Standard Test Method for Hardness Strength and Ductility Testing of Metallic Materials for Tensile Strength Properties

DRAFT – LAST UPDATED 2017 NOVEMBER 10

1. Scope

1.1 This test method covers procedures for determining the tensile properties of metallic materials with the Hardness Strength and Ductility (HSD) Tester. This test method is applicable to metallic materials that exhibit a power-law stress-strain curve, including steel, aluminum, copper, and brass. Tensile properties include the complete stress-strain curve that allows for identification of the yield strength describing the initiation of permanent plastic strain and the ultimate tensile strength (UTS) of the material.

1.2 *This standard does not purport to address all of the safety concerns, if any, associated with its use. It is the responsibility of the user of this standard to establish appropriate safety and health practices and determine the applicability of regulatory limitations prior to use.*

2. Referenced Documents

2.1 *ASTM Standards:*

E6	Terminology Relating to Methods of Mechanical Testing
E8	Test Methods for Tension Testing of Metallic Materials
E646	Test Methods for Tensile Strain-Hardening Exponents (n-Values) of Metallic Sheet Materials

3. Terminology

3.1 *Definition*–The definitions of terms relating to tension testing appearing in Terminology E6 shall be considered as applying to the terms used in this test method.

3.2 *Definitions of Terms Specific to This Standard*:

3.2.1 *Frictional sliding*–a contact mechanics test method where a hard stylus penetrates the surface of a softer substrate and slides across the surface at a constant velocity.

3.2.2 *Normal force*, *P*–a quantity, expressed in units of force, that defines the force applied to the moving stylus and the surface that is being deformed by the stylus, and which is perpendicular to the undeformed surface.

3.2.3 *Groove*–the permanent deformed geometry that remains on a substrate surface after a frictional sliding test due to the deformation induced by the stylus.

3.2.4 *Groove width*, a–a quantity, expressed in units of length, that defines the peak-to-peak distance of material displaced by the stylus to form the groove. The groove width is measured perpendicular to the direction of the stylus travel, and represents the extent of material being contacted by the stylus during the test.

3.2.5 *Hardness, H*–a quantity, expressed in units of force per unit area, that characterizes the resistance of the metallic specimen to penetration of a moving stylus with a given geometry under a constant normal force and speed; namely,

$$H = \frac{8P}{\pi a^2}$$

where:

$P =$ normal force

a = groove width

3.2.6 *Attack angle,* ϕ–a quantity, expressed in radians, that describes the relative angle between the stylus and the undeformed surface. For a spherical stylus this is given by,

$$\phi = \frac{\pi}{2} - \cos^{-1}(\frac{a}{2R})$$

where:

$R =$ radius of the spherical stylus

a = groove width

3.2.7 *Hardness Strength and Ductility (HSD) Tester*–a portable device that fixtures to the surface of larger assemblies to perform a frictional sliding test on the surface of a metallic material. The HSD Tester utilizes 2 or more styluses to deform the surface, force transducers to measure the normal force, and a groove measurement system to measure the groove width.

3.2.8 *Floats*–component of the HSD Tester alignment system that contact the specimen surface away from each stylus and does not interfere with groove measurements. These additional contact points allow the HSD Tester to establish a constant position and alignment of the styluses with respect to the undeformed surface of the test specimen as the styluses travel across the surface. This enforces a constant contact condition for both flat and curved surfaces.

3.2.9 *Representative strain,* ε_r–a quantity, expressed without units, that describes the effective magnitude of total tensile strain induced in the metallic material by the stylus during a frictional sliding experiment. The representative strain is a function of the attack angle, and this relationship has been established through numerical analysis of power-law hardening metallic materials.

3.2.10 *Representative stress,* σ_r– a quantity, expressed in units of force per unit area, that describes the effective magnitude of total tensile stress induced in the metallic material by the stylus during a frictional sliding experiment. The representative stress is a function of the representative strain and hardness, and this relationship has been established through numerical analysis of power-law hardening metallic materials.

4. Summary of Test Method

4.1 This test involves producing multiple grooves on a solid surface by moving 2 or more hard styluses of specified geometry along a path under a known normal force and with a constant speed. The depth of penetration of the styluses is shallow with respect to the dimensions of the metallic specimen and is therefore considered nondestructive. Each stylus generates a permanent groove on the surface of the material. During a test, the groove width is measured with a groove measurement system that provides the geometry of the groove perpendicular to the direction of stylus travel, and the normal force on each stylus is measured with a force transducer. Each set of groove width and normal force measurements is used to calculate the hardness with units of force per area. The measured groove width is used along with the known radius of the spherical stylus to compute the attack angle in units of radians. The hardness and attack angle for each stylus is then used to calculate a representative stress and representative strain value. A complete uniaxial true stress versus true strain curve can then be obtained by performing a least-squares power-law regression to the calculated representative stress and strain values of 2 or more styluses. The geometry and depth of penetration for each stylus is predefined for a metallic material to sample the uniaxial true stress-strain curve at targeted magnitudes of representative strain, allowing for robust determination of the resulting power-law curve. The true stress-strain curve is converted to engineering stress-strain units to allow for the determination of the tensile strength properties, including the 0.2% offset yield strength, 0.5% elongation under load (EUL) yield strength, and ultimate tensile strength (UTS). Other tensile properties including the strain hardening exponent (n) and strength coefficient (K) are determined directly from the power-law regression fit.

4.2 For heterogeneous metallic specimens, additional characterization methods may be used to improve correlations between laboratory tensile tests and the surface measurements obtained with the HSD Tester. One example of a heterogeneous specimen is longitudinal seam welded pipe, where manufacturing processes induce an inhomogeneous distribution of material properties through the wall thickness as a flat plate is cold formed into a cylinder and then welded along its length. Subsequent forming operations such as cold expansion or compression further modify this material property distribution. These fabrication processes induce changes in material properties due to varying magnitudes of plasticity and strain hardening throughout the thickness of the pipe wall. As a consequence, the outer surfaces of the pipe that are exposed for nondestructive testing with the HSD Tester will exhibit a higher strength measurement than laboratory tensile tests that average the full-wall thickness. For these heterogeneous specimens, additional measurements including the grain size and pearlite volume fraction from metallographic analysis of surface replicas, and chemical composition from spark optical emission spectroscopy (OES), may be utilized to establish the difference between surface measurements on strain-hardened surface material and the laboratory tensile test equivalent.

4.3 This test is conducted under a lubricated condition and at ambient temperatures. The provisions of this standard allow for testing without lubrication or under either low or high temperature conditions provided that an appropriate correction is available to account for deviations in the standard test conditions that tensile property predictions have been established. Temperature corrections have been established for a mild steel (50 ksi 0.5% EUL yield strength) ranging from 0°F to 120°F, as shown in Fig. 1.

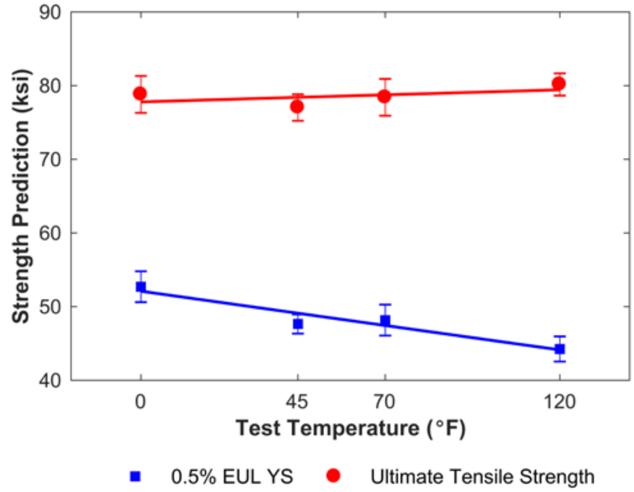

FIG. 1 Effect of temperature on HSD Tester tensile strength properties for the 0.5% elongation under load (EUL) yield strength and ultimate tensile strength.

5. Significance and Use

5.1 This test method is intended to measure the tensile strength properties of metallic specimens through a frictional sliding contact mechanics test performed with the HSD Tester. This provides a nondestructive alternative to tensile testing which requires that a coupon of material is removed from an existing structure and sent to a laboratory for destructive evaluation. The yield strength measurement obtained from an HSD Tester can be used to determine the elastic limit strength of the material. This data is used along with specimen geometry and loading conditions to determine safe operating limits for structural analysis and design. Additional tensile properties such as the UTS and strain hardening exponent provide data that can be used for identifying unknown materials of similar manufacturing batches or processes. The strain hardening exponent also provides an index of ductility that describes how much strain a material can sustain prior to necking in a laboratory tensile test.

5.2 This test method is applicable to metallic materials, including steel, aluminum, copper, brass and nickel alloys. The main criteria for application is that the material deforms according to a power-law curve for plastic stress-strain behavior, which is true for most engineering metals. To ensure the test is nondestructive, the specimen should be much larger than the localized deformation induced by the stylus. For a typical maximum penetration depth of 50 μm (0.002 inches), a minimum specimen wall thickness of 5 mm (0.20 inches) ensures that the groove depth will be less than 1% of the wall thickness. The groove geometry is shallow and spherical so there is a limited stress concentration around the deformed area. However, grooves can be buffed from the surface after testing if long-term fatigue performance is a concern.

5.3 Frictional sliding enables the continuous monitoring of changes in material properties as the stylus travels along the surface of the metallic material. This allows the HSD Tester to be used to characterize local gradients in material properties where they exist, such as transitions from base metal, heat-affected-zone and fusion zone across a welded connection. Changes in the material response can be used to characterize the welding processes and to identify whether a post-weld-heat-treatment was performed. For electric-resistance-welded (ERW) pipes, this enables the determination of low frequency (LF), high frequency (HF) and HF normalized seams which have implications on the fracture toughness of the specimen. This data can also be used to distinguish between ERW, direct submerged arc welds (DSAW) and flash welded pipes.

6. Apparatus

6.1 *General Description*–the apparatus consists of (1) a rigid fixture for hosting multiple styluses and mounting to the external surface of the test specimen, (2) two or more styluses that deform the surface of the material, (3) a means to apply and monitor normal force while traversing the stylus along the surface at a constant speed, (4) a means to establish a constant orientation of the styluses with respect to the undeformed test surface as the styluses travel, (5) a means to measure the groove geometry after deformation from the stylus, and (6) a system for data acquisition and data analysis for tensile strength property determination.

6.2 *Styluses*–the stylus shall be of a known axisymmetric geometry and of a material that provides sufficient wear resistance and fracture toughness to sustain 50 or more HSD Tests on high strength materials (e.g. X80 pipeline steel). For spherical styluses at a constant depth, the representative strain increases with a decreasing radius, and this radius should be known to within $\pm$ 2 μm. Styluses should be polished and free of surface defects.

6.3 *Normal force system*–each stylus requires a normal force that is applied and maintained as the stylus travels across the test surface. The normal force on each stylus may vary based on the geometry of the stylus, desired depth of penetration, and tensile properties of the metallic test specimen. Force transducers are used to measure the normal force on each stylus throughout the test. Force transducers should have a nonlinearity and non-repeatability not exceeding $\pm$ 0.05% and $\pm$ 0.02% of the maximum load cell capacity, respectively.

6.4 *Drive system*–a drive system such as an electric motor and mechanical actuator is used to displace the styluses at a constant velocity across the surface of the test specimen. The drive system should provide linear position data with a linear step size of 0.01 μm.

6.5 *Groove measurement system*–the groove measurement system consists of two components, (1) a contact, optical, or laser profilometer that makes measurements of the groove in the depth direction, and (2) a bracket that hosts the profilometer and travels laterally perpendicular to the direction of stylus travel. The combination of these two components allows for the measurement of the two-dimensional cross-section of the groove geometry. The profilometer is positioned directly behind the styluses to measure the groove geometry as the HSD Tester travels across the specimen surface. The profilometer should provide depth measurements with a repeatability of $\pm$

0.15 μm, and a maximum depth range of 6.35 mm (0.25 inches). The movement of the bracket should be through a motor that provides linear position data with a step size of 0.01 μm.

6.6 *Stylus alignment system*–additional contact points, or floats, contact the specimen to establish the position and orientation of the undeformed surface. This enables the alignment of the styluses with respect to the testing surface as they travel across a flat or curved surface. Floats should have a large spherical curvature to distribute pressure over a greater contact area, and should not interfere with the styluses used to measure the metallic specimen response. Float materials should provide sufficient wear resistance to sustain 250 or more HSD Tests. The stylus alignment system requires that sufficient force is provided to maintain contact between the floats and the specimen surface throughout a test.

6.7 *Data acquisition and analysis system*–a portable computer is required to acquire data from the drive system, groove measurement system, and normal force system. The processing system should also be equipped with the latest InstaHSD.exe software for analyzing data throughout the test, and obtaining an automated surface tensile strength property report after the test has completed.

7. Calibration and Standardization

7.1 The components of the apparatus that require calibration are (1) the normal force system, (2) groove measurement system, and (3) overall apparatus. Regular stylus inspection should also be performed to ensure consistent performance.

7.2 *Normal force system*–The force transducers used to measure the normal force applied to the stylus shall be calibrated every two months. This calibration procedure consists of increasing the applied load from 0 to 150% of the expected stylus load in six linear loading increments. This procedure is repeated twice to confirm repeatability.

7.3 *Groove measurement system*–The groove measurement system should be calibrated every two months. The profilometer depth measurement calibration is performed from 0 to 100% of the total travel range in six equal increments using a micrometer with an accuracy of 1 μm. The motor that translates the bracket and moves the profilometer laterally is calibrated from 0 to 7.6 mm (0.30 inches) in seven equal increments using a micrometer with an accuracy of 1 μm.

7.4 *Overall apparatus*–The HSD tester shall be calibrated daily by measuring tensile properties of homogeneous material with known tensile properties. The calibration material shall be prepared according to the guidelines of Section 8.2 of this standard. Calibration consists of a minimum 1 inch (25.4 mm) long test that is performed on the known material in accordance with Section 8 of this standard. After testing, the predicted yield strength and ultimate tensile strength (UTS) of the calibration material must be within $\pm$ 2.5 ksi (20 MPa) of the known value.

7.5 *Inspection of the styluses*–Inspect the stylus tip with a microscope or other topographic inspection method to ensure there are no cracks, chips, wear, or adhering material left from manufacturing or resulting from a previous test. The stylus should be replaced if these defects or contaminants are observed.

8. Procedure

8.1 *General*–This section provides general details for performing field experiments with the HSD Tester on metallic specimens. Detailed operation instructions are provided within the User's Manual of the HSD Tester (e.g. MMT002).

8.2 *Specimen Preparation*–Surface preparation is critical to ensuring the performance of the HSD Tester. Surface coatings must be removed to expose the underlying metallic surface. For seam welded pipes, a minimum of 0.004 inches (100 μm) of surface material must be removed from the outer surface of the pipe to ensure the test is not conducted within material that experienced decarburization during manufacturing. Additional material removal may be required to ensure surface pits and defects are removed. The maximum amount of material removed is 12.5% of the nominal pipe wall thickness which should be determined from pipe documentation or ultrasonic thickness (UT) measurements. After the initial grinding, a 4x4 inch (100x100 mm) area should be prepared through the MMT Surface Preparation Procedure (MMT005) which progressively buffs the test surface from 50 to 2000 grit in multiple steps. The final surface should be wiped clean of contaminants and an isostearic acid lubrication should be applied.

8.3 *HSD Tester mounting*–Attach the HSD Tester fixture to the test specimen. For pipe geometries, use ratchet straps to attach the HSD Tester to the pipe after positioning the styluses within the prepared surface region. If a test has already been conducted, ensure that the new grooves are at least 5 groove widths away from the prior test location. Confirm that the HSD Tester fixture is level and making contact with the pipe surface at all intended locations after the ratchet straps are fully tightened. For flat specimens, electromagnets or alternative mounting systems can be employed.

8.4 *Normal force*–The normal force is selected to produce a measurable groove on the surface at the desired magnitude of representative strain. The normal force on each stylus should be set to the desired load within ± 1 lbf (4.5 N).

8.5 *Test conditions*–The test conditions should be specified through the user interface of the HSD Tester software prior to performing a test. These conditions include the total linear length of the test, linear velocity of the drive system, linear velocity of the groove measurement system, and sampling rate of the profilometer. Standard test conditions are detailed in the User's Manual of the HSD Tester (e.g. MMT002).

8.6 *Conducting the test*–Ensure that the data acquisition system is acquiring data for the force transducers and groove measurement system. Initiate the test through the HSD Tester software and use the InstaHSD.exe program to monitor the measured groove profile data and calculated hardness for each stylus throughout the duration of the test. A minimum of two HSD Tests are required for tensile strength property predictions. One welded seam test is sufficient provided that the test successfully travels over the full width of the weld.

8.7 *Evaluate test results*–After a test is complete, the InstaHSD.exe software uses the groove width and normal force to calculate the hardness and attack angle for each measurement of the groove geometry along the length of the test. Calculated values are then analyzed to identify and remove outlier measurements based on the calculated normalized median absolute deviation (MAD). Outliers occur during normal test conditions due to local hard or soft spots on the test specimen surface, surface irregularities that were not completely removed during surface preparation, and/or irregular groove geometry that may be caused by inclusions or grains within the material. The InstaHSD software averages the accepted measurements to perform a least-squares regression of the averaged representative stress and strain values for each stylus over the total length of the test. The resulting power-law stress-strain curve is used for the determination of the tensile strength properties.

8.8 *Remove surface grooves (Optional)*–After HSD Testing is completed, the grooves that remain on the specimen surface may be removed through buffing until no sign of the test remains.

8.9 *Metallographic measurements (Optional)*–Surface replicas provide an impression of the metallographic grain structure for a metallic material. This data can be combined with HSD Tester measurements to provide more accurate tensile property predictions for pipeline steel materials. Replicas should be prepared through MMT procedure MMT004. Metallographic analysis is conducted by examining the surface replica with a microscope to quantify features of the specimen grain structure.

8.10 *Chemical measurements (Optional)*–Surface chemical composition can be measured through spark optical emission spectroscopy (OES) or other suitable means. The chemistry of the metallic specimen can be combined with HSD Tester measurements to provide more accurate tensile property predictions for pipeline steel materials. Chemical measurements should be performed in accordance with MMT procedure MMT003.

9. Calculation of Results

9.1 *Hardness*–the hardness is a measurement of the resistance of the metallic specimen to plastic deformation. Hardness is calculated by dividing the normal force on the stylus by the projected area of frictional sliding contact which is assumed to be a semi-circle whose diameter is given by the measured groove width.

$$H = \frac{8P}{\pi a^2} \qquad (1)$$

where:
H = hardness (Pa or ksi)
P = normal force (N or lbf)
a = groove width (mm or inch).
If the normal force

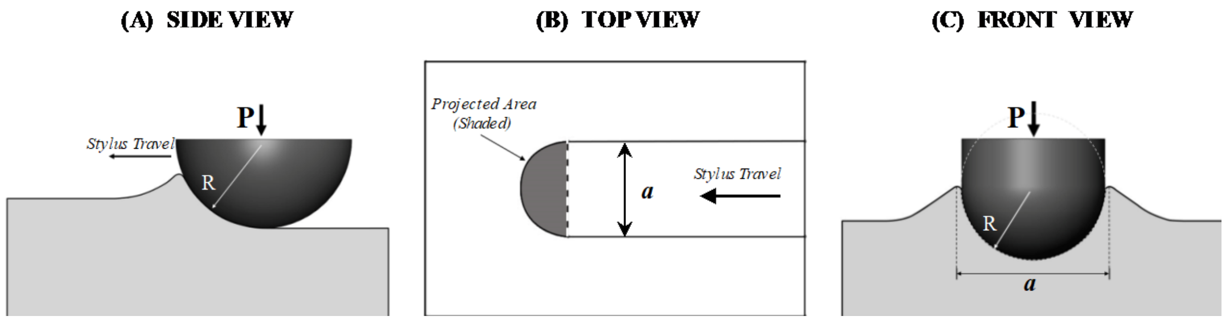

FIG. 2 Multiple views of a groove generated by a spherical stylus.

9.2 *Attack angle*–the attack angle describes the relative angle between the stylus and the undeformed surface. A higher attack angle will induce a greater magnitude of deformation in the material. For a spherical stylus, the attack angle varies based on the stylus radius, depth of penetration, and height of material pile-up around the stylus. The attack angle can be calculated from the stylus radius and groove width using,

$$\phi = \frac{\pi}{2} - \cos^{-1}\left(\frac{a}{2R}\right) \quad (2)$$

where:

R = radius of the spherical stylus

a = groove width

Note 1–At high attack angles the material response may transition from ductile plastic flow to chipping which will alter the measured groove width. Reliable strength property predictions cannot be obtained if chipping occurs during testing. For lubricated contact between a ceramic stylus and metallic specimen, a maximum contact angle of 15 degrees should be enforced to ensure chipping will not occur.

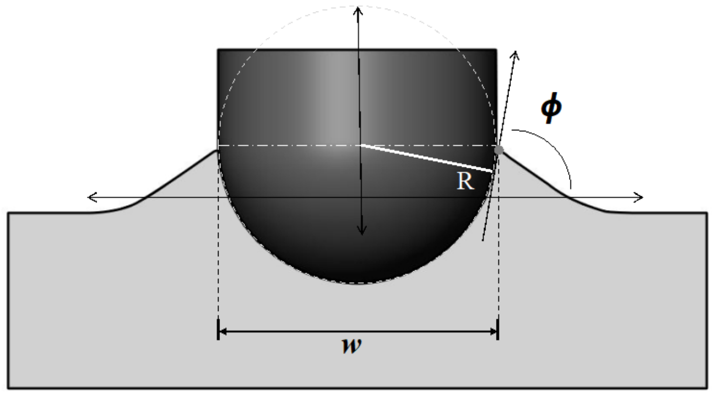

FIG. 3 Attack angle for a spherical stylus.

9.3 *Representative stress and strain*–A representative stress and strain value is calculated for each stylus based on the hardness and attack angle from the measured groove width and normal force. These functions are determined through numerical analysis simulations of the frictional sliding response of hundreds of combinations of elastic-plastic material properties, stylus geometries, and contact conditions. These functions are proprietary to MMT.

9.4 *Calculation of Power-Law curve*–A power-law is fit to the true stress versus true strain measurements of two or more styluses through a least-squares regression. The power-law function describes the plastic deformation of the material given by,

$$\sigma_t = K\varepsilon_t^n \qquad (3)$$

where:

σ_t = true stress (Pa or ksi)

ε_t = true strain (unitless)

K = strength coefficient (Pa or ksi)

n = strain hardening exponent (unitless)

The strength coefficient modifies the amplitude of the stress-strain curve, whereas the strain hardening exponent describes the flow behavior of the material from low to high strains. Although no necking occurs during a frictional sliding experiment, the strain hardening exponent is associated with the true strain at the ultimate tensile strength of the material where a plastic flow instability occurs in a laboratory tensile test. Therefore, the strain hardening exponent provides an index of ductility of the metallic specimen. An example of the fitting of Eq. 3 to calculated stylus representative stress and representative strain values is shown in Fig. 4.

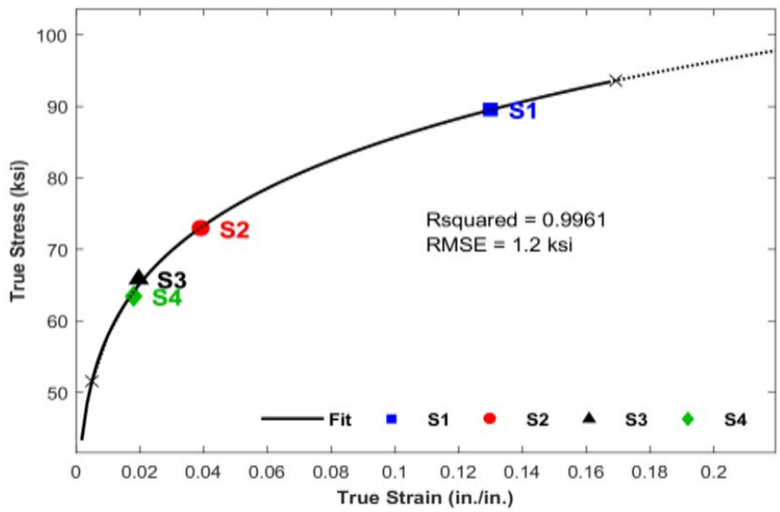

FIG. 4 Power-law curve fit of Eq. 3 with representative stress and strain values of four styluses (S1, S2, S3, S4) calculated from a HSD Tester experiment on a 4130 steel plate.

9.5 *Calculation of tensile strength properties*–Tensile strength properties of the surface material of the metallic specimen can be obtained from the HSD Tester by converting the true stress and true strain values to their engineering stress-strain equivalent with,

$$\varepsilon_e = \exp(\varepsilon_t) - 1 \quad (4)$$

where:

ε_e = engineering strain (unitless)

ε_t = true strain (unitless)

$$\sigma_e = \sigma_t/(1 + \varepsilon_e) \quad (5)$$

where:

σ_e = engineering stress (Pa or ksi)

σ_t = true stress (Pa or ksi)

ε_e = engineering strain (unitless)

The yield strength properties that describe the transition from elastic to plastic deformation can then be determined through standard practices applied to laboratory tensile testing. The 0.2% offset yield strength is calculated by offsetting the material Young's Modulus (e.g. 200 GPa for steel) by 0.2% engineering strain and finding the intersection with the calculated engineering stress-strain curve. The 0.5% elongation under load (EUL) yield strength is measured from the engineering stress value at 0.5% engineering strain. Ultimate tensile strength (UTS) is calculated by evaluating the true stress at a true strain given by the strain hardening exponent with Eq. 3, and then converting to engineering stress units with Eqs. 4 and 5.

9.6 *Seam determination of welded pipes (Optional)*–The seam type is determined through the analysis of the hardness variation across the longitudinal welded seam. The number of local increases in hardness associated with the presence of heat-affected-zones, magnitude of local hardness increases, and the overall size of the affected area, all provide data that can be used to classify the weld fabrication process or presence of post-weld-heat-treatment. These are determined through comparison with an established database of ERW, DSAW and flash welded pipe samples using MMT standard MMT007.

9.7 *Metallographic analysis of surface replicas (Optional)*–Metallographic analysis is performed on images of surface replicas obtained with an appropriate microscope. The recommended magnification for imaging is between 20 and 80x, depending on the size of the grain structure. Image processing software is used to measure the mean linear intercept (mli) according to ASTM E112 which provides an index of the specimen grain size. Pearlite volume fraction can be estimated through the contrast within images according to ASTM E562.

9.8 *Multivariable regression for heterogeneous materials (Optional)*–The HSD Tester provides tensile properties local to the surface of the specimen where styluses deform the metallic material. For heterogeneous materials, like seam-welded pipes, the outer surface tensile property measurements obtained with the HSD Tester differ from those obtained from full-wall thickness tensile tests. The difference between HSD Tester outer surface yield predictions and the corrected measurements are shown in Fig. 5 for 65 seam-welded pipes. These results indicate that the HSD Tester generally measures a higher strength on the outer surface of the pipe because a larger magnitude of strain hardening has occurred within the surface material during seamed-pipe manufacturing. Additional measurements of grain size, pearlite volume fraction, and chemical composition can be used within multivariate regression equations that are established from an internal database of pipeline materials to correct for the differences between surface HSD measurements and full-wall thickness measurements. MMT's current equations are based on 74 steel pipeline materials which include ERW, DSAW, and flash welded pipes of varying vintage and grade. The range of yield strength spans from 29 to 80 ksi (200 to 550 MPa) for 0.5% EUL yield strength, with yield / UTS ratios ranging from 0.59 to 0.96, and strain hardening exponents ranging from 0.04 to 0.20.

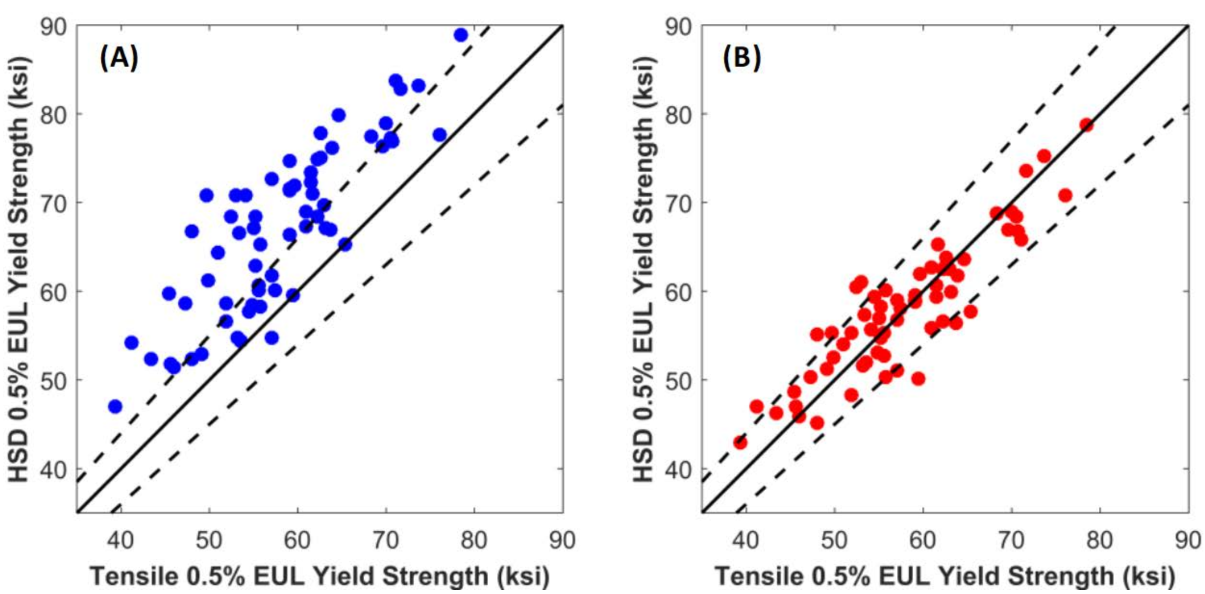

FIG. 5 (A) HSD Tester outer surface tensile yield strength measurements of 65 heterogeneous seam-welded pipe materials. The HSD Tester generally overestimates the yield strength because of greater magnitudes of strain hardening of outer surface material. (B) Corrected HSD Tester tensile yield strength measurements of the same 65 seam-welded pipes when accounting for differences between surface measurements and full-wall thickness laboratory tensile tests. The solid line indicates perfect correlation, and the dashed line indicates +/- 10% of the tensile test measurement.

10. Report

10.1 The recommended report includes the following:

10.2 *Test specimens*–Provide sufficient information to establish the source, processing history, and surface treatment of the test specimen, if available. Diameter, wall thickness and location of longitudinal seam should be provided for pipeline specimens.

10.3 *Field conditions*–Site location, sample designations, and sufficient documentation to establish the location of the test sample with respect to surrounding structures should be reported.

10.4 *Test conditions*–Drive system velocity, groove measurement system velocity, profilometer sampling rate, test temperature, and surface finishing for polishing procedures should be provided. Deviations from the standard test conditions, such as unlubricated contact or extreme test temperatures, should be indicated. The model and serial number of the HSD Tester, as well as serial numbers of the profilometer and stylus should be recorded.

10.5 *Measurement data*–Report the calculated hardness for each stylus along the length of the test, the number of groove width measurements that were accepted after outlier removal, and the overall mean and standard deviation of stylus hardness.

10.6 *Tensile strength properties*–The surface yield strength and UTS obtained from the HSD Tester is reported, along with a figure of the equivalent tensile stress-strain curve in engineering stress-strain units. Optional tensile strength properties that can be reported include the strength coefficient (K), strain hardening exponent (n).

10.7 *Non-mechanical measurement data (Optional)*–Report the chemical composition from spark OES, carbon content from surface replicas, and/or grain size from surface replicas. This information can be used to predict tensile strength properties of heterogeneous materials, if available.

11. Precision and Bias

11.1 *Precision*–The precision of tensile strength determination is dependent on the type of metallic material tested (e.g. steel or aluminum), and whether the metallic specimen is homogeneous or heterogeneous (e.g. flat plate or seam-welded pipe). Massachusetts Materials Technologies (MMT) LLC has tested the precision of the HSD Tester by comparing the tensile strength predictions of the HSD Tester with laboratory tensile tests measurements. Any comparison of the HSD Tester measurements should also consider the inherent variability of tensile testing. ASTM E8 states that the standard deviation of inter-laboratory tensile testing of a stainless steel exhibits a coefficient of variation of up to 4.06%, or a standard deviation of 2.83 ksi (19.5 MPa). MMT has tested 24 homogeneous steel materials consisting of flat plates and seamless pipes. A unity plot comparing the HSD Tester 0.5% elongation under load (EUL) yield strength and tensile test measurement is shown in Fig. 6. Comparing the percent error between HSD Tester and tensile test measurements, we find a mean absolute error of 4.3%. MMT has tested 74 pipeline steel materials consisting of heterogeneous seam-welded pipes (ERW, DSAW, flash) and homogeneous seamless pipes. Applying multivariable regression predictions with the HSD Tester, surface replica and surface chemistry, the mean absolute error between HSD Tester measurements and tensile test measurements is 5.1% and 4.0% for the 0.5% elongation under load (EUL) yield strength and ultimate tensile strength (UTS), respectively. The unity plot comparing the 0.5% EUL yield strength and ultimate tensile strength of HSD Tester and tensile testing for all 74 pipes is shown in Fig. 7.

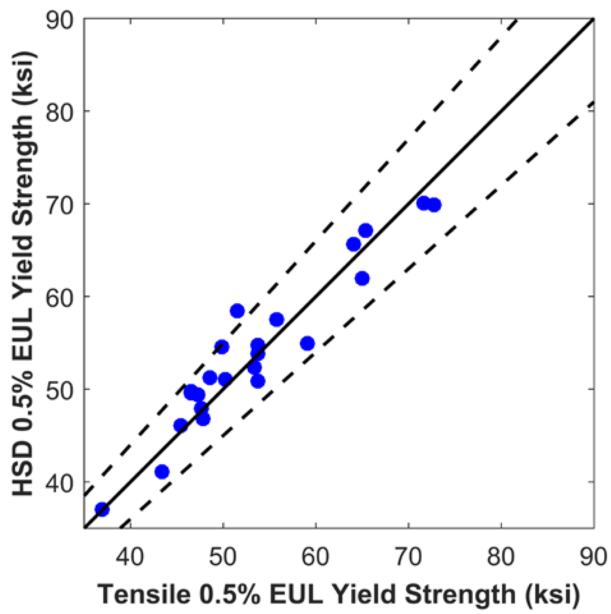

FIG. 6 Results for 24 homogeneous steel materials comparing the HSD Tester 0.5% EUL Yield strength and tensile test measurements. The solid line indicates perfect correlation, and the dashed line indicates +/- 10% of the tensile test measurement.

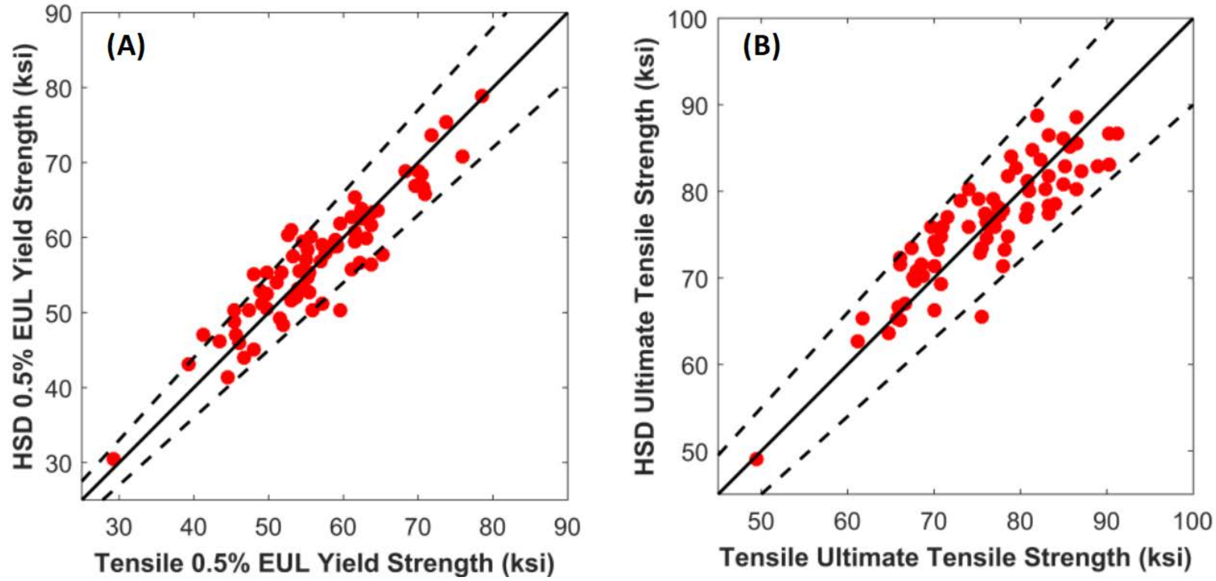

FIG. 7 (A) Results for 74 pipeline steel materials comparing the HSD Tester 0.5% EUL Yield strength and tensile test measurements. (B) Results for the same 74 pipes comparing the HSD Tester ultimate tensile strength and tensile test measurements. The solid line indicates perfect correlation, and the dashed line indicates +/- 10% of the tensile test measurement.

11.2 *Repeatability*–The repeatability of scratch hardness testing results is dependent on the type of metallic material tested (e.g. steel or aluminum), testing conditions (e.g. lubricated or unlubricated), and adequate completion of the surface preparation procedure. Fig. 8 provides examples of the repeatability of tensile strength predictions for four homogeneous steel materials of varying grade and composition which have been tested 10 or more times. These homogeneous materials are used for overall system calibration as detailed in Section 7.4 of this standard.

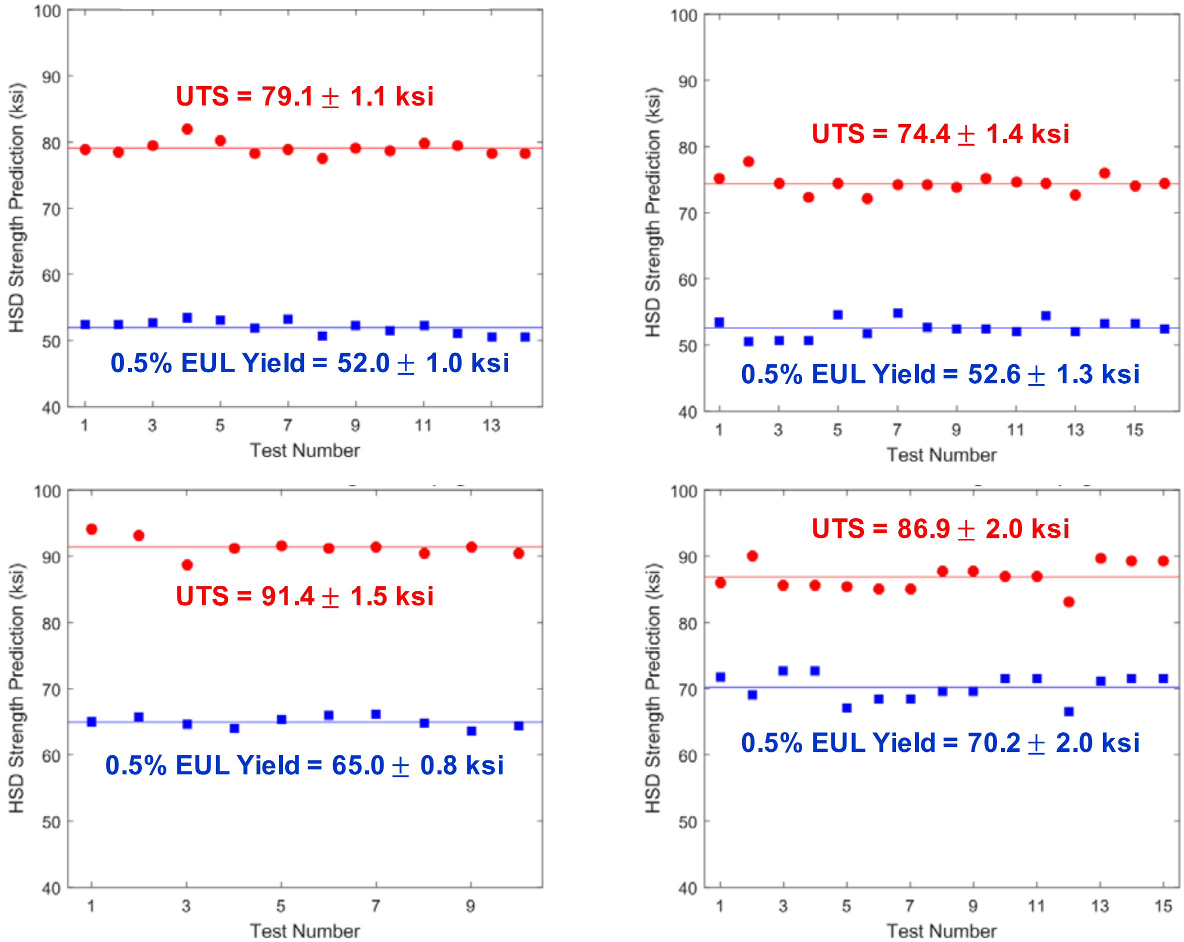

FIG. 8 Repeatability of tensile strength property predictions for four different homogeneous steel plate materials. The mean and standard deviation of the material 0.5% EUL yield strength and ultimate tensile strength (UTS) for the tests shown are also shown.

12. Keywords

12.1 Hardness Strength and Ductility, frictional sliding, nondestructive, yield strength, ultimate strength, strain hardening exponent, strength coefficient