Measuring Pipe Seam Toughness via Frictional Sliding

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Abstract

The growing use of advanced In-line Inspection (ILI) for detecting seam anomalies has increased the demand for Engineering Critical Assessment (ECA) to differentiate the many non-severe features that do not need repair from features in certain assets where repairs are warranted. To perform the ECAs and reduce the number of unnecessary excavations of vintage lines, pipe cutting for laboratory testing has become more common to obtain Charpy V Notch (CVN) toughness, which is often unavailable when legacy manufacturing standards did not require such testing. Non-destructive evaluation (NDE) of pipe seam toughness as a part of opportunistic data collection is an attractive alternative to pipe cutouts and can be applied to prior excavations with sufficient NDE data. An NDE process using the frictional sliding method and other surface measurements has been recently validated for assessing the seam toughness of vintage electric resistance welded (ERW) pipes. This paper details this NDE process and its validation, along with results from case studies of its initial field deployment. The field instrumentation is the same as used for pipe grade determination using the frictional sliding method. When certain conditions are met for a given ERW pipe population, a ductile fracture initiation and an associated CVN toughness of 10 to 15 ft-lbs. can be positively confirmed when conservatively accounting for measurement uncertainty. Utilizing a toughness of 10 to 15 ft-lbs. is a significant advantage over conservative values such as 4 ft-lbs. for gas transmission pipelines with no history of failure.

1. Introduction

Background

ERW pipes made before 1970 have higher failure rates due to seam manufacturing defects (e.g., cold welds, selective seam weld corrosion) that fail at lower stress levels than expected based on pipe body toughness (Kiefner et al., 2014). The toughness of the bond line areas is challenging to determine and varies from pipe to pipe. Pipeline operators can verify pipeline integrity using hydrostatic tests or ILI crack tools. However, they may need to learn the adequate toughness that decides if a crack needs excavation and repair. With known pipeline bond line toughness, it is easier to determine priorities for anomaly examination. Traditionally, in such scenarios, two options to improve the effectiveness of an ILI integrity assessment are available: either assume a conservative level of toughness and identify critical defects while minimizing unnecessary digs or back-calculate the toughness levels associated with the known crack sizes to identify defects at a specific level of confidence (Kiefner et al., 2020). The drawbacks of these approaches are that if the chosen toughness level is overly conservative, it could trigger unnecessary excavations for benign defects, increasing costs and potentially damaging the pipeline. This approach relies on pre-defined toughness values, offering less flexibility for tailoring the assessment to specific pipelines or defect characteristics. In the case of back-calculation, the toughness and defect assessment probability approach requires complex analysis of failure data and statistical calculations, demanding specialized expertise and resources. Back-calculated toughness values may contain inherent uncertainties due to limitations in the failure data and analysis methods. While the approach is data-driven, interpreting the probability of defect detection and making repair decisions can still involve subjective judgment. Lastly, neither approach tests seam welds.

Alternatively, assessing seam toughness using destructive methods like pipe cutouts for laboratory testing, while effective, is disruptive, time-consuming, and costly. A novel non-destructive evaluation (NDE) process that utilizes the frictional sliding method and other surface measurements to assess

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seam toughness without compromising the pipeline's integrity to address the above limitations is presented in this paper. Several other NDE methods that predict CVN test results, which differ in validation levels and database sizes, have also been developed. BMT Fleet developed models using input parameters to predict impact energy values at select temperatures but not for upper/lower shelf CVN or transition temperature estimates (Riccardella et al., 2018). Reliability Safety Integrity Pipeline Solutions (RSI) and Pacific Gas and Electric (PG&E) developed similar models using chemistry and grain size (Switzner et al., 2021). However, future work is needed to validate the methodologies using in-situ collected data and expand the training dataset. Furthermore, gas transmission pipeline assets are regulated under 49 CFR Part 192. The gas Mega Rule aims to reduce yearly incidents but cannot achieve "zero incidents" alone. Collaboration between PHMSA, pipeline operators, and third-party vendors is crucial. Our prior work discusses the regulatory aspect and the Mega Rule related to the non-destructive evaluation of fracture toughness (Rizwan i Haque et al., 2023). This paper provides details of the approach, its validation, and results from a field trial.

Transition temperature as 85% shear area

Multiple prediction models using machine learning (ML) were developed to evaluate regions of the Charpy V-notch (CVN) transition curve for the ERW seam, including the ductile-to-brittle transition temperature (DBTT) and the impact energy at the upper shelf. These non-destructive estimates are to be compared to curve fits of the CVN impact energy defined by

$$C_v = A + B * \tanh\left(\frac{T - C}{D}\right) \tag{1}$$

where T is the CVN test temperature and A, B, C, and D are fitting coefficients define the shape of the curve. Compared to tensile strength tests of the pipe body, CVN lab tests of the ERW seam are associated with more significant uncertainties due to material variation, data interpretation, and curve-fitting implementation, which leads to higher uncertainties in the NDE models developed to predict those lab values.

All NDE predictions of the CVN impact energy are for full-size specimens, assuming a linear relationship when scaling the impact energy for sub-size specimens. The ductile-to-brittle transition temperature (DBTT) is given for a full-size specimen in a drop-weight tear test (DWTT) using the relationship (Rosenfeld, 1996)

$$T_D = T_C + (66 * t_w{}^{0.55} * t_c{}^{-0.70} - 100) \tag{2}$$

where T_C is the CVN 85% shear-area transition temperature (SATT), t_w is the pipe wall thickness, and t_c is the CVN specimen width. The result of the applying curve fit on raw Charpy data for one pipe sample is shown in Figure 1.

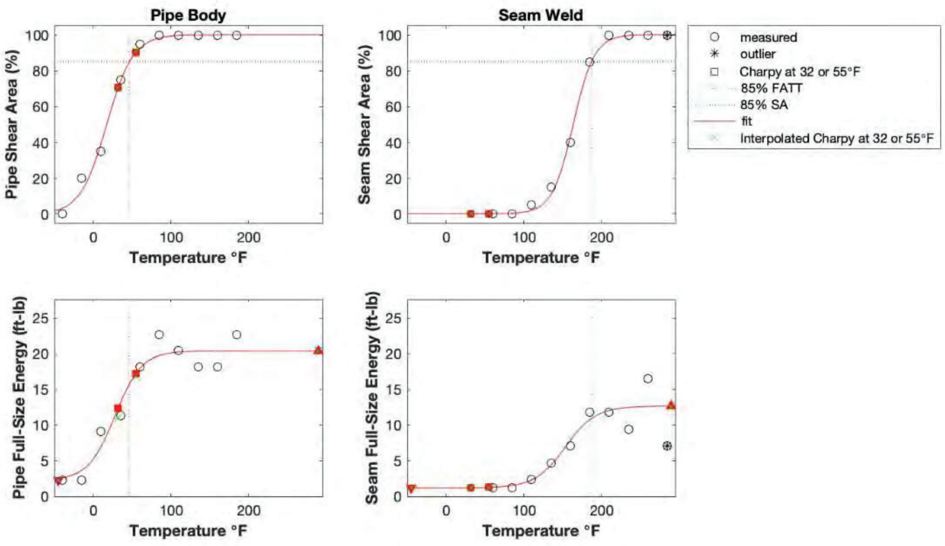

Figure 1. CVN tanh curve-fits for shear area vs. temperature and Charpy energy vs. temperature for pipe body and seam weld.

Figure 1 shows the tanh curve fits applied to raw Charpy data. The pipe sample was Charpy tested at ten different temperatures; the raw values are shown with circles. Charpy impact energy was also measured at 32°F and 55°F and is shown with squares. Seam weld toughness is not the same as pipe body toughness.

2. Technical description of the NDE process

Frictional sliding method

Hardness, strength, and ductility (HSD) testing applies the concept of frictional sliding by incorporating four styluses comprising different geometries to measure the material response at various locations along the uniaxial stress-strain curve (Palkovic et al., 2019). Each stylus uses a unique, controlled strain on the sample, resulting in a unique material response. Each stylus creates a groove on the surface, so a profiling probe captures the resulting groove geometry. A schematic of an HSD test across the ERW seam of a pipe joint and the resulting grooves are shown in Figure 2.

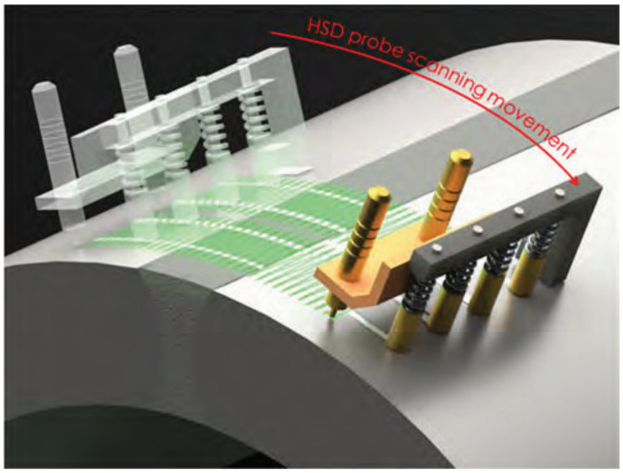

Figure 2. HSD Testing is being performed across the ERW Seam of a pipe joint.

Data analysis and interpretation

ERW seam type classification

The ERW seam type needs to be determined before estimating NDE seam toughness. In prior work, a non-destructive method was proposed to identify the welding process used in electric-resistant welded (ERW) pipelines (Palkovic et al., 2020). In this approach, a classification model based on a known ERW seam database predicts the seam type using NDE data, as shown in Figure 3. This method combines hardness variations measured using HSD testing and macro-etching to measure features like heat-affected zone width and hardness changes across the weld to determine ERW seam types as low frequency (LF), high frequency (HF), and high frequency normalized (HFN) without the pipe cutouts. High-frequency normalized means high-frequency pipes with post-weld heat treatment (PWHT). These measurements are then normalized for pipe size and grade, allowing for comparisons and classification of unknown samples of different sizes and grades.

In Figure 3, the color regions on the plot show the different seam-type decision boundaries. Data points for building the model are filled in, and a black border and label identify the tested field samples. Each sample is tested twice, resulting in two data points in the above plot.

Algorithm for determining ductile fracture initiation

Predicting CVN Transition Temperature: A proprietary ML model was trained on 100 samples that estimate the ductile-to-brittle transition temperature (DBTT) based on the HSD test and pipe chemistry data. A conservative value is added using a 1-sided prediction interval with 80% certainty ("tool tolerance"), accounting for measurement uncertainty per 192.607 for example.

Converting to Fracture Initiation Temperature: The estimated temperature is adjusted for the difference in strain rate between CVN impact testing and fracture initiation (quasi-static) using API 1176 Annex (E.5) equation: $\Delta T = 215 - 1.5 \times (SY)$, where ΔT is the quasi-static shift and SY is the yield strength. This converts the fracture propagation transition temperature (FPTT) to a lower fracture initiation transition temperature (FITT): $FITT = FPTT - \Delta T$, allowing for a direct comparison with the operating temperature. Other conversion methods to obtain FITT may be used.

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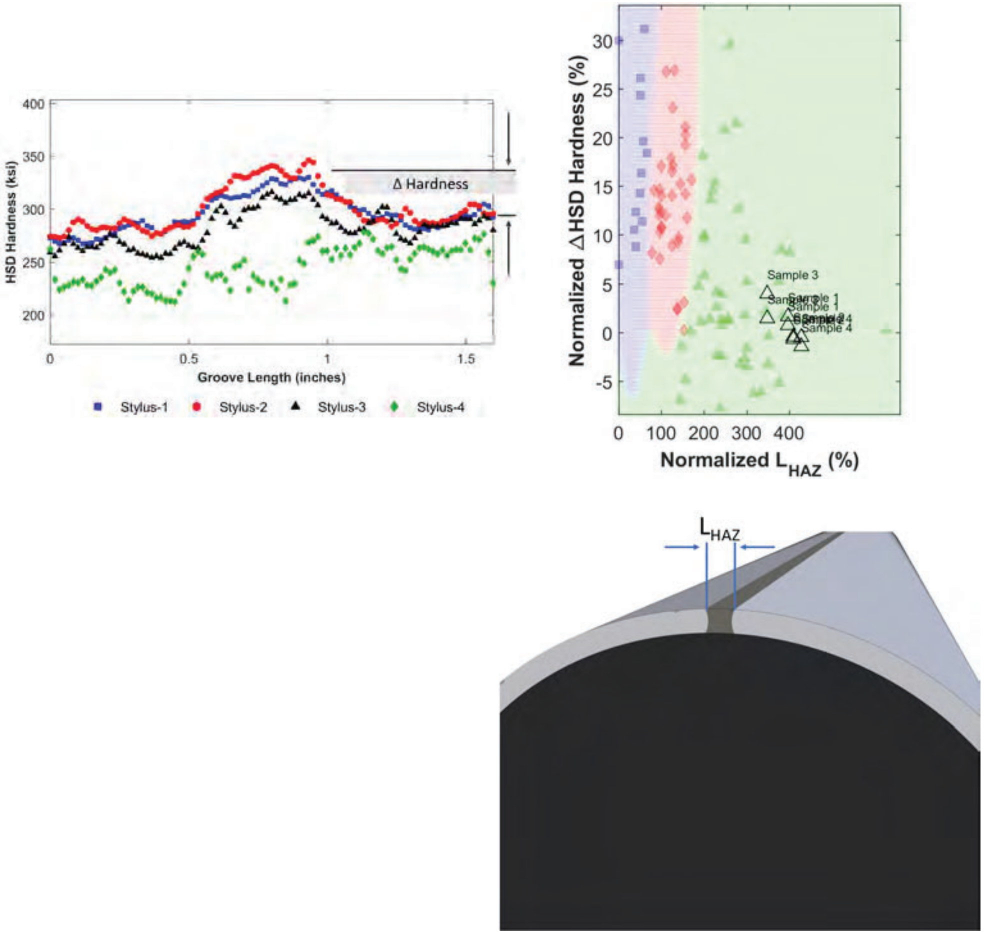

Figure 3. The ERW seam classification plot (top right) provides a visual map of the conditions to identify the seam as HF, LF, and HFN.

Assessing Upper Shelf Behavior: The minimum operating temperature (32°F/55°F) is a threshold. If the predicted FITT is less than or equal to this threshold, the pipe material is assumed to be in the upper shelf region of the CVN curve, implying sufficient toughness, which is higher than the lower shelf toughness. Once the upper shelf is confirmed, a secondary ML Model estimates the actual toughness value. A conservative value is determined by reducing the estimated toughness value by 10 ft-lbs. to account for measurement uncertainty for all pipe samples above 20 ft-lbs. For pipe samples, with toughness estimated to be between 10 and 20 ft-lbs., a conservative value of 10 ft-lbs. is used. If the predicted toughness is 25 ft-lbs. as an example, 15 ft-lbs. may be conservatively used.

3. Application of the new NDE technique

Blind testing

Figure 4 illustrates the calibration and blind test results for the ductile to brittle transition temperature ML model. The blind set contained 22 independent samples and was not used for

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training the ML Model. As shown, all blind samples were estimated to be within +/- 50°F which was adapted as the acceptance criteria.

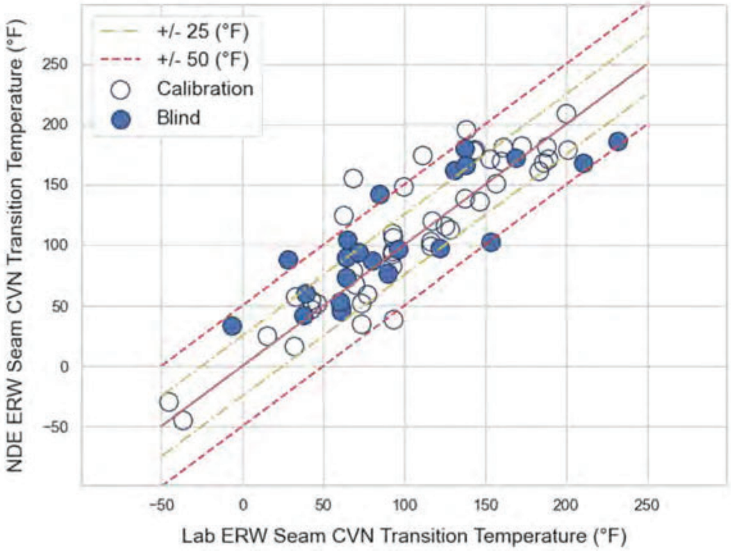

Figure 4. NDE Transition Temperature versus Lab Transition Temperature.

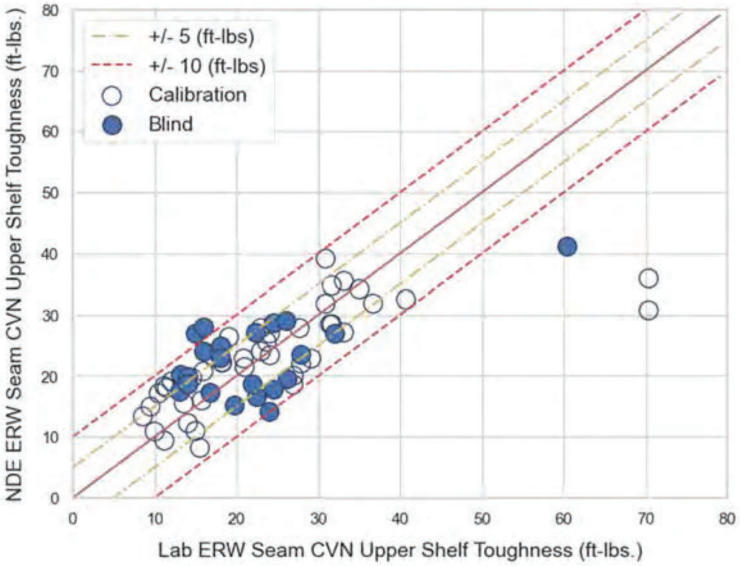

Figure 5. NDE CVN toughness versus Lab CVN toughness.

Figure 5 illustrates the calibration and blind test results for the secondary ML model to estimate the upper shelf seam toughness. Like the transition temperature ML Model, the blind set contained 22 independent samples and was not used for training the ML Model. All blind samples were estimated to be within +/-10 ft-lbs., which was adapted as the acceptance criteria. One high-toughness pipe sample was estimated conservatively by 20 ft-lbs. due to the lower representation of such samples in the current pipe database. However, since the estimate was on the conservative side, the results were deemed acceptable.

Case study of field deployment

In a recent project, the assessment of electric resistance welding (ERW) seams in in-service pipelines involving four pipe joints was performed. The analysis identified all four joints as high frequency with post-weld heat treatment (HF-PWHT) seams, indicating a potentially higher fracture resistance than other ERW types. These samples are shown in the ERW classification plot in Figure 3. The transition temperature ML Model assessment values are provided in Table 1. The NDE transition temperatures were shifted to convert from Impact Fracture to Quasi-Static Fracture Initiation Temperature. As stated earlier, turning the NDE transition temperatures to the quasi-static fracture initiation temperature makes them directly comparable to the pipeline operating conditions. The histogram distribution of the converted values is provided in Figure 6.

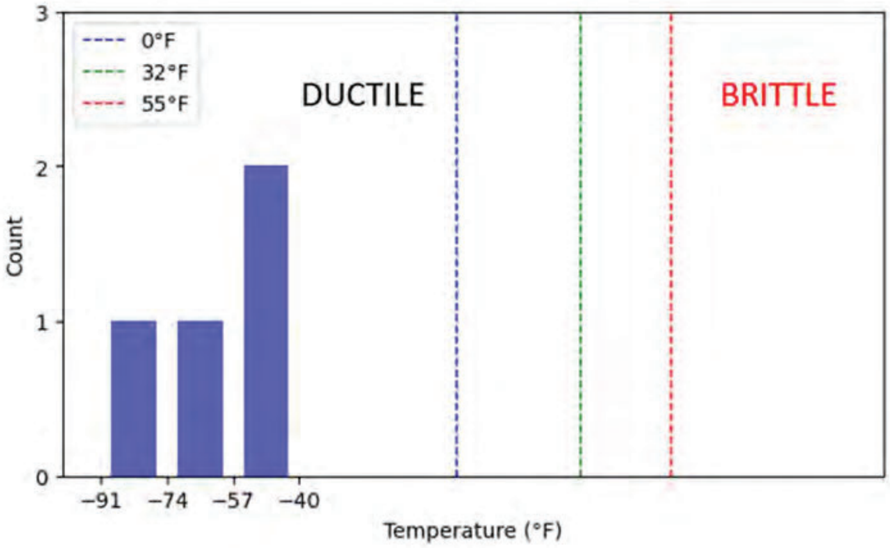

Figure 6. Histogram distribution of Quasi-Static Fracture Initiation Transition Temperature of the tested in-service pipe samples compared with the operating temperature to determine ductile versus brittle region.

As seen in Figure 6, all in-service pipe samples have converted NDE transition temperature less than the operating temperature (32°F/55°F) threshold and thus meet the criteria for the pipe joints considered on the upper shelf of the CVN transition curve region. Also, the transition temperature values were sufficiently lower than the threshold operating temperature to minimize the risk of unknown brittle fracture under normal operational conditions. Meanwhile, the range of NDE toughness values for the HFN seams was between 27-33 ft-lbs., resulting in conservative estimated values in the range of 17-22 ft-lbs., after accounting for measurement uncertainty. The results are

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provided in Table 2. This data from the four excavations shows that the current field process provides sufficient supporting data for taking 15 ft-lbs. toughness on this ERW HFN seamed pipeline.

Table 1. Field Trial – Transition Temperature

Sample Name	Seam Type	Tests	NDE Impact Fracture (85% Shear Temperature)				Fracture Propagation to Fracture Initiation Conversion		Converted NDE 85% Shear Temperature			
			Est. (°F)	**Avg. (°F)**	**Cons. (°F)**	**Avg. (°F)**	**Ref. Yield Strength (SY) (ksi)**	**API 1176 Temp. Shift (°F)**	**Est. (°F)**	**Avg. (°F)**	**Cons. (°F)**	**Avg. (°F)**
Sample 1	ERW HFN	01	-22	-23.5	38	36.5	58.6	127	-149	-150.5	-89	-90.5
		02	-25		35				-152		-92	
Sample 2	ERW HFN	01	-3	-4.5	57	55.5	60.9	124	-127	-128.5	-67	-68.5
		02	-6		54				-130		-70	
Sample 3	ERW HFN	01	14	17.5	74	77.5	64	119	-105	-101.5	-45	-41.5
		02	21		81				-98		-38	
Sample 4	ERW HFN	01	7	10	67	70	60.8	124	-117	-114	-57	-54
		02	13		73				-111		-51	

Table 2. Field Trial Upper Shelf NDE Seam Toughness Estimate

Sample Name	Tests	Upper Shelf Impact Energy (ft-lbs.)	Avg.	Conservative Upper Shelf Impact Energy (ft-lbs.)	Avg.
Sample 1	01	30	32	20	22
	02	34		24	
Sample 2	01	28	28	18	18
	02	28		18	
Sample 3	01	27	26.5	17	16.5
	02	26		16	
Sample 4	01	28	28	18	18
	02	28		18	

Duplicate HSD tests where each of the 4-styluses proceeds across the seam provide duplicate values for the transition temperature and upper shelf seam toughness. Each test involved measuring four complete hardness profiles. However, only three of those profiles were considered independent measurements for each test due to excluding a profile that failed to meet ML Model design criteria. Therefore, three independent profiles per test and two tests per pipe sample provide six independent measurements. This exceeds the minimum 5-test requirement specified in the regulation to comply with CFR 192.607. Furthermore, as seen from the tables, for the transition temperature, the repeated test showed a variation of less than +/-5°F, while the upper shelf toughness was less than +/-2 ft-lbs. Based on this data, duplicate testing may be sufficient.

4. Discussion

Advantages over traditional methods

The NDE approach presents several significant advantages over traditional methods:

- Non-destructive: Unlike destructive testing methods that require cutting out pipe sections, the NDE process is entirely non-destructive. This avoids disruption to the pipeline's operation, minimizes potential damage, and eliminates the need for expensive repairs to restore the cut sections.

- Reduced costs: Avoiding the need for pipe cutouts and repairs significantly reduces the overall cost of assessing seam toughness. This can particularly benefit operators managing extensive pipeline networks with pre-1970 ERW sections.
- Improved defect assessment: The NDE process allows for more accurate evaluation of seam toughness, leading to better prioritization of anomalies for repair. This reduces the likelihood of unnecessary excavations for benign defects while ensuring critical defects are addressed promptly.
- Flexibility and data-driven approach: Machine learning models used in the NDE process can be tailored to specific pipe characteristics and defect features. This provides greater flexibility and precision in assessing seam toughness compared to traditional methods that rely on pre-defined toughness values or statistical calculations.

Implications of assuming upper shelf behavior if the temperature is close to the threshold

Assuming upper shelf behavior when the operating temperature is close to the FITT due to measurement uncertainty can have positive and negative implications, depending on the specific context and the consequences of potential errors. Here are some points to consider:

Positive Implications:

- Less over-conservative assessments: Assuming upper shelf behavior can simplify calculations and potentially allow for the use of less stringent repair criteria. This can lead to cost savings and increased maintenance flexibility.

Negative Implications:

- Increased risk of brittle fracture: If the actual fracture toughness at the operating temperature is lower than assumed and falls within or below the transition region, there is a higher risk of brittle fracture occurring unexpectedly. This can lead to catastrophic failures with potentially serious consequences. Operating close to the FITT reduces the safety margin against brittle fracture. In some cases, this can be acceptable with strict controls and monitoring but may not be suitable for applications where high reliability and safety are critical.

Additional Factors to Consider:

- The magnitude of the difference between the operating temperature and the FITT: The closer the operating temperature is to the FITT, the greater the risk of assuming upper shelf behavior.
- The consequences of potential failure: The severity of the impacts of a potential failure should be weighed against the potential benefits of assuming upper-shelf behavior.

Based on these factors, a determination of Brittle to Ductile Transition Temperature may be warranted.

Strengths and limitations of the NDE process

The NDE process can determine if the material exhibits ductile vs brittle behavior for a given operating temperature, and the estimate can be used to quantify the risk. For a material that behaves as ductile, the NDE process can estimate the toughness values, which are higher than the traditional estimate for seam weld based on default values (1/5 ft-lbs.) as per the regulations.

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The NDE process is currently limited to vintage ERW pipes and will be expanded to other seam types soon. The database size is currently limited to 100 ERW pipes laboratory tested for the full S-Curve and will be expanded, as explained below.

Potential for further development and improvement

Combining with NDE for body toughness assessment

Currently, another testing tool is under development to estimate pipe body toughness. Another model was developed and tested to see the impact of using pipe body upper shelf toughness as an input to the ERW seam CVN upper shelf ML model. The reason for considering pipe body toughness as input is due to its good correlation with ERW seam CVN upper shelf toughness, which comes out to be 0.6 using the Pearson correlation method on 65 pipe samples. The results of seven blind-tested samples are provided in the table below:

Table 3. Blind-Tested ERW Seam CVN Upper Shelf Toughness

Sample Name	Existing ML Model		New ML Model		Lab Upper Shelf (ft-lbs.)
	NDE Upper Shelf Impact Energy (ft-lbs.)	**Conservative NDE Upper Shelf Impact Energy (ft-lbs.)**	**NDE Upper Shelf Impact Energy (ft-lbs.)**	**Conservative NDE Upper Shelf Impact Energy (ft-lbs.)**	
Sample 1	24	14	22	12	16
Sample 2	27	17	27	17	15
Sample 3	25	15	23	13	18
Sample 4	23	13	23	13	18
Sample 5	27	17	22	12	32
Sample 6	29	19	33	23	26
Sample 7	28	18	20	10	16

As seen from Table 3, the average difference between the predicted value and its corresponding lab value for the new ML Model with pipe body toughness as input is 4.14 ft-lbs. The errors range from -10 to 12 ft-lbs. This suggests a moderate spread, indicating some variability in the accuracy of predictions. Sample 5 has a relatively large negative error of -10 ft-lbs., suggesting a potential outlier. The errors do not exhibit a consistent pattern of over- or under-prediction across different ranges of lab values. This suggests that the model's accuracy might not be systematically related to the magnitude of the actual values. Because of the empirical relationship between ERW seam toughness and pipe body toughness, adding the pipe body toughness as an input to the ERW upper shelf seam model reduces the error determined using root mean square error by 7.3% for a dataset of 7 pipe samples. The analysis is based on a relatively small sample size of 7. The model's performance will be evaluated on a larger dataset to ensure its reliability and generalizability in future work. Additionally, instead of Charpy toughness, the use of fracture toughness stress intensity factor (K) as an input will be assessed.

Database size

Based on sensitivity studies, the current ML model is sensitive to the database size. This can be overcome by testing additional samples to incorporate a broader range of ERW samples, expanding the data diversity on which the model is trained. This helps capture a more comprehensive representation of the real world, making the model less susceptible to specific biases or patterns in a smaller dataset. Increasing the database size to include a more extensive database will reduce the number of outliers in the predicted estimates. The more extensive database gives the model more statistical power. This means it has a better chance of identifying and accounting for outliers, leading to more robust and generalizable predictions. Additionally, with more data points, the influence of individual outliers is lessened, leading to smoother and more accurate estimates. While increasing the database size, the additional data quality is crucial. Adding irrelevant data can worsen model performance. Therefore, collecting high-quality, representative ERW samples that align with the model's requirements is essential.

5. Conclusion

Summary of key findings

This paper introduced a novel non-destructive evaluation (NDE) process for assessing the seam toughness of vintage electric resistance welded (ERW) pipes. This method, which utilizes the frictional sliding technique alongside other surface measurements, significantly advances vintage pipeline integrity management.

Key outcomes

1) Data from the field project with four excavations shows that the current field process can provide supporting data for taking 15 ft-lbs. on an ERW HF seamed pipe when certain criteria are met after data processing.

2) From duplicate HSD tests where each of 4-styluses proceeds across the seam allows to provide duplicate values for the 85% shear area transition temperature and because 3 of the 4 complete hardness profiles for each of the two tests are made, the number of independent measurements is 6, allowing to meet the 5-test requirement per 192.607.

3) Because of the empirical relationship between ERW seam roughness and pipe body seam toughness, adding the pipe body as an input to the ERW upper shelf seam model increases the accuracy by 7.3% percent when blind tested on a dataset of 7 pipe samples.

4) The predictions and recommendations produced by the model trained using an expanded database will become more relevant and accurate for the specific assets being tested, as they are based on a deeper understanding of their unique properties and behavior. This increases confidence in the model's ability to identify potential issues and make informed decisions for the specific assets under consideration.

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