Integrated Material Property Verification – Combining State-of-the-Art ILI and In-Ditch Testing

Simon Slater[1], Ollie Burkinshaw[1], Christopher de Leon[1], Steven Palkovic[2] and Simon Bellemare[2]

[1] ROSEN

[2] Massachusetts Materials Technologies (MMT)

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Abstract

Driven by safety and added regulatory requirements, operators are working diligently to characterize the material properties of pipe within their assets. Opportunities to remove pipe from the ground and perform traditional mechanical testing in a laboratory are limited. Fortunately, operators are able to use a combination of enhanced ILI and state-of-the-art in-ditch testing to characterize material properties. This paper presents the most robust process available to ensure accurate data is collected – from the segments where it is required and with statistical relevance. ILI establishes a baseline that is used to determine where excavations are required and to align opportunistic digs with a unique knowledge of what is in the pipeline, aligned with operator records. In-ditch testing is used to gather accurate and complete information from the excavation; it enhances the verification process and increases the confidence that the material properties are adequately characterized. The product provides compliant with traceable, verifiable and complete (TVC) pipeline material properties that can be used in effective integrity programs to satisfy regulatory requirements.

Introduction

PHMSA is revising the Federal Pipeline Safety Regulations to improve the safety of onshore gas transmission pipelines. The amendments introduced in the first rulemaking address integrity management and other requirements, focusing on the actions an operator must take to reconfirm the maximum allowable operating pressure of previously untested natural gas transmission pipelines and pipelines lacking certain material or operational records. A central theme within the new regulations is an acknowledgement that robust, i.e. Traceable, Verifiable and Complete (TVC), material properties are essential for effective integrity management. Where robust material properties are not available, they must be established and the regulations include a prescriptive clause, 192.607, describing the requirements for Material Property and Attribute Verification. This paper will describe an integrated approach using enhanced In-line Inspection (ILI) and state of the art Non-Destructive testing (NDT) in-situ to address the new regulatory requirements.

Material Property Verification

Material Property Verification is described in clause 192.607. There are a number of key constituents to the process; definition of the properties and attributes that must be verified, non-destructive and destructive testing methods, the use of *populations* to ensure the verified properties are valid and sampling frequency.

The regulations are prescriptive. When existing TVC material records are not available, the following pipe properties and attributes must be verified: diameter, wall thickness, seam type, and grade (e.g., yield strength, ultimate tensile strength). In a specific circumstance, toughness is also required. The above properties and attributes can be established using non-destructive and/or destructive methods using tools, procedures, and techniques that have been validated, account for measurement accuracy and uncertainty and have been calibrated. With respect to this paper, the focus is on using non-destructive techniques.

Populations are required in order to ensure that the data collected using non-destructive methods is valid and that it adequately describes the different types of pipes and hence different material properties in the required sections of the pipeline. A population is described in 192.607 as pipe with the same combination of diameter, wall thickness, grade, pipe-manufacturing process, manufacturing date and construction date. In each population, the material properties are considered verified for each population when data is collected on one pipe per mile or an alternative statistical sampling basis is applied, providing it achieves 95% confidence that the properties are valid.

Defining the strategy for Material Property Verification

With the introduction of new regulations, operators are faced with a significant undertaking. At this stage, the amendments are focused on establishing robust material properties as part of MAOP reconfirmation, clause 192.624, and providing representative inputs to defect assessments. Material property verification and clause 192.607 should be considered in relation to the wider issue of effective Integrity Management. As stated by PHMSA: "PHMSA hopes that operators will use this method for material properties verification even when not specifically required by part 192 because it provides a common-sense, opportunistic, and practical approach for gathering the records necessary to substantiate safe MAOPs, properly implement IM, and otherwise ensure the safe operation of the nation's pipeline network."

When considering the new regulations, the task of material property verification may appear daunting since by definition the pipelines affected will be older, more likely to have missing documentation and be made up of a wide range of pipe types. The premise of an effective strategy is to establish the current state of knowledge, define what material property verification is needed and where and when it is needed by. A critical task is aligning the existing documentation along the pipeline length. This establishes the 'what we know', 'what we assume' and 'what we definitely don't know'. The driver for material property verification could be to provide accurate data inputs for assessment of metal loss or crack-like defects, or it could be for MAOP validation in HCAs, Class 3 or Class 4 locations. The HCAs, Class 3 and Class 4 locations can be aligned with the status of existing documentation. An example schematic is given in Figure 1~~Figure 1~~, with the TVC properties and attributes, existing pressure test records and class one or two locations defined in green and the gaps identified in red. Applying the guidance in clause 192.624 for MAOP verification there is only one area along the pipeline that requires action, highlighted in Figure 1~~Figure 1~~.

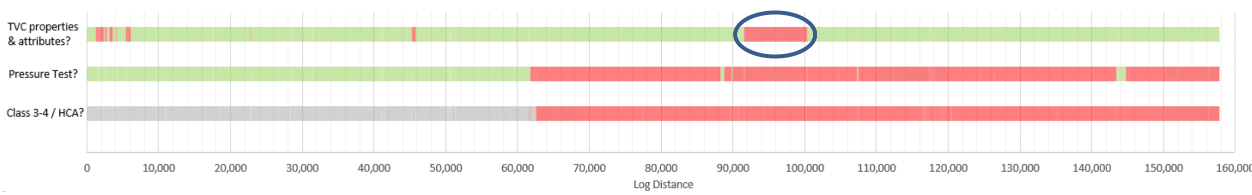

Figure 1 Alignment of existing knowledge

In terms of what material property verification is required, the aforementioned grade, wall thickness, diameter and pipe type are all needed as they are integral parts of the Barlow Equation, along with pipe type for joint efficiency factors, used for defining the MAOP. Grade, wall thickness and diameter are also required when assessing the integrity threats such as corrosion or crack-like features. This is important within the wider Integrity Management Plan when it comes to remediation, but it is also explicitly required as part of MAOP re-confirmation if using Method 3 of 192.624, an Engineering Critical Assessment. For crack-like features, 'toughness' is also required which currently requires either destructive testing of representative materials or highly conservative assumptions if it is not documented within existing records. Ongoing developments in non-destructive methods to measure the toughness of pipelines are briefly discussed later in this study.

With the drivers and requirements identified, it is possible to collect the necessary material property data, in accordance with time frame established in the regulations (if applicable, for MAOP validation) and considering the overall Integrity ~~management~~ Management Plan, to close out Material Property Verification as efficiently as possible through an optimum combination of opportunistic digs or specific planned digs.

An Integrated Approach for Material Property Verification

In order to meet the requirements of clause 192.607, an integrated approach of enhanced ILI and state of the art NDT is required. ILI provides the bird's eye view along the pipeline length, re-creating the as-built condition and describing the various populations of pipe. Effective material property verification is established on the [SP1]baseline. In-situ NDT provides verification of the ILI and completes the material property data gathering process, with augmented accuracy, detail and confidence. Only with such a combined approach, can the required properties be captured with sufficient accuracy and linked to the various pipe types present in the line ensuring the data is representative and valid.

Enhanced ILI

The enhanced ILI service provided by ROSEN is called RoMat PGS. It incorporates a range of ILI components, the main one being high-resolution eddy current measurement technology, with the signal response being a function of specific pipe chemistry and microstructure. The RoMat PGS technology is incorporated onto a standard MFL tool, Figure 2~~Figure 2~~, meaning it can be run as part of a *standard* inspection campaign. The signals are used to determine a yield strength (YS) and ultimate tensile strength (UTS) for each pipe using algorithms developed through extensive pull tests correlated with material test data. The other ILI components are RoCorr MFL-A and RoGeo XT to define diameter, wall thickness, joint length and pipe type, and RoGeo IMU to define spatial alignment and route analysis. Enhancement in the definition of pipe type can be achieved using RoCorr MFL-C. The multiple data sets described above are integrated through ROSEN's 'Pipeline DNA' process to determine populations as referenced in the new regulations.

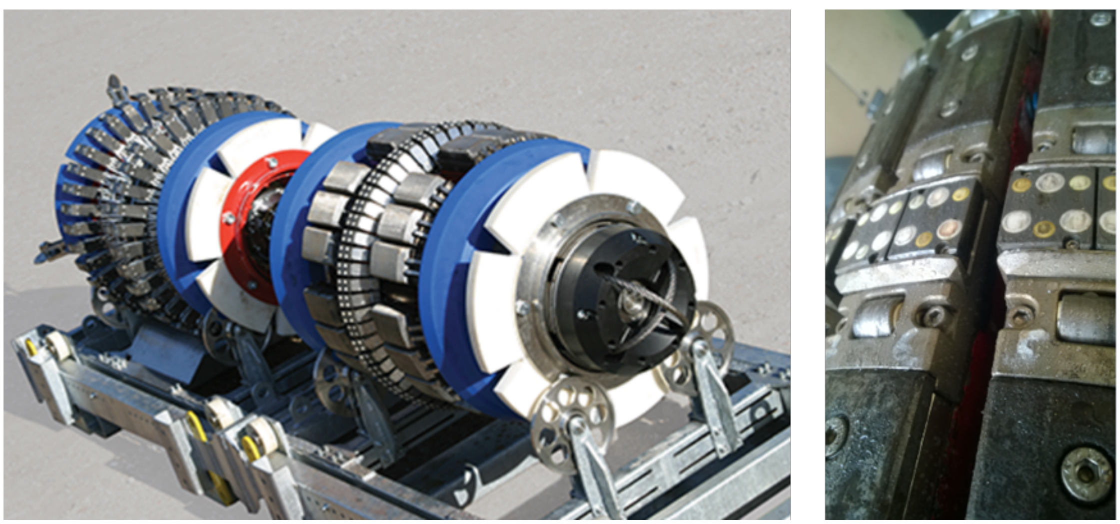

Figure 2 RoMat PGS Sensors and a standard MFL A ILI tool

The Pipeline DNA process has been described in detail in previous papers [1, 2]. The process uses all available data and critically the YS and UTS data to establish robust populations of pipes with the same attributes. Measurement of strength data for every pipe allows identification of any outliers that many be of particular interest, which is only possible using an ILI approach as opposed to a strategy based on excavations alone. The Pipeline DNA process is underpinned by the knowledge that each population of pipes will have a distinct combination of diameter, wall thickness, Grade (as established using the YS and UTS), nominal joint length and pipe type (welded or seamless). In the absence of documentation, a distinct combination of these variables is a proxy for a specific pipe manufacturing process, i.e. pipe made by a specific manufacturer at a certain point in time.

Figure 3~~Figure 2~~ shows the distribution of YS for a specific pipe population and a pipe that can be identified as not belonging to that population. This single pipe could actually be an outlier and a potential integrity concern, not only in terms of a difference in strength, but as an indication of a different supply of pipe with differences in the manufacturing process, perhaps translating to differences in the toughness or the manufacturing seam weld properties. In the example shown in

Figure 3~~Figure 3~~ the statistical distribution and 3 times the standard deviation is used to define a best estimate Grade of X46.

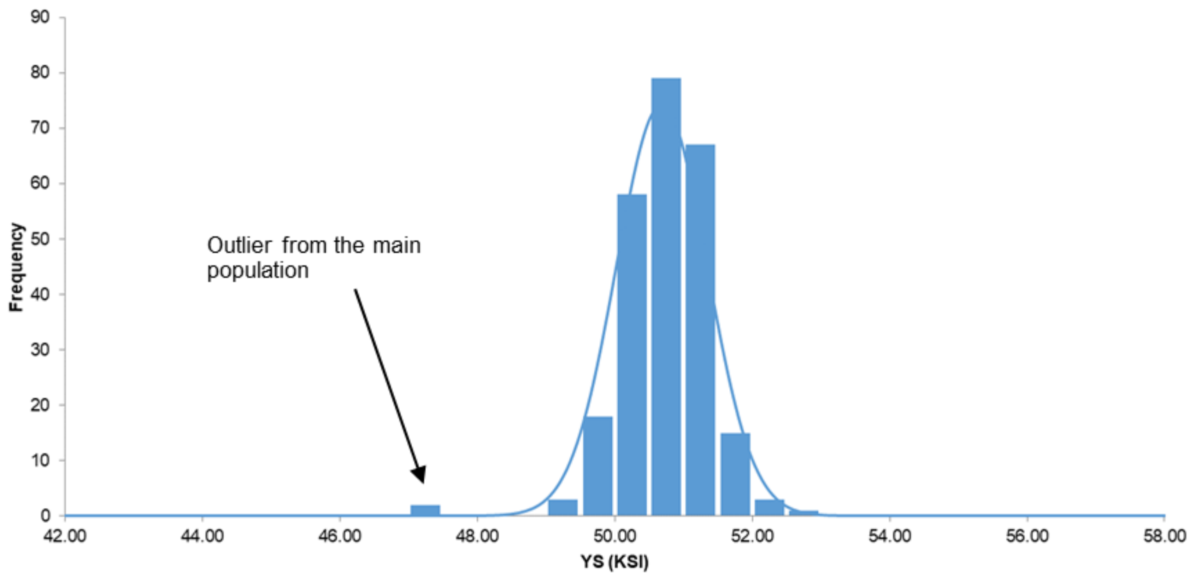

Figure 3 Normal distribution of pipe YS for a specific population

The guidance in the new regulations to consider construction date is more difficult to address as pipes purchased at one point in time can be stored and used for construction later. However, using the Pipeline DNA process in combination with existing documentation, analysis of the pipeline routing and satellite imagery, information about construction date can be re-established.

Figure 4~~Figure 4~~ shows an example of different populations identified along a pipeline as a function of YS. Although this example shows a number of populations, it is important to remember that the requirements are linked to the drivers and strategy. It is typically the case that only a small number of the populations require action, since 192.624 is only applicable under a combination of three factors: specific locations, missing pressure test records, and missing records of attributes and properties. It is not possible to identify the populations that require action and link back the data collected from digs to close out the Material Property Verification process without using enhanced ILI as the baseline.

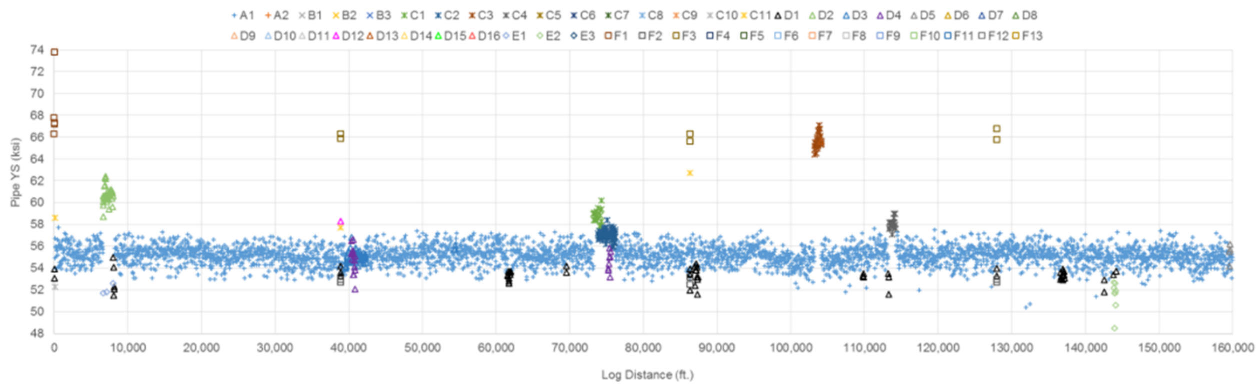

Figure 4 The different populations along a pipeline identified using RoMat PGS and the DNA process

The data from Figure 1~~Figure 1~~ and Figure 4~~Figure 4~~ are overlaid in Figure 5~~Figure 5~~, showing that action would be required in one area. The highlighted area falls in an HCA and is not covered by pressure test or material property records, so MAOP Validation is required under 192.624. This area falls within the main population, identified as A1 (blue crosses). As RoMat PGS has established this undocumented section as belonging to population A1, to which TVC material property records are already available in other locations, those records can be applied to this section. If needed, for confirmation, equivalence could be evidenced opportunistically by chemical analysis and non-destructive strength testing. Conversely, if this population were undocumented, excavations would be required in accordance with 192.607.

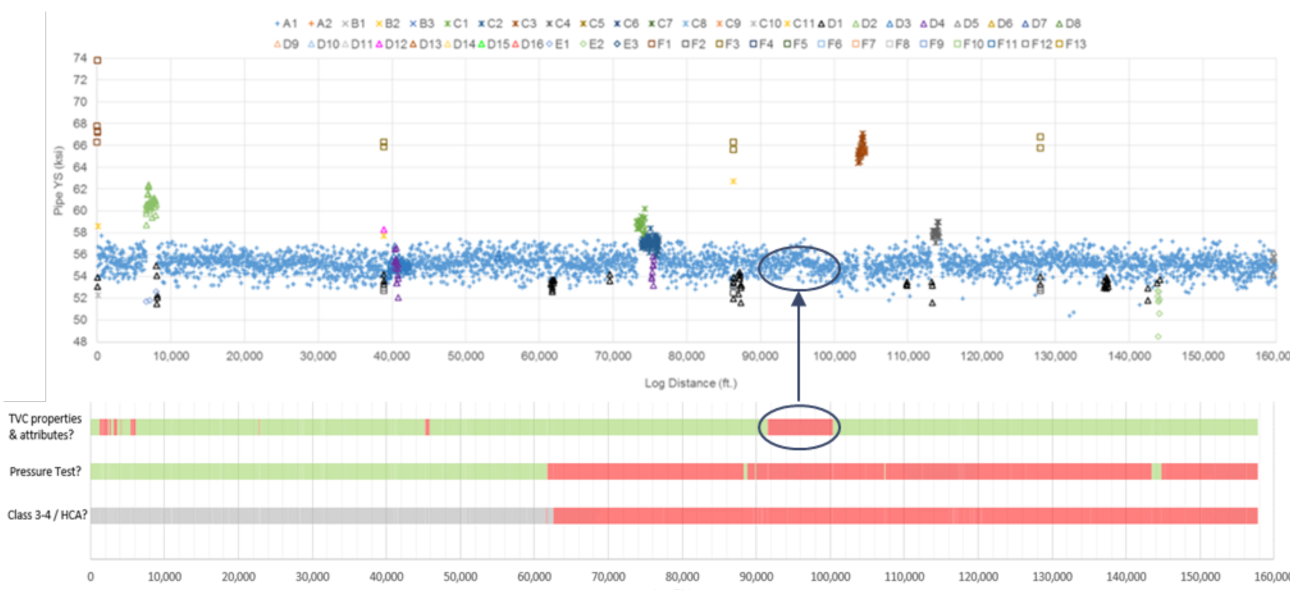

Figure 5 Example of Material Property Verification

State of the Art NDT

With the enhanced ILI baseline and strategy in place, the focus can shift to collecting NDT data in the ditch to augment records and provide verification of ILI results. The requirements of 192.607 for non-destructive tests, in terms of the material properties and attributes that must be collected, can be captured in one procedure that includes NDT elements in combination with the Hardness, Strength, and Ductility (HSD) Tester. The HSD is a portable implementation of the contact mechanics technique known as frictional sliding that was developed by Massachusetts Materials Technologies (MMT). During in-ditch material verification, the HSD is implemented along with additional assessments of the pipe geometry, microstructure, and longitudinal welded seam to provide complete documentation of material properties. This process is summarized in Figure 6~~Figure 6~~, and further detailed below:

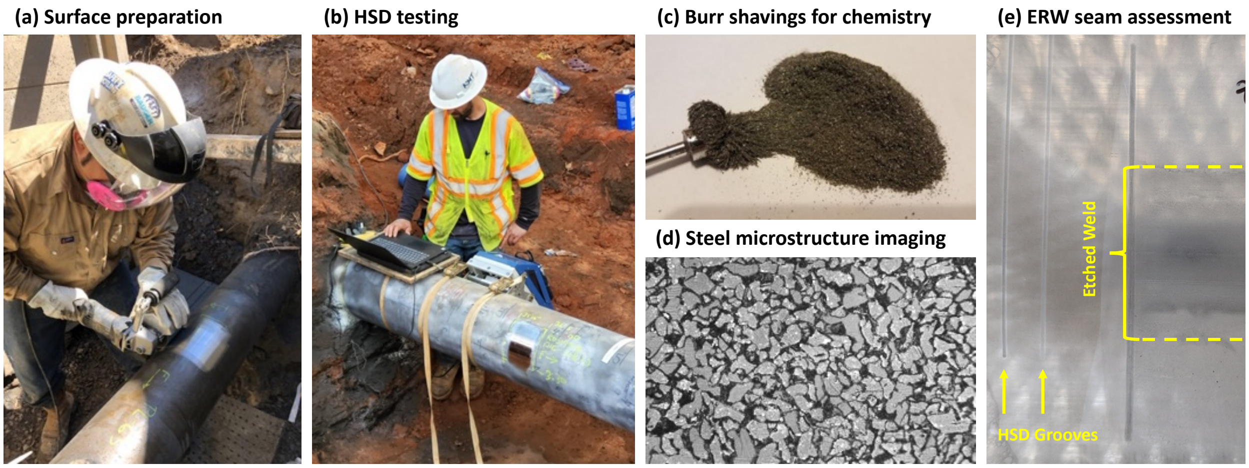

Figure 6 Overview of in-ditch NDE methods. (a) Surface preparation is performed at suitable test locations. (b) The HSD is strapped to the pipe joint for testing. (c) Burr shavings are removed for chemical analysis. (d) The steel microstructure is etched and imaged. (e) Additional seam characterization is performed to assess the visual size of heat affected regions and mechanical variation in the weld.

Visual Inspection and NDT

An important part of the in-ditch material verification work is visual inspection. This visual inspection must start before any of the coating is removed. In many instances, visible markings can be observed with specific information stenciled, written or stamped on the coating or pipe. This information can include grade, wall thickness, pipe mill or coating mill identification and even date of manufacture.

Before performing any of the NDT an initial examination of each pipe joint is conducted through visual observations, ultrasonic testing (UT), and magnetic particle inspection to identify locations that are safe for testing. Two quadrants around the circumference of each pipe are selected for strength characterization with the HSD, with one of these locations centered on the longitudinal seam for electric resistance welded (ERW) pipe joints. These locations are progressively buffed through a surface preparation procedure that removes any decarburized layer and provides a polished surface for HSD testing. A UT wall thickness survey from the in-ditch examination is also used to monitor the wall thickness and validate the pipe attributes in combination with the ILI results and existing records.

Metallography and Chemical Analysis

Surface metallographic imaging of the steel microstructure is performed in the same location that pipe body strength properties are measured. The microstructure is etched with a Nital solution and then imaged using a portable microscope and camera with a high magnification lens. These images are then processed with an in-house software to segment grain boundaries and determine the average grain size using the mean-linear-intercept (MLI) method [3].

Chemical composition is measured through laboratory testing of burrs removed from the pipe surface. Burrs are collected using a die grinder at a location on the pipe surface that is near one of the HSD base metal test locations. Combustion analysis is used to measure carbon and sulfur content and Inductively Coupled Plasma Optical Emission Spectroscopy (ICP-OES) is used for all other elements.

The metallography and chemical analysis can be used in combination with the other data sets to verify material records or to establish new records where none exist. Chemical composition and microstructure are also the clearest evidence of equivalence between different pipes, which is essential to validating or combining the population assignments.

Determination of Seam Type

An important part of the new regulations is identification of seam type. ILI can do a good job of providing an initial differentiation that can then be augmented by detailed investigation in the ditch for each population. Seam types for flash-welded, submerged arc welded (SAW), and lap-welded pipes are determined from observations of external weld features and reinforcement, but additional examination is required for ~~electric resistance welded (ERW)~~ERW seams that do not have characteristic surface features. For ERW pipes, the heat-affected-zone (HAZ) surrounding the seam is visually assessed by performing a macro-etch of the weld on the outer surface of the pipe joint. After etching, an apparent HAZ and bond line are visible as discoloured regions on the pipe surface, and the width of the etched HAZ (L_{HAZ}) can be determined. The HSD is also used to measure variations in hardness from a circumferential test across the width of the ERW longitudinal seam to characterize changes in mechanical properties from different welding processes and post-weld-heat-treatments (PWHT). Representative hardness profiles and etched seam images are provided in Figure 7~~Figure 7~~ for Low Frequency (LF), High Frequency (HF), and HF welds that were normalized (HFN) through an effective post-weld-heat-treatment.

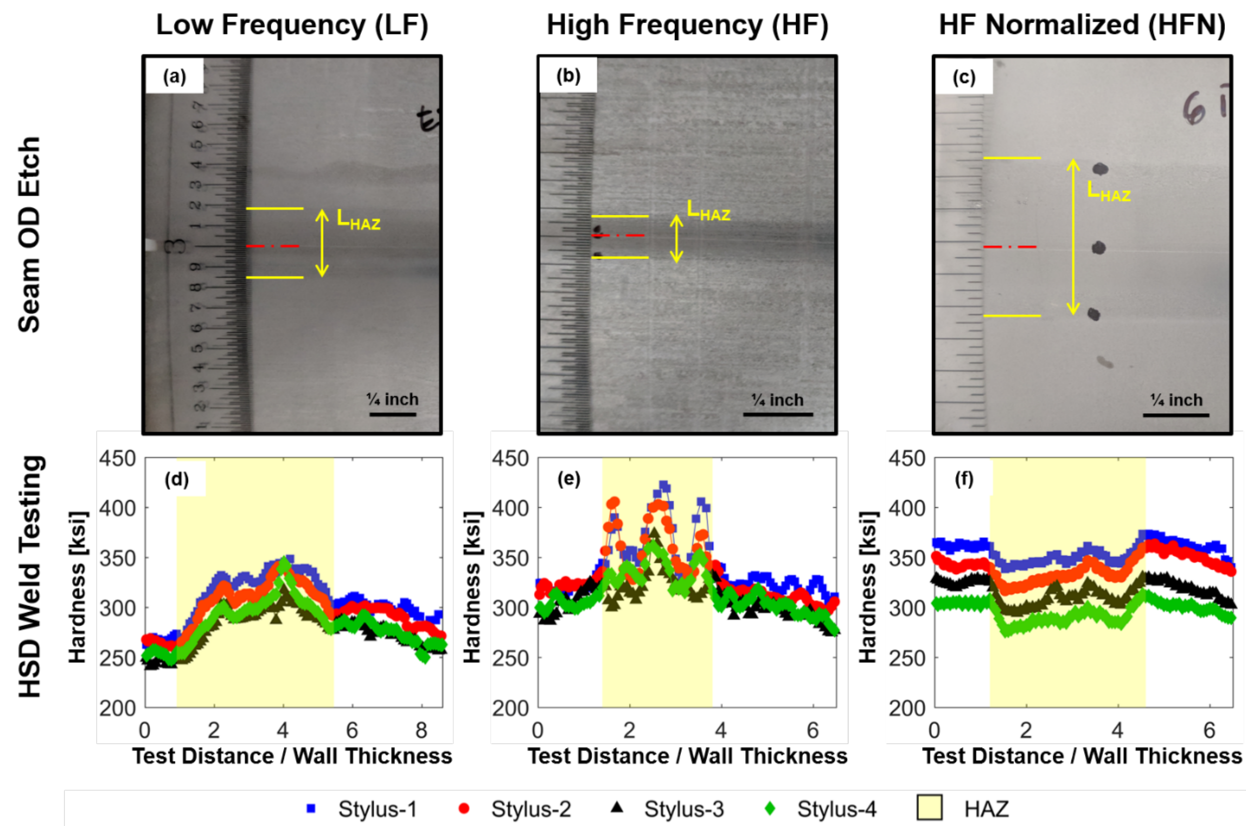

Figure 7 Representative etched seams (a-c) and hardness profiles (d-f) for LF, HF, and ~~HFN~~ HFN-ERW welds.

MMT has developed a methodology for using the width of the HAZ and the HSD hardness changes from weld tests to classify ERW pipe joints as LF, HF, or HFN-ERW [4]. This approach has been applied to a welded seam database of 54 ERW pipe samples where the welding process was confirmed through a destructive visual examining of the etched pipe wall cross-section containing the seam. These results are shown in Figure 8~~Figure 8~~, along with decision boundaries that have been determined through different classification models applied to the database.

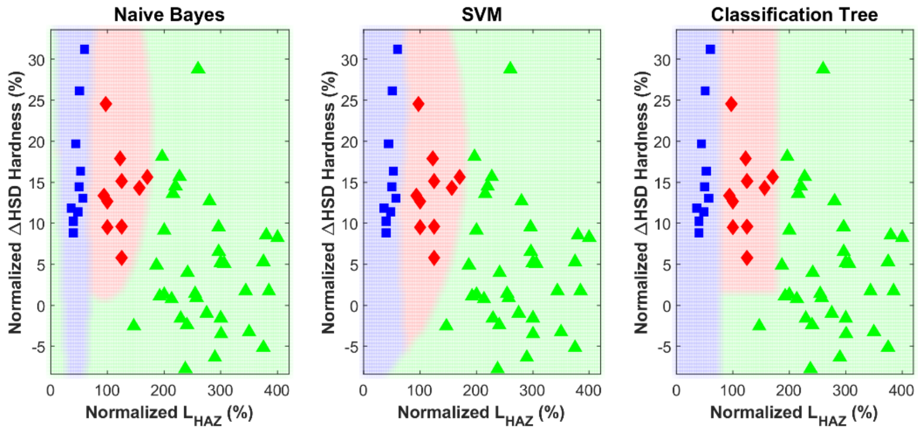

Figure 8 Seam classification for database of 54 unique ERW pipe samples. Blue indicates HF, red indicates LF, and green indicates HFN. Each plot is a different classification algorithm applied to the database, resulting in differences for the decision boundaries dividing the welding processes.

In-ditch Measurement of Strength Properties

The HSD can be utilized to provide a measurement of the pipeline strength properties that provides additional confidence to the baseline established through ILI. The HSD method meets the requirements of 192.607 pertaining to non-destructive methods for measuring strength properties. The approach was validated through Pipeline Research Council International (PRCI) program NDE-4-8 [5], and the determination of material properties can conservatively account for measurement inaccuracy and uncertainty using reliable engineering tests and analysis. Tests are performed in two circumferential quadrants and the technology gathers hundreds of measurements during each test. This data is analysed to ensure at least five averaged readings at each quadrant, and a minimum of 10 for the pipe joint.

The data collected during in-ditch assessments are input within proprietary data analytics to provide an accurate determination of strength properties. These analytics are based on the application of machine learning to a database of pipe samples that are characterized using both conventional and NDT approaches. The current method combines HSD strength measurements with additional information of the seam type, microstructure grain size, and chemical composition through a Bayesian regression model that has been trained to a database of 167 unique pipe joints that include seamless, flash-welded, ERW, and SAW construction. The current model performance is summarized by the unity charts in Figure 9~~Figure 9~~ for API 5L YS and UTS [6]. A previous regression model trained to a smaller database of 75 pipe samples was assessed during the PRCI NDE-4-8 validation program for which the testing and analysis was completed in 2017 [5]. The greater sample size provides a more representative population for increased accuracy and robustness of NDE strength predictions.

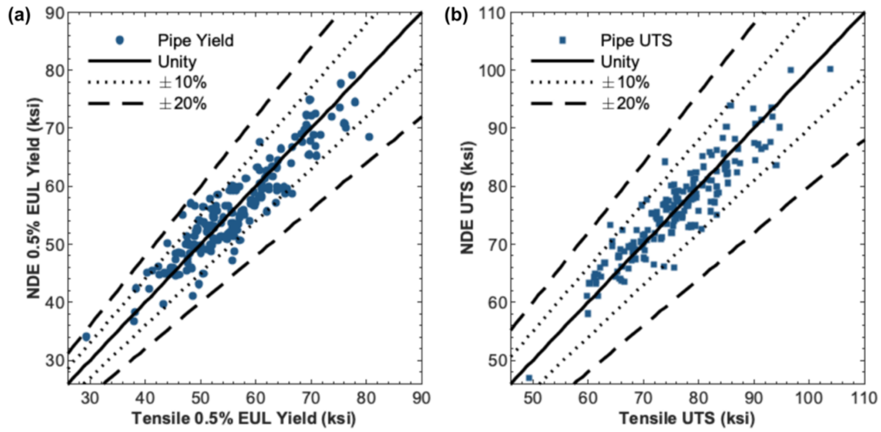

Figure 9 Unity plots comparing NDE and laboratory tensile measurements for (a) YS and (b) UTS

Assigning Pipe Grade

A best-fit grade is assigned to each population at the ILI stage and then further refined with added confidence for the testing of an individual pipe joint within a specific population through in-ditch NDT. The grade is determined by comparing the measured YS and UTS values of the population or pipe joint with the specified minimum requirements of API 5L. In both cases, since the grade determination is based on actual strength properties, the grade that is reported will also meet the requirements of all lower grades (e.g. X46 meets Grade A, B, and X42 as well). The grade defines the specified minimum ~~strength~~ yield strength (SMYS) that ~~are~~ is used within the regulations for calculation of MAOP and any reconfirmation process.

The 192.607 requirements stipulate that strength properties measured with a non-destructive method must account for uncertainty of the technique used. This uncertainty can be determined from a prediction interval, which provides the confidence for a predicted response based on prior performance of the same methodology on a database of samples with similar characteristics. Both the ILI and NDT techniques have defined tolerances and confidence limits for the YS and UTS of any individual pipe measured. For the HSD process, the measurement uncertainty for YS and UTS predictions for varying confidence levels has been determined from the model performance shown in Figure ~~8~~9, and the results are plotted in Figure 10~~Figure 10~~.

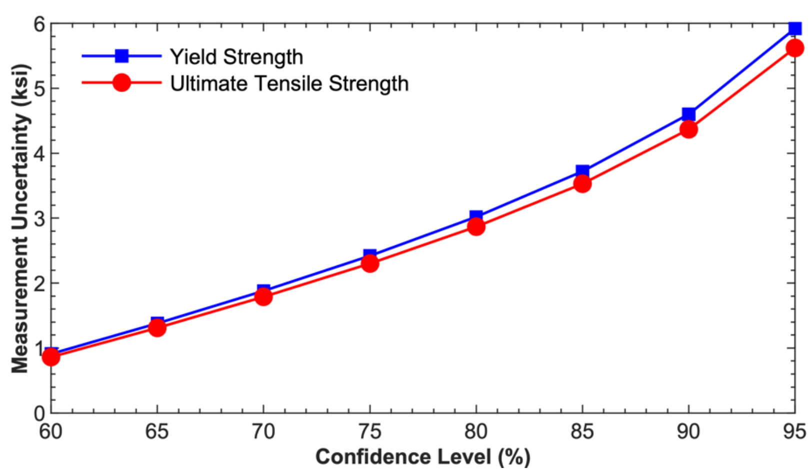

Figure 10 Strength measurement uncertainty of the HSD for varying confidence levels.

The use of ILI and NDT data to assign a grade to the whole population of pipes must also consider the sampling frequency and treatment of the multiple data points collected from that population. Using an integrated ILI and NDT approach provides significant confidence that representative material properties have been assigned, as it combines the benefit of testing every pipe (from ILI) to ensure the process is statistically valid with the necessary accuracy and confidence (from NDT). In order to close out compliance with 192.607 the regulations permit two approaches to sampling. The 'standard' approach requires sampling at one location per mile within each population. Once this sampling frequency has been reached, material properties can be assigned using the collected data. The regulation requires that the accuracy of the technique is accounted for and higher accuracy techniques therefore reduce conservatism in the final material property assignment. Alternative processes are also permitted through submission to PHMSA and receipt of a 'no objection'. An alternative process would make use of statistical treatment of collected data to enable a reduced sampling frequency, whilst retaining a valid and rigorous statistical approach at a defined confidence level. For larger populations (i.e. over a few miles in aggregate length) this approach offers a significant reduction in the number of excavations needed to close out the process compared with a 'standard' 1 per mile sampling program. In order for a statistical approach to be valid it is first essential that a population is proven to be uniform i.e. is a 'true' and complete population. This can be attained through ROSEN's Pipeline DNA process leveraging RoMat PGS. The accuracy of the in-situ NDT technique for strength measurements is critical, as the variance in measured properties within a population and the magnitude of the measurement uncertainty has a large impact on the final material property assignment using any statistical approach. As a result, the ~~Use~~ use of NDT techniques with high accuracy and confidence will translate into a significantly less conservative material property assignment.

Toughness

To address the specific requirement in clause 192.624 for assessing crack-like features as part of an ECA, toughness is required. Toughness is a material property parameter that is determined through Fracture Toughness Testing (K, CTOD, J testing) or Charpy Impact testing. The parameter required is linked to the assessment method being used, and at the very least Charpy Impact test data is required. There is currently no commercially available and validated NDT technique for determining actual quantitative toughness values. There are qualitative approaches where some operators assign different seam toughness values based on the determination of a weld that is LF, HF, or HFN that can be assigned through the weld classification approach discussed above. There are ongoing developments to produce ILI toughness testing services and an NDT methodology to obtain a quantitative index of toughness in the pipe body [7] and the seam. Until such a time that these NDT methods becomes available, testing of representative pipe is required. Due to the operational issues associated with removing pipe from the ground, it is imperative that operators follow an optimized strategy based on a complete and robust population assessment.

Case Studies on Gas Transmission Pipelines

A recent example of the integrated approach is presented below. Following the enhanced ILI opportunistic digs were available coinciding with remediation work based on another ILI technology. The enhanced ILI and DNA process identified that the opportunistic digs covered three different populations with the wall thickness, tensile properties, estimated Grade and pipe type as shown in Table 1~~Table 1~~.

Pipe	Population	Pipe type	ILI YS (KSI)	ILI UTS (KSI)	ILI Grade (of Population)	Nominal wall thickness from ILI (inches)
A	1	Welded	53.5	74.0	X46	0.281
B	2	Welded	55.8	76.9	X46	0.375
C	3	Welded	54.3	75.0	X52	0.281

Table 1 Data from enhanced ILI and the DNA process

The MMT NDT procedure was performed in the ditch at these three locations. In this case, no testing was performed on the weld seam. The results from the NDT are presented in Table 2~~Table 2~~.

Pipe	Population	Pipe type	NDT YS (KSI)	NDT UTS (KSI)	NDT Grade	Measured wall thickness (inches)
A	1	EFW	48.4	73.1	X46	0.300
B	2	ERW	47.4	65.8	X46	0.375
C	3	ERW	48.4	65.8	X46	0.298

Table 2 Data from NDT in the ditch

The grades reported by ILI and by NDT are in broad agreement with some differences due to the respective tolerances. The NDT data from the ditch does not contradict the ILI values but rather refines the values assigned from ILI by virtue of a higher accuracy and confidence. The data points from the MMT HSD meet all requirements of 192.607 for non-destructive testing and can be used to verify the pipe grade of this undocumented population, if the sampling frequency requirements specified in 192.607 are fulfilled.

The ILI and DNA process identified all of the populations to be welded pipe, and the NDT in the ditch was able to refine that definition by identifying populations 2 and 3 as ~~Electric Resistance Welded (~~ERW~~)~~ pipe and population 1 as Electric Flash Welded (EFW) pipe. If the more detailed testing had been performed on the weld then the definition could have been refined further to possibly differentiate whether populations 2 and 3 were Low Frequency ERW or High Frequency ERW, and if any heat treatment had been performed.

The nominal wall thickness identified by the ILI and Pipeline DNA process was confirmed through the NDT process with a measured wall thickness that was at least equivalent to the nominal recorded.

The chemical analysis for each pipe is presented in Table 3. The analysis helps to confirm that the populations are different. It is interesting that populations B and C have very similar chemistries. A review of the joint length and tensile property histograms shows that the populations share the same characteristics apart from the wall thickness, Figure 11~~Figure 11~~. This suggests that the pipe was manufactured at the same time by the same manufacturer but at two different thicknesses. This is entirely plausible and an excellent example of how the approach described in this paper can be implemented to characterize the different types of pipe within a pipeline.

Pipe	**A**	**B**	**C**
Carbon (C)	0.25	0.18	0.17
Silicon (Si)	0.03	<0.01	<0.01
Manganese (Mn)	0.68	0.71	0.61
Phosphorus (P)	0.01	0.006	<0.005
Sulfur (S)	0.022	0.019	0.016
Chromium (Cr)	0.02	0.19	0.17
Molybdenum (Mo)	<0.01	<0.01	<0.01
Nickel (Ni)	0.03	0.02	0.02
Aluminum (Al)	<0.01	<0.01	<0.01
Copper (Cu)	0.04	0.25	0.26
Niobium (Nb)	<0.01	<0.01	<0.01
Titanium (Ti)	<0.01	<0.01	<0.01
Vanadium (V)	<0.01	<0.01	<0.01
CE	**0.376**	**0.358**	**0.328**

Table 3 Chemical Analysis

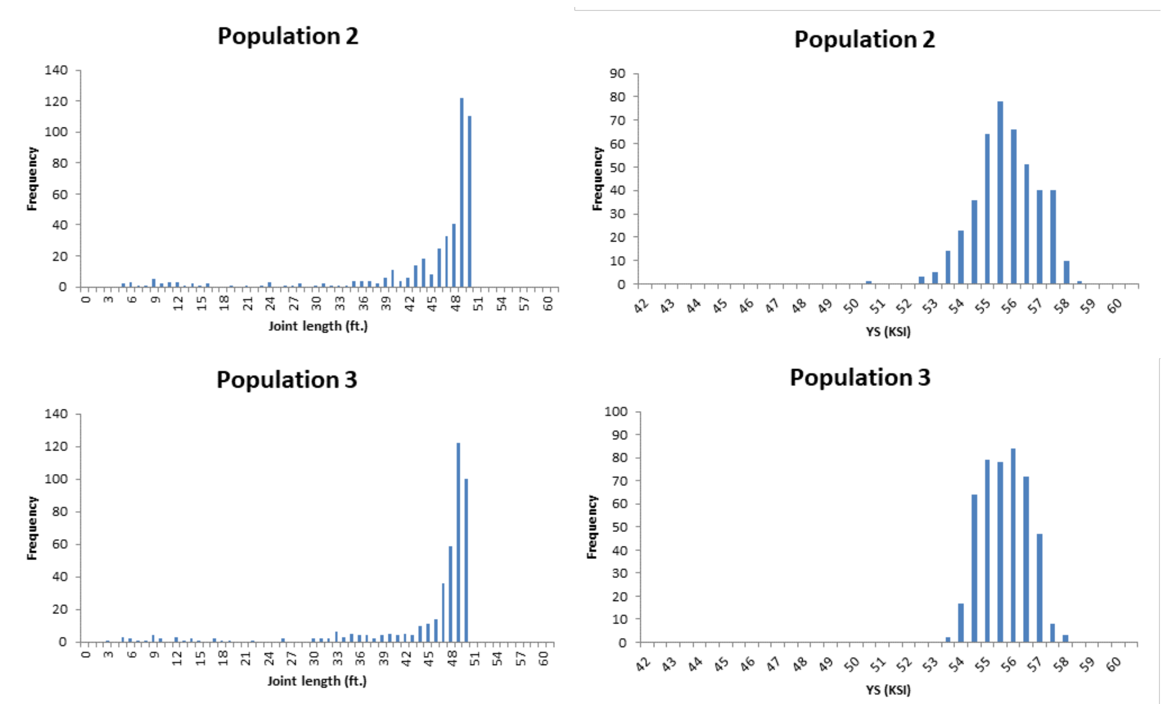

Figure 11 Similar pipe joint length and YS for populations 2 and 3

Returning to the issue of sampling frequency, in this case the number of miles in each population is greater than 1 mile and therefore completing the material verification process requires further testing. For example, population 1 is cumulatively 3.8 miles long, so a further three digs are required in order to reach a sampling frequency of one per mile. The integrated approach becomes increasingly beneficial as the length of covered segments increases. For very long segments, sampling requirements of 1 per mile may be impractical, and in that case operators may elect to use an alternative sampling process as permitted in the clause 192.607 (e) (5), working towards a 95% confidence limit. The ILI and NDT approach supports this type of ~~approach~~ analysis to reduce ~~reducing~~ the number of digs that might normally be required. Once the required sampling frequency has been achieved, the final grade and other attributes can be assigned to each population.

A further example is shown below to illustrate the benefit of doing NDT testing on the weld seam. The enhanced ILI defined the pipe as welded, and the NDT technique performed by MMT confirmed the weld to be high frequency ERW. The welded seam assessment is summarized in Figure 12~~Figure 12~~. The etched HAZ width was 260% of the pipe wall thickness, indicating that a PWHT was applied to normalize the microstructure. An HSD weld test was used to measure the hardness variation across the weld and found only a moderate increase in hardness with no large spikes in hardness within the HAZ that would be expected if the pipe did not receive an effective PWHT. These NDT measurements can be compared to the database of known ERW pipe joints to predict the welding process. For this sample, all three classification models predicted the weld to be HFN-ERW, with a probability of 100%.

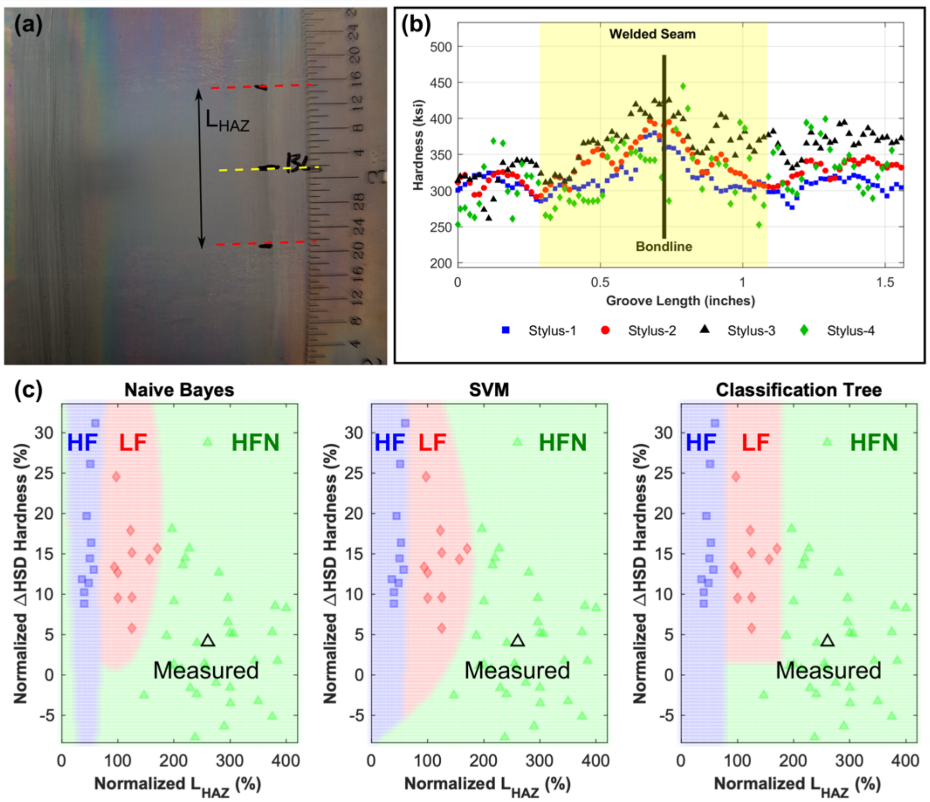

Figure 12 Overview of welded seam analysis including the (a) etched weld and (b) HSD weld test with the HAZ identified by the shaded region. (c) The measured results can be compared to the ERW database to see that all classification models determine the pipe joint to be HFN-ERW.

The outcome from seam assignment agrees with expectations based on additional data collected like the vintage, chemistry, grain size, and pipe grade shown in Table 4~~Table 4~~. An image of the base metal microstructure showing the fine grain size is shown in Figure 13~~Figure 13~~.

Vintage	Late 1970
Grade	X65
MLI grain size (µm)	5.4
Carbon (C)	0.04
Silicon (Si)	0.20
Manganese (Mn)	1.08
Phosphorus (P)	0.015
Sulfur (S)	<0.005
Chromium (Cr)	0.02
Molybdenum (Mo)	0.01
Nickel (Ni)	0.03
Aluminum (Al)	0.03
Copper (Cu)	0.07
Niobium (Nb)	0.03
Titanium (Ti)	0.01
Vanadium (V)	<0.01
Nb + Ti + V	<0.05
CE	0.23

Table 4 Chemical analysis

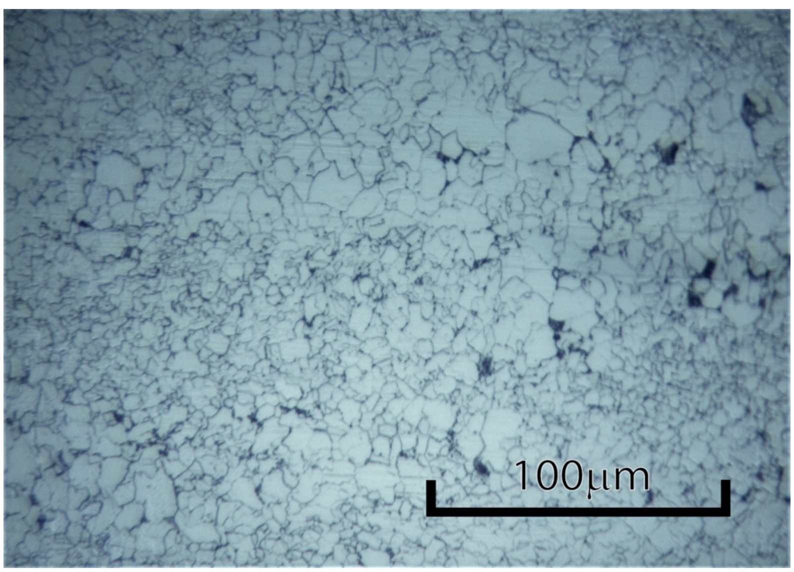

Figure 13 Pipe body microstructure image from in-situ metallography.

Conclusions

New regulations pertaining to the characterization of the material properties have been established for gas transmission pipelines. Based on a well-defined strategy for material property verification, an integrated approach of state of the art ILI and NDT testing in the ditch can be implemented to close out the process effectively. The ILI process enables robust *populations,* with unique combinations of variables (including a best-fit grade) that are compliant with the requirements prescribed in the regulations, to be identified along the pipeline length. As part of the *pipeline DNA process* outliers and deviations from expectations are identified. The HSD is a validated methodology that is used in combination with additional NDT measurements to determine the pipe properties in line with the specific requirements of clause 192.607. The HSD also provides unique capabilities to identify and assess the welding process and quality of a longitudinal ERW seam through the measurement of variations in properties along the length of a test and a macro-etch on the surface of the seam. The final integrated approach can be used in accordance with either of the sampling frequency options in the new regulations to define the traceable, verifiable and complete (TVC) pipeline material properties that can be used for effective integrity programs and to satisfy regulatory requirements.

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