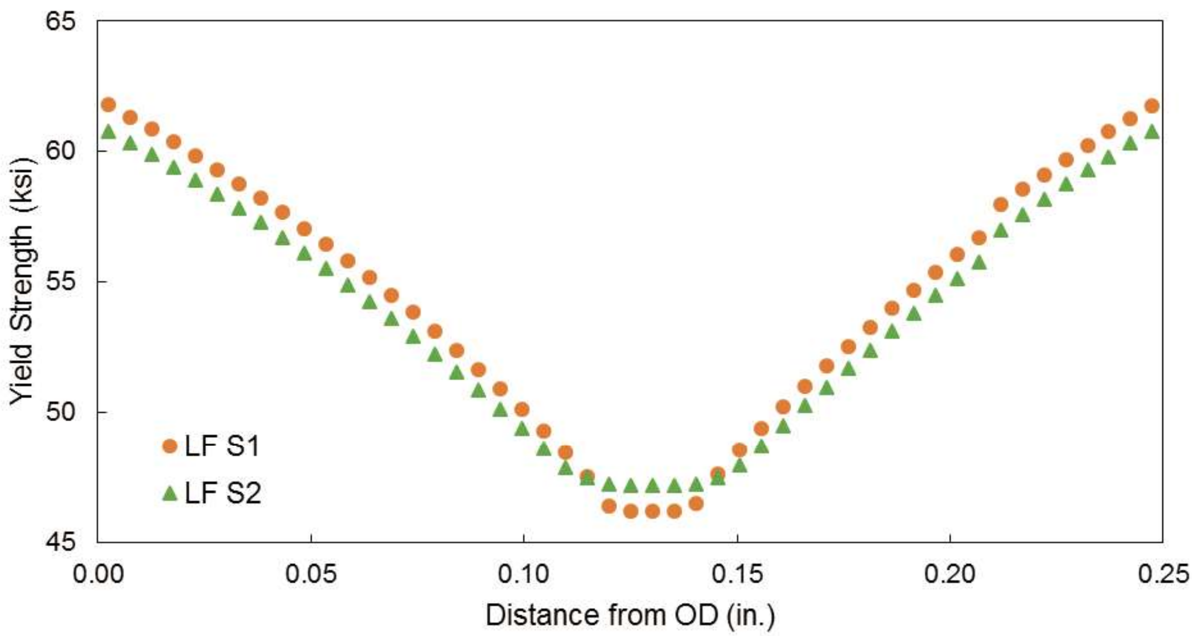

Fig.6. FEA prediction of the gradient in yield strength from cold forming operations of the LF pipe sample.

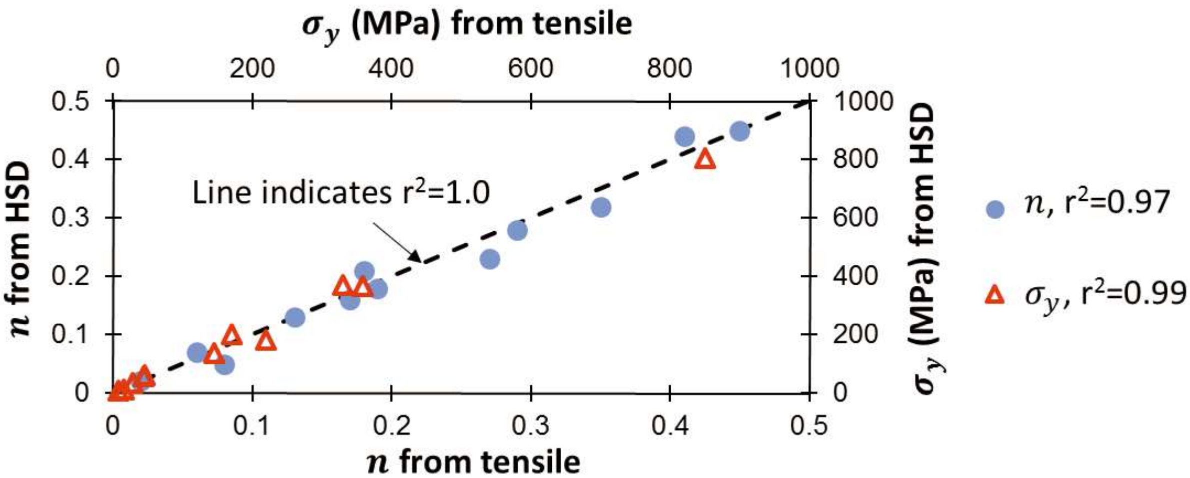

Fig.7. Correlation between mechanical properties predicted using the HSD Tester and uniaxial tensile tests. Data includes tests on copper, brass, nickel, aluminum and steel materials. The coefficient of determination (r2) is also shown from a linear regression.

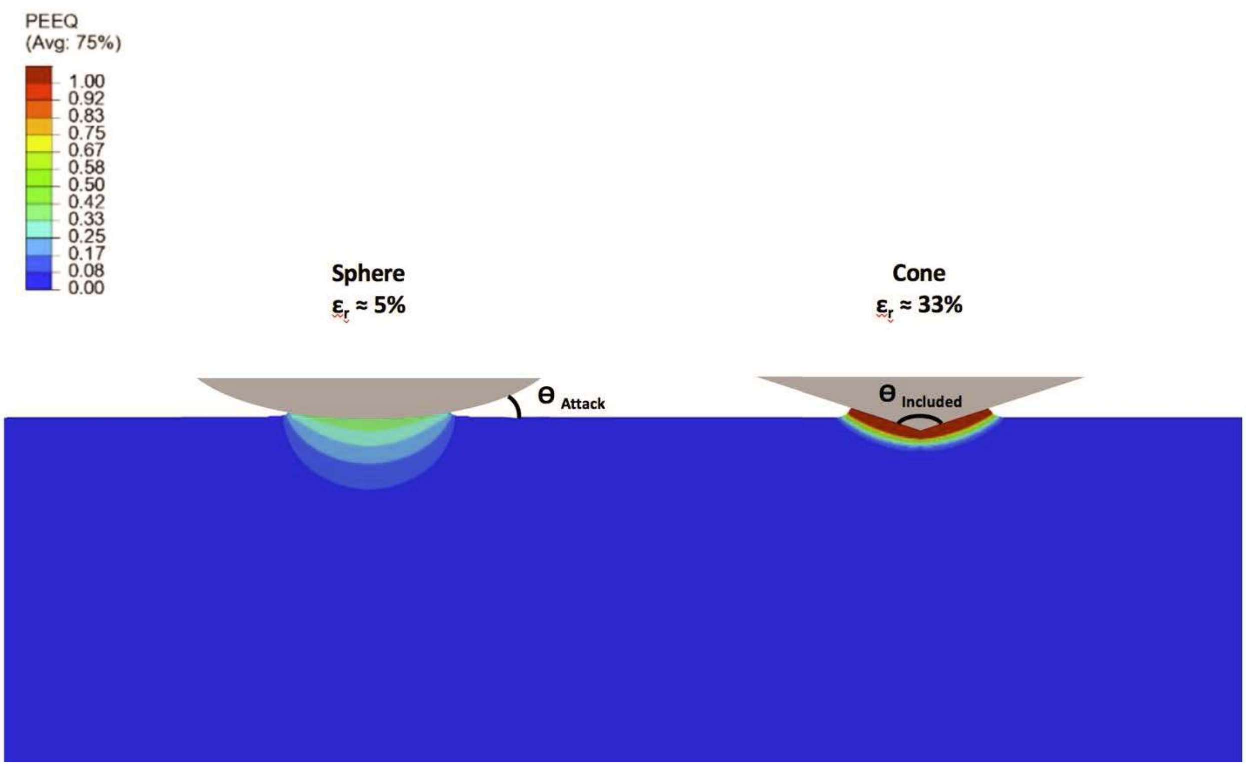

Fig.8a. Plastic strain distribution of spherical and conical tip from finite element analysis. The larger attack angle of the conical tip generates larger representative strain (ε_r) compared to the spherical tip.

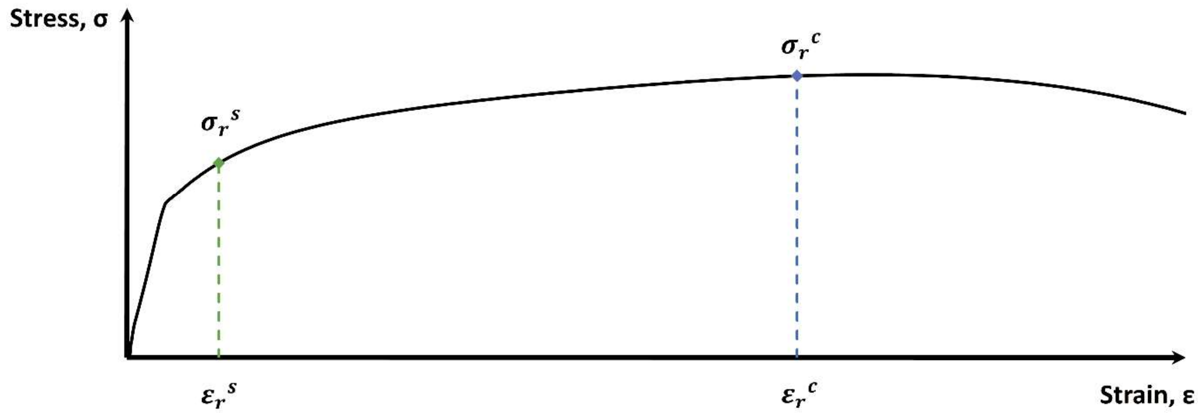

Fig.8b. Uniaxial stress-strain curve shows spherical tip representative strain ($\varepsilon_r{}^S$) near the yield stress and conical tip ($\varepsilon_r{}^C$) representative strain near the ultimate tensile strength.

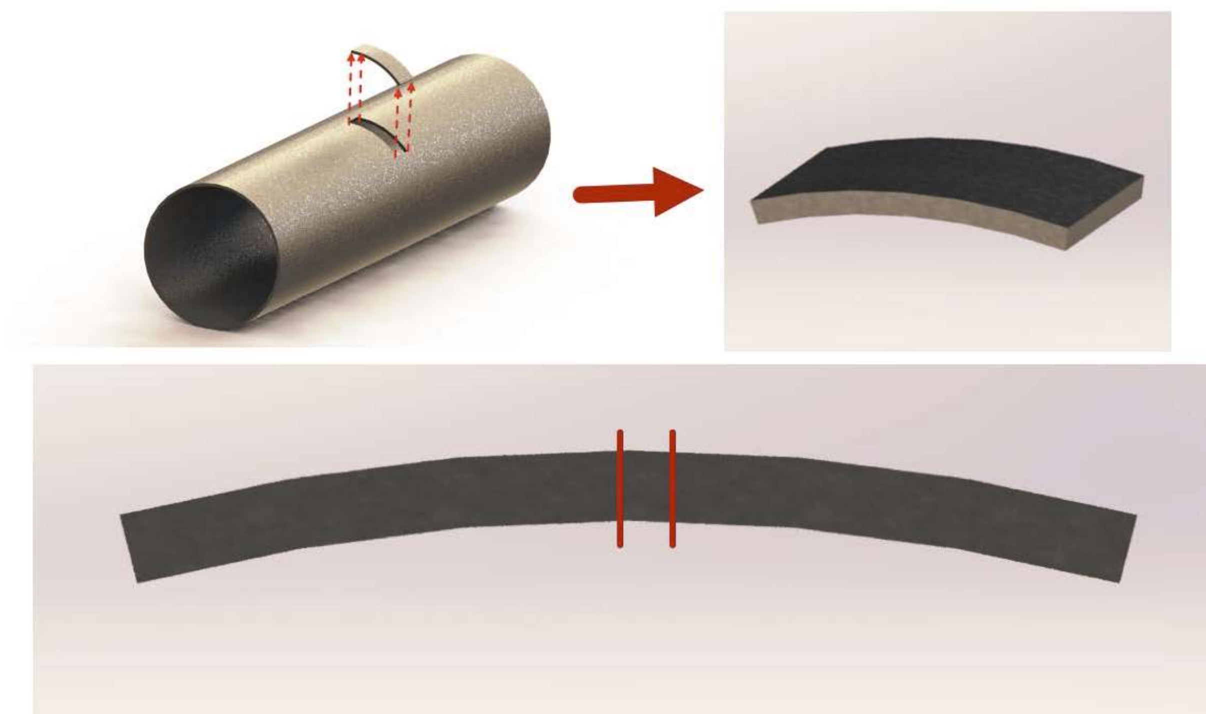

Fig.9. Schematic of sampling method for full wall thickness frictional sliding measurements. The red lines mark the locations and orientation of the HSD Tester grooves.

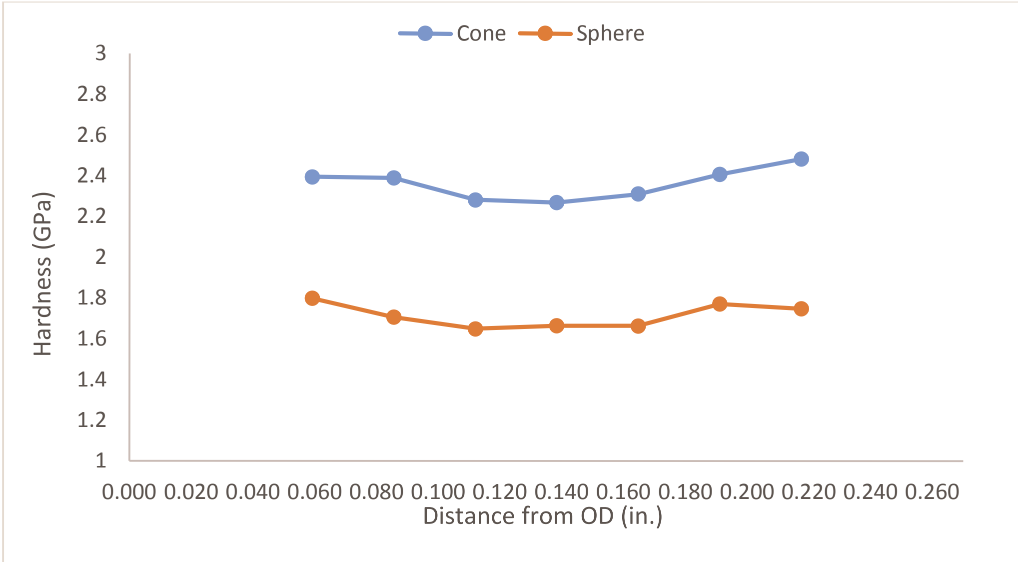

Fig.10. Hardness data from the HSD Tester cone and sphere styluses for Sample 1, a 16" OD, 0.264" wall thickness LF ERW pipe.

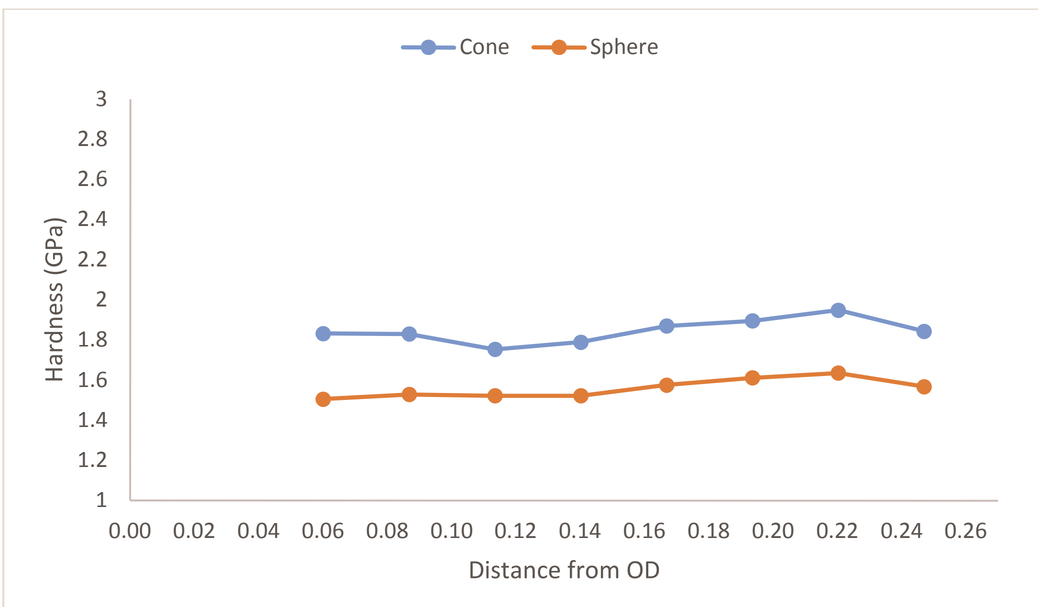

Fig.11. Hardness data from the HSD Tester cone and sphere styluses for Sample 2, a 16" OD, 0.267" wall thickness LF ERW pipe.

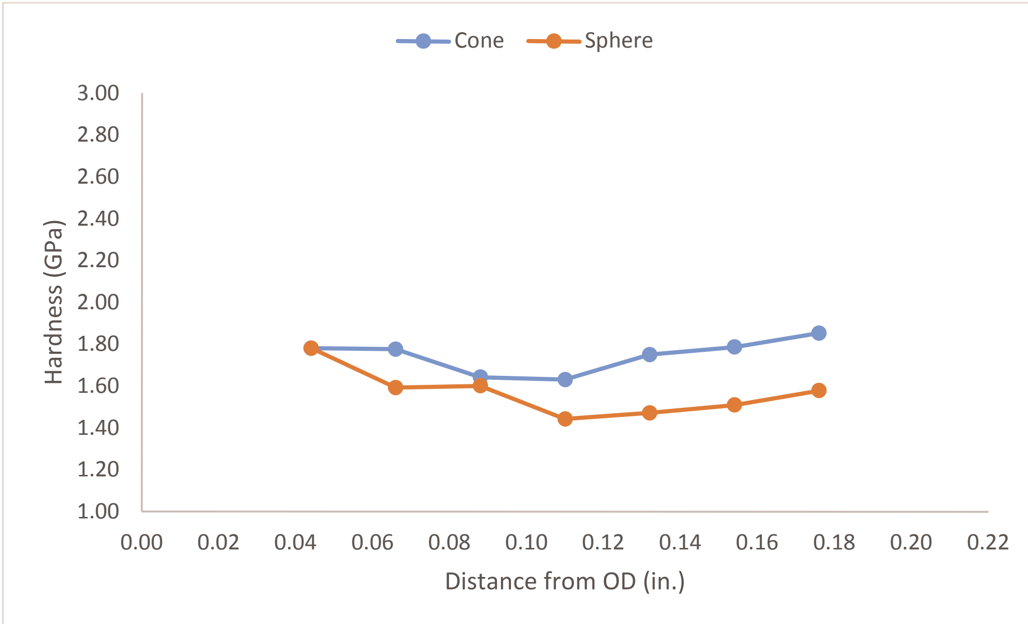

Fig.12. Hardness data from the HSD Tester cone and sphere styluses for Sample 3, a 8.625" OD, 0.222" wall thickness LF ERW pipe.