Nondestructive classification of LF, HF, and HF-normalized electric-resistance-welded (ERW) longitudinal seams

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A nondestructive assessment of electric-resistance-welded (ERW) seam types through in-situ inspection can provide valuable data for pipeline integrity programs. The durability of ERW seams is known to depend on pipe manufacturing practices that have evolved over decades. However, for pipelines that have incomplete or missing material test reports (MTRs), there is no method to accurately identify the seam type and quality without the destructive removal of a section of the pipe wall at the seam for laboratory examination. This work presents a new methodology to accurately and nondestructively identify low frequency (LF), high frequency (HF) and high frequency normalized (HFN) ERW seams. The approach combines multiple nondestructive evaluation (NDE) techniques including a characterization of the macro-etched heat-affected-zone (HAZ) and assessment of hardness variation across the seam obtained through Hardness, Strength, and Ductility (HSD) tests. These quantitative measurements are input into a classification model that is calibrated with an existing database of known ERW pipe joints to automatically classify the ERW seam type. Case studies on in-service ERW pipe joints from in-ditch assessments are also provided. Future work will extend this multi-variable model to include characteristics of the steel quality and grade to establish correlations with an index of seam toughness.

Introduction

Line pipe is commonly manufactured by cold forming a flat plate of steel into a tube, and then welding the edges of the steel along a longitudinal seam. Several methods have been used to fabricate seam-welded pipe joints, including electric resistance welding (ERW), flash-welding, and submerged-arc-welding (SAW) or double-submerged-arc-welding (DSAW).

ERW pipes are produced by heating the opposing faces of the tube with an electrical current and then applying mechanical pressure to join the seam without the need for filler metal. The earliest ERW pipes used a low frequency (LF) process that was widely used for ERW pipe manufactured from 1920 to 1960, but this method was superseded by a high frequency (HF) process that accounts for almost all pipes fabricated after 1970 [1]. HF seams are sometimes normalized (HFN) through a post-weld-heat-treatment (PWHT) that further improves performance because of the associated reduction in local hard spots and residual stresses. Flash-welded joints were produced by A.O. Smith Corporation between 1930 and 1969 and are similar in construction to LF-ERW pipes, however, they have exhibited less bondline failures than early ERW seams [2]. SAW or DSAW pipe joints are fabricated with a filler weld metal along the seam and are often used for larger diameters.

The quality, reliability and durability of seams vary between processes, and have changed over time due to advances in manufacturing methods. As a result, seam type is an important consideration for integrity management programs and risk assessments. When the pipe joint is not fully documented, or material test reports (MTRs) are not available, determining the seam type can be challenging. A visual inspection can typically be used to differentiate between flash, SAW and ERW welds, however, further classifying LF, HF or HFN processes for ERW seams typically requires a sample of the pipe wall to be removed for metallographic analysis of an etched cross-section of the seam.

This paper describes a new nondestructive evaluation (NDE) approach for assessing seam type without the need for material removal. This methodology utilizes the Hardness, Strength and Ductility (HSD) Tester, a contact mechanics device that performs a frictional sliding experiment where multiple hard styluses travel circumferentially around a pipe surface to generate superficial grooves that measure the material response to plastic deformation [3-4]. These measurements can be used to accurately and nondestructively predict tensile strength properties of steel pipelines [5-9], and to classify longitudinal seam types based on changes in the material response along the length of a test. This mechanical testing is supplemented with in-field macroetching on the pipe outer surface to measure characteristic sizes of the apparent heat-affected-zone (HAZ) in the seam region. These features are then compared to an in-house database of known pipe joints to classify the seam as flash, SAW, LF, HF or HFN-ERW. Case studies are presented where this approach has been successfully implemented during in-ditch field assessments of in-service assets.

NDE Methods for Longitudinal Seams

Multiple techniques are used to investigate the longitudinal seam, including visual observation of any weld reinforcement, macroetch inspection of the seam on the outer surface of the pipe joint, and HSD tests performed across the longitudinal seam. This section provides general procedures and typical observations for each assessment method.

Visual Examination of Weld Reinforcement

An initial visual inspection is performed to determine if any external weld reinforcement is present. If weld reinforcement is observed, then the geometry of the reinforcement can be used to immediately identify a flash or SAW seam. Flash seams have square profiles with sharp edges, whereas a SAW seam has a rounded profile. Figure 1 provides examples of the characteristic weld reinforcement observed for these seam types. If no reinforcement is present, then the seam is likely ERW and additional characterization is performed as described below.

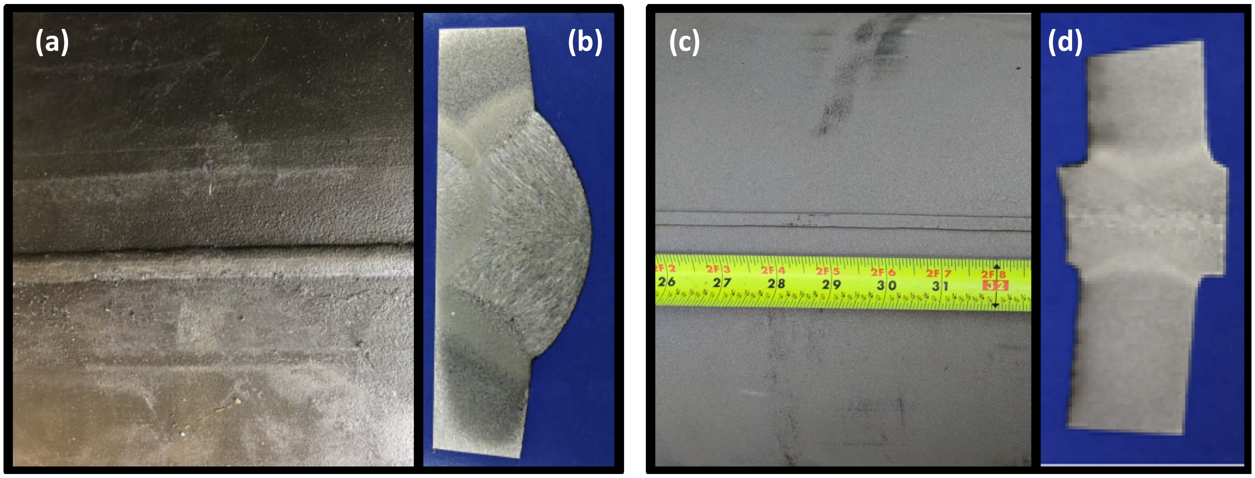

Fig. 1: Rounded external reinforcement for a SAW seam (a), and a typical metallographic cross-section (b). Square reinforcement observed on a flash welded seam (c), along with a typical metallographic cross-section (d).

Visual Examination of Etched HAZ for ERW Seams

The HAZ surrounding the longitudinal seam can be visually assessed by etching a polished area on the outer surface of the pipe joint. For ERW pipes, there is no external indicator of the location of the seam, but an ultrasonic thickness (UT) survey around the circumference of the pipe can be used to identify the position of the seam. During this inspection, the seam exhibits larger differences in measured wall thickness than the surrounding base metal. Once this change in thickness is detected, the seam location is confirmed by a macroetch inspection. The area is prepped incrementally to a 600-grit finish, and then etched using a Nital solution to confirm that a HAZ and bondline is present.

Once the seam has been located, an area centered on the bondline is further prepped to a 2000-grit finish. A Nital etchant is applied to the polished area, further revealing the bondline, an apparent HAZ, and any other seam characteristics that are a result of the pipe fabrication. This etched region is properly documented and photographed. If additional contrast is needed for improving images, Fry's Reagent can be applied to act as a stain that further defines features of the seam.

The etched seam allows for the identification of several characteristics that are used to classify the welding process. These characteristics are summarized in Fig. 2 for LF, HF, and HFN-ERW seams. An etched weld can be used to identify (1) the seam bondline, (2) the apparent HAZ surrounding the seam bond line, and (3) the presence of contact points parallel to the longitudinal seam that are the result of electrodes used for some LF and HF welding processes [10]. A typical LF-ERW etched region is shown in Fig. 2(a), and consists of a relatively narrow HAZ whose width is typically on the order of the pipe wall thickness and which is often surrounded by contact lines. Figure 2(c) is a HF-ERW seam that exhibits a very narrow HAZ that is sometimes surrounded by contact lines. A HFN-ERW seam is shown in Fig. 2(e), and has a very wide HAZ which is often off-centered with respect to the bond line. These different HAZ profiles are also observed from a cross-section of the pipe wall at the seam, as shown in Fig. 2(b,d,f).

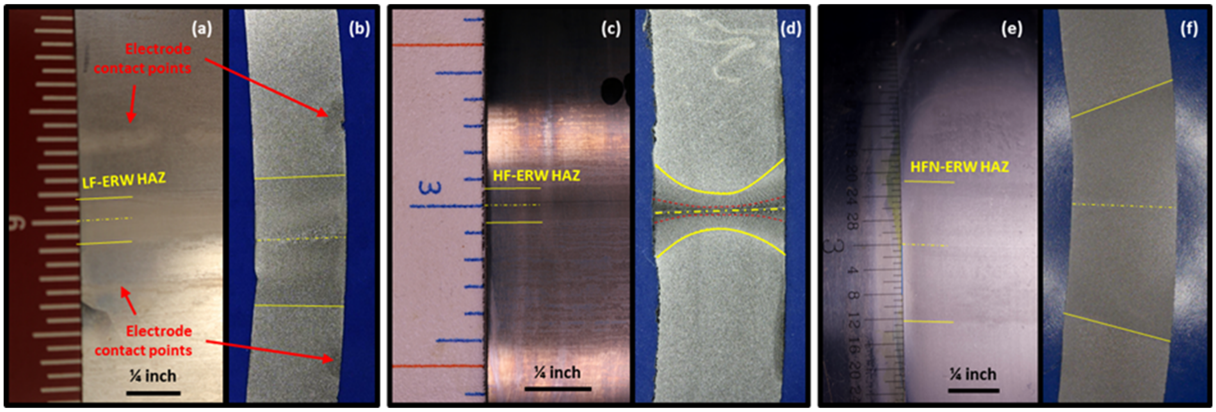

Fig. 2: Representative etched longitudinal seam welds on the outer surface of the pipe joint and an etched cross-section centered on the seam for LF-ERW (a-b), HF-ERW (c-d) and HFN-ERW (e-f). The approximate extents of the apparent HAZ are shown with solid yellow lines, and the seam position is indicated by a dashed yellow line.

For each pipe joint, measurements of the etched HAZ are recorded from images of the pipe surface. This includes the apparent HAZ width L_{HAZ}, and a measure of the HAZ asymmetry with respect to the bondline given by $\delta_{HAZ} = \max(L_{BL1}, L_{BL2}) / \min(L_{BL1}, L_{BL2})$. These measurements are shown for a HFN-ERW pipe in Fig. 3.

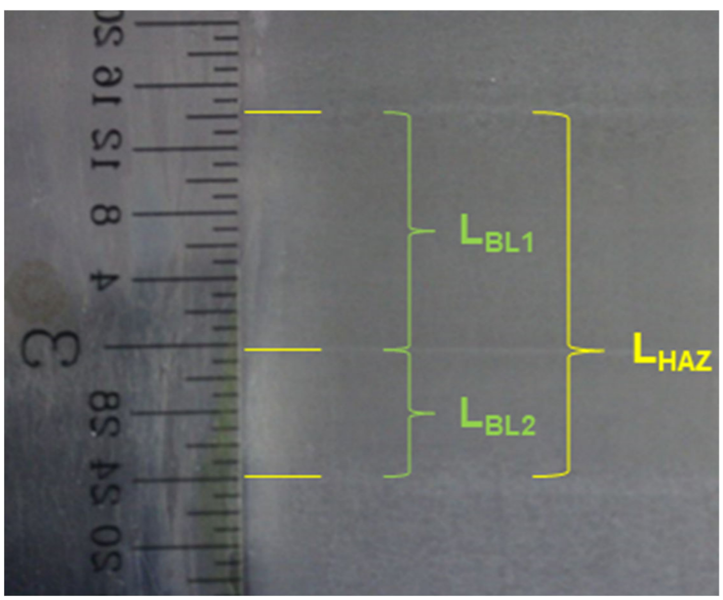

Fig. 3: Measurements of the apparent HAZ on the outer surface of a HFN-ERW seam

HSD Tests Across the Longitudinal Seam

The HSD Tester is a portable instrument that performs a contact mechanics technique known as frictional sliding. During a frictional sliding test, a stylus indents a sample surface under a known load and then slides along the surface at a constant velocity to generate a permanent groove. During a test, the normal force (P) and the width of the groove (a) are measured. The force and groove width are used to calculate the hardness with units of pressure given by,

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

where the projected contact area resisting the applied normal force is a semi-circle.

The HSD Tester is shown attached to a pipe joint in Fig. 4(a). Prior to testing, an approximately 6x6 inch area of material is progressively buffed to a 2000 grit finish. During a test, profilometers are used to continuously measure the dimensions of the groove profile as the styluses slide across the sample surface, and the load on each stylus is monitored with a calibrated force transducer. Frictional sliding allows for the continuous monitoring of changes in material properties as the stylus slides along the surface. As a result, the HSD Tester can be used to characterize local gradients in material properties where they exist, such as transitions from base metal, HAZ, and fusion zone across a welded connection. This is shown schematically in Fig. 4(b), where the four styluses of the HSD Tester slide circumferentially over a longitudinal seam weld. The grooves that remain on the surface after a test are shown in Fig. 4(c) and are less than 0.002 inches (50 microns) deep, allowing for the test to be considered as nondestructive for most engineering applications. These grooves are buffed away at the end of the assessment.

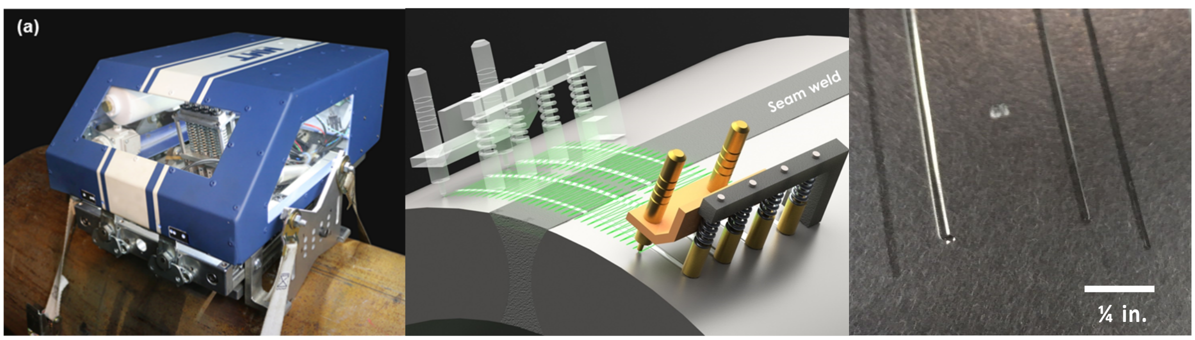

Fig. 4: (a) HSD Tester attached to the external surface of a pipe. (b) Continuous measurements performed across a welded seam. (c) Image of the four superficial grooves on the sample surface.

Changes in the measured hardness across a weld can be used to characterize welding processes and to identify whether a PWHT was performed. For ERW pipes, this enables the determination of LF, HF, and HFN processes based on an analysis of the hardness variation across the weld. Figure 5 provides examples of the measured response for representative ERW seam types. For the LF seam in Fig. 5(a), the increase in hardness is over a distance that spans across the two heat-affected zones without a sharp peak in the middle of the seam at the bondline. The HF seam in Fig. 5(b) exhibits a significant spike in hardness at the bondline, whereas a normalized seam in Fig. 5(c) shows a reduced hardness within the seam compared to the surrounding material.

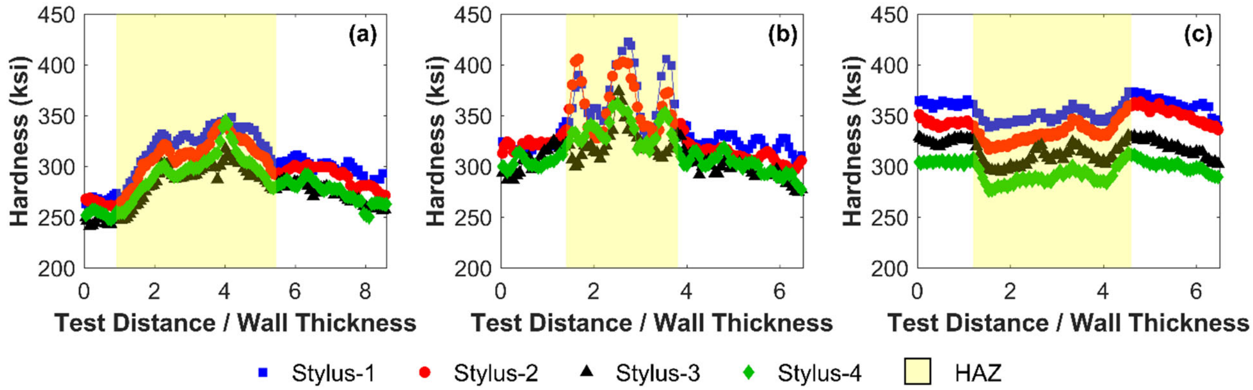

Fig. 5: Hardness profiles measured during circumferential tests across the longitudinal welded seam of (a) LF, (b) HF, and (c) HFN-ERW pipes.

From each HSD test across a weld, the HAZ and base metal region is identified to calculate characteristics of the measured material response. Specific parameters that are investigated include the relative difference between the average hardness of the HAZ with respect to the base metal $H_{HAZ} - H_{BM}$, the normalized hardness difference $(H_{HAZ} - H_{BM})/H_{BM}$, and the average difference of local hardness peaks with respect to the base metal $H_{HAZ}^{Peak} - H_{BM}$. Local hardness peaks are identified by examining the local maxima along the length of the test, and considers a minimum peak threshold of 25 ksi to distinguish local hard spots from typical material variation. An example of an HSD test performed across an HF-ERW seam and the resulting characterization is shown in Fig. 6.

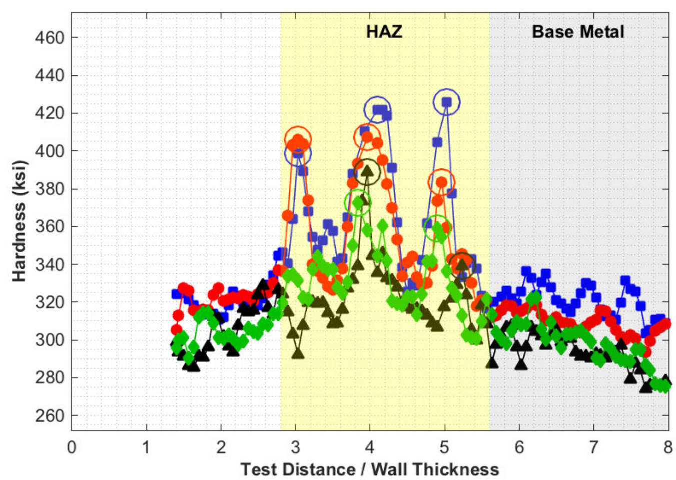

Fig. 6: Analysis of the hardness across a HF ERW seam. Local hardness peaks are shown as circled data points, and the HAZ and base metal are identified as shaded regions.

Characteristic Features of ERW Seams in the MMT database

The NDE methods were applied to a database of 32 ERW pipes, including 7 HF, 15 HFN, and 10 LF. This database can be provided upon request to the corresponding author of this report. Final seam determination for ERW joints in the database relied on the destructive removal of the seam cross-section for metallographic analysis and etching like those shown in Fig. 2(b)(d)(f). Even with this additional information, and discussions with multiple industry experts, a consensus conclusion could not be reached on three samples designated UIN696B, 16SLF and UIN913. This illustrates the challenges associated with identifying seam types for ERW joints without documentation on the pipe manufacturer or vintage, but the approach outlined below provides a new NDE alternative that is less subjective and more quantitative for classifying seam types. This section examines the relationships between several seam characteristics, and their ability to classify LF, HF, and HFN-ERW seams. A summary of all measured characteristics is provided in Table 1.

Table 1: Measured seam characteristics for pipes in the MMT database

Sample Name	Seam Type	L_{HAZ} (in.)	L_{HAZ}/t (%)	δ_{HAZ}	H_{BM} (ksi)	H_{HAZ} (ksi)	H_{HAZ}^{Peak} (ksi)
06-80	LF	0.188	94	1.00	277	299	327
08-73	LF	0.250	125	1.17	281	305	368
10-71	LF	0.313	125	1.00	264	279	300
10-72	LF	0.313	156	1.00	284	313	352
12-69	LF	0.250	100	1.00	275	299	329
12SLF	LF	0.250	100	1.00	257	281	304
16-62	LF	0.313	125	1.00	302	318	358
22SLF	LF	0.600	160	1.00	N/A	N/A	N/A
UIN693C	LF	0.375	170	1.00	274	303	342
UIN696B	LF*	0.175	97	1.00	255	307	367
06-79	HFN	0.600	300	5.00	251	265	287
06-81	HFN	0.688	344	1.75	264	270	319
08-74	HFN	0.688	229	1.20	330	322	345
08-76	HFN	1.000	306	1.00	325	345	367
08T2-025	HFN	0.550	289	1.20	325	304	329
12ERW	HFN	0.500	200	1.50	299	316	328
16-94	HFN	0.700	187	2.50	307	318	347
16SLF	HFN*	0.800	213	1.67	275	286	311
16X42	HFN	0.550	147	1.00	250	244	270
16X52	HFN	1.500	200	2.00	270	295	319
20-67	HFN	0.900	257	2.00	334	331	367
20X52	HFN	1.031	275	2.00	267	263	260
UIN1073B	HFN	1.125	296	1.40	343	376	410
UIN640C	HFN	0.650	260	2.25	202	270	315
UIN913	HFN*	0.800	296	1.67	275	283	309
08-78	HF	0.090	36	1.00	241	277	297
08SHF-1	HF	0.100	40	1.00	305	343	386
08SHF-2	HF	0.141	56	1.00	278	324	370
08SHF-3	HF	0.125	50	1.00	294	340	376
12Y64	HF	0.125	57	1.00	259	308	329
14-98	HF	0.100	40	1.00	253	295	348
14GRB	HF	0.175	44	1.00	250	294	352

*Seam classification was not conclusive based on discussions with multiple metallurgical pipeline experts

Figure 7 summarizes the averages and standard deviations between seam types for measurements of the apparent HAZ on the outer surface of the pipe joint. These results show that the apparent HAZ width L_{HAZ} and the width normalized by the pipe wall thickness L_{HAZ}/t show significant changes with different seam types. HF pipes that are not normalized exhibit a very narrow L_{HAZ} with an average value of 0.12 inch (46% of wall thickness), whereas HFN pipes have a significantly wider L_{HAZ} with an average of 0.81 inch (253% of wall thickness). LF seams are in-between, with an average L_{HAZ} of 0.27 inch (121% of wall thickness). The narrower apparent HAZ for HF pipes is attributed to the rapid heating and cooling process compared with LF for which farther grains remain less affected by recovery, recrystallization and growth, whereas the HAZ for a HFN seam is much larger as a result of the PWHT that produces nucleation and nearly even growth in grain size over a large area around the bond line. This PWHT is often not centered with respect to the bondline, which explains why the HAZ asymmetry δ_{HAZ} is much greater for HFN pipes compared to LF and HF.

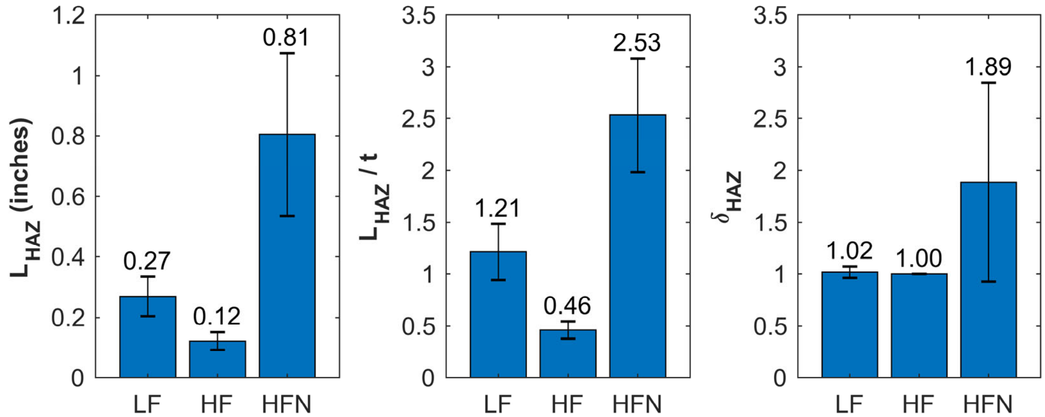

Fig. 7: Bar charts showing the average and standard deviation of measurements obtained from the apparent HAZ on the etched outer surface of the pipe joint. Results are shown for the (a) apparent HAZ width (L_{HAZ}), (b) normalized apparent HAZ width (L_{HAZ}/t), and (c) HAZ asymmetry with respect to the bond line (δ_{HAZ}).

Figure 8 shows that characteristics measured from the HSD Tester exhibit significant differences between seam types, but also significant variation for samples from the same welding process. As expected, HFN seams show the most limited increase in hardness with respect to the base metal steel due to the PWHT. The PWHT balances the grain size and orientation in the weld area that was disturbed by melting/solidification and additional relevant thermal effects. HF seams are harder than LF seams, likely as a result of the greater heat input and rapid cooling associated with the HF process that increase the possibility of harder steel phase structures such as martensite and bainite within the weld zone. The three parameters evaluated from HSD tests of hardness increases between the HAZ and base metal show similar behaviour and relative rankings.

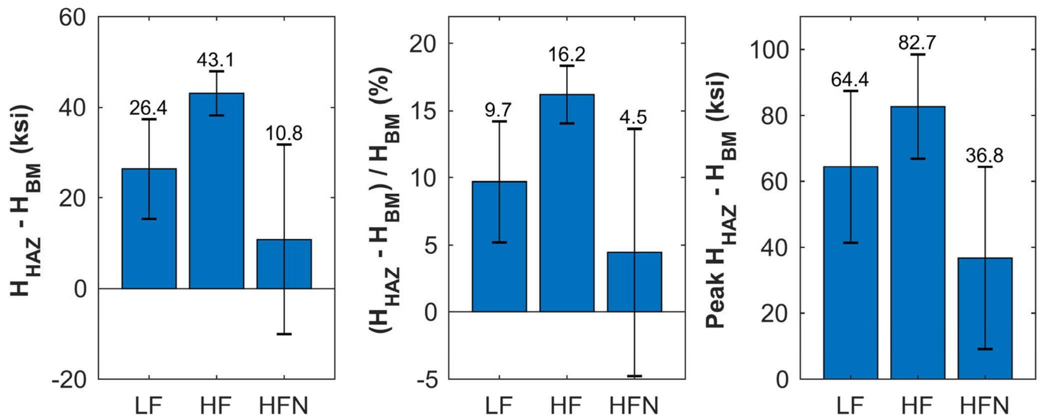

Fig. 8: Bar charts showing the average and standard deviation of measurements obtained from HSD tests performed across the longitudinal seam. Results are shown for (a) the average change in HAZ hardness with respect to the base metal $H_{HAZ} - H_{BM}$, (b) the normalized change in HAZ hardness $(H_{HAZ} - H_{BM})/H_{BM}$, and (c) the average relative magnitude of local hardness peaks identified within the HAZ $(H_{HAZ}^{Peak} - H_{BM})$.

We can investigate the grouping of seam types for different parameters by plotting the measurements for different NDE methods. Figure 9 shows a scatter plot of the normalized apparent HAZ width as a function of normalized increase in HAZ hardness. These results indicate known pipe joints from the same seam type exhibit similar characteristics which results in them being grouped together. HFN samples show the largest variability in both hardness and apparent heat-affected-zone measurements, which is attributed to differences in the quality and effectiveness of PWHT. This information can be used to determine decision boundaries for seam classification, as described in the next section.

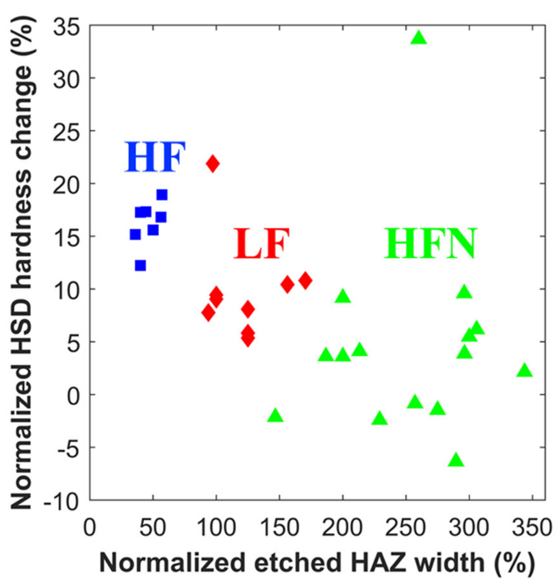

Fig. 9: Scatter plot of different ERW seams groupings based on the normalized apparent HAZ width (L_{HAZ}/t) and normalized HSD hardness change $(H_{HAZ} - H_{BM})/H_{BM}$.

Automated Classification of ERW Seams

The measured seam characteristics can be used to train a classification algorithm that will mathematically identify decision boundaries between ERW seam types. The two most statistically significant parameters for classification were identified as the normalized HAZ width (L_{HAZ}/t) from the etched seam surface, and the normalized hardness increase from HSD tests $(H_{HAZ} - H_{BM})/H_{BM}$. These parameters were input into three different classification methods, Naïve Bayes, Support Vector Machines (SVM) and a classification tree, and the results are visualized in Fig. 10. The Naïve Bayes and classification tree model correctly fit all samples, whereas SVM incorrectly diagnosed 1 joint. However, this sample was UIN696B which was examined by multiple pipeline metallurgical experts who could not reach a consensus conclusion on the seam type based on the destructive etched cross-section. Applying a 10-fold cross validation of the models, the cross-validation errors for the Naïve Bayes, SVM, and classification tree was 9.7%, 6.5%, and 3.2%, respectively. This means that we would expect to correctly classify more than 90% of new ERW pipe joints added to the database with any of these classification models, assuming that the current pipe inventory is representative of the actual population of pipe seams. Additional seam characteristics can also be considered within the classification algorithm. If the carbon content of the base metal was added to the Naïve Bayes classification the cross-validation error reduces to 6.5%, however, care must be taken to avoid over-fitting with the limited size of the current database.

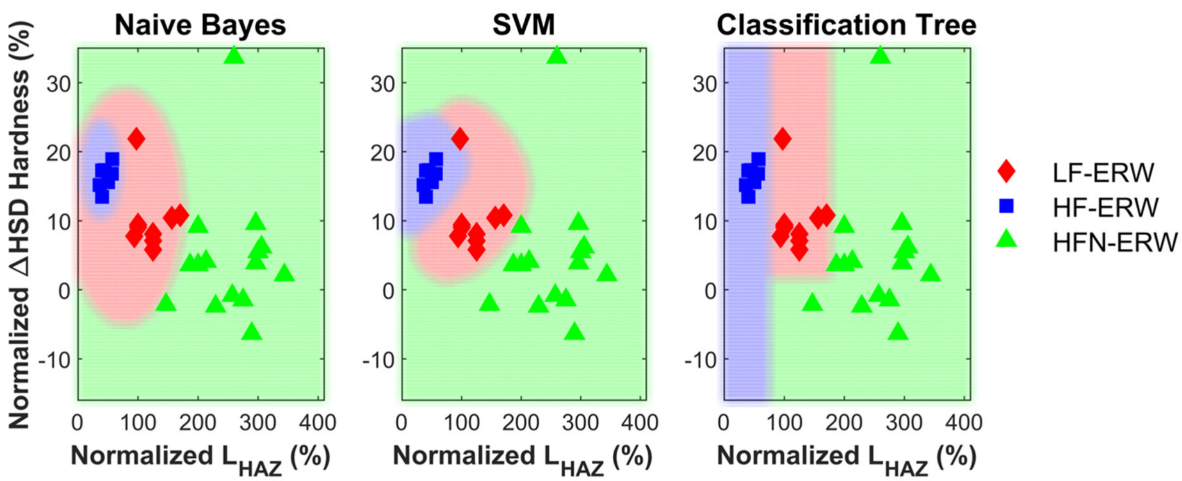

Fig. 10: Application of 3 supervised learning classification methods for algorithmically identifying LF, HF and HFN ERW seams. Decision boundaries are shown by the transitions between shaded regions.

Flow Chart Summarizing Classification Methodology

The combination of NDE techniques discussed above are summarized graphically using a flow chart in Fig. 11. Flash and SAW seams are identified through visual inspection of the weld reinforcement, whereas LF, HF, and HFN-ERW seams are characterized through a consideration of multiple seam characteristics.

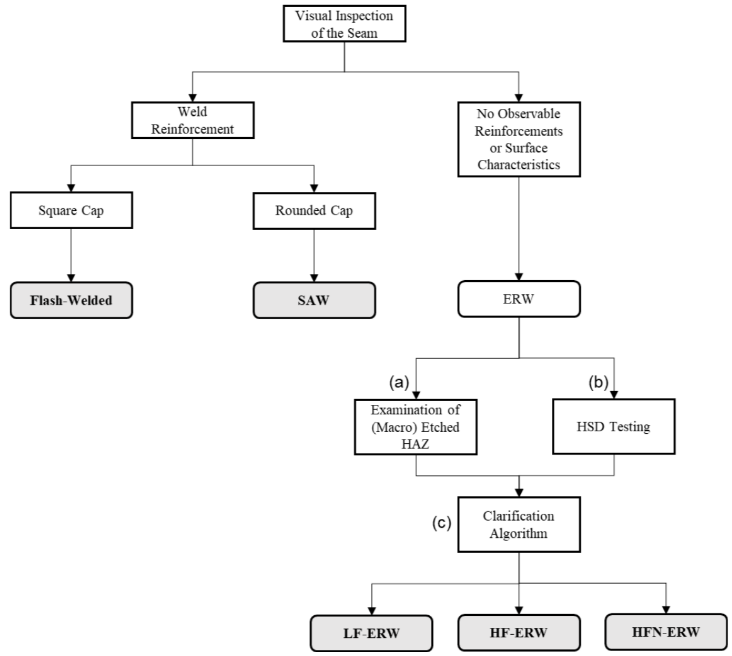

Fig. 11: Flow chart summarizing the MMT seam classification process.

Field Applications

The seam classification methodology detailed above has been used for more than 150 in-ditch inspections since 2017. A typical assessment requires two field technicians and takes 3 to 4 hours for each pipe joint when combined with material verification through measurement of tensile strength properties performed on two quadrants of the sample. Figure 12 shows the HSD Tester being prepared for testing of an in-service pipeline.

Fig. 12: In-ditch assessment utilizing the HSD Tester and NDE methodology for longitudinal seam verification.

This section details results collected on ERW pipe joints that was collected throughout 2018 for a transmission gas pipeline operator. Data was collected on more than 10 different pipeline sections through over 30 in-ditch assessments on seamless, DSAW, and ERW pipe joints of varying vintage and grade. Figure 13 shows the NDE measurements on 13 ERW pipe joints compared to the prior known database samples used to parameterize the classification models. For both Naïve Bayes and a classification tree, all of the field data falls within the HFN-ERW class, whereas 2 data points are on the boundary between LF and HFN-ERW for the SVM algorithm. Documentation indicated that these ERW joints were all installed after 1980, and therefore are likely HFN-ERW seams as the models indicate. These results suggest that the Naïve Bayes and classification tree perform better than the SVM for HFN-ERW classification, although all three models will continue to be updated as more data becomes available. Specific examples of the HSD seam test and outer diameter seam etch are shown in Fig. 14 for 4 of the samples shown in Fig. 13. These plots and images show the variability that pipe joints can exhibit even for the same ERW welding process. The seam data collected can supplement existing records and allow for more informed decisions within integrity management programs.

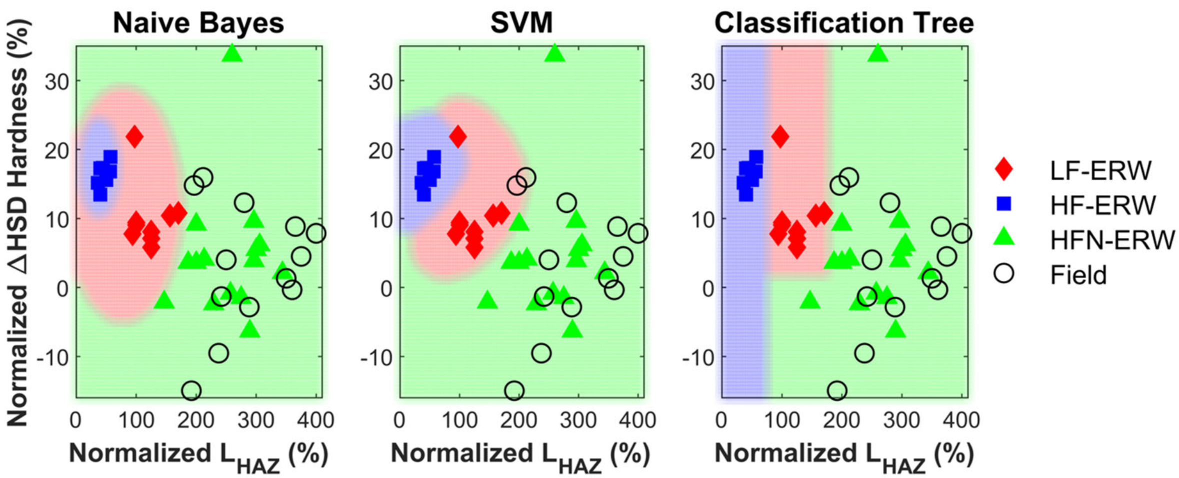

Fig. 13: Performance of different classification algorithms for collected field data.

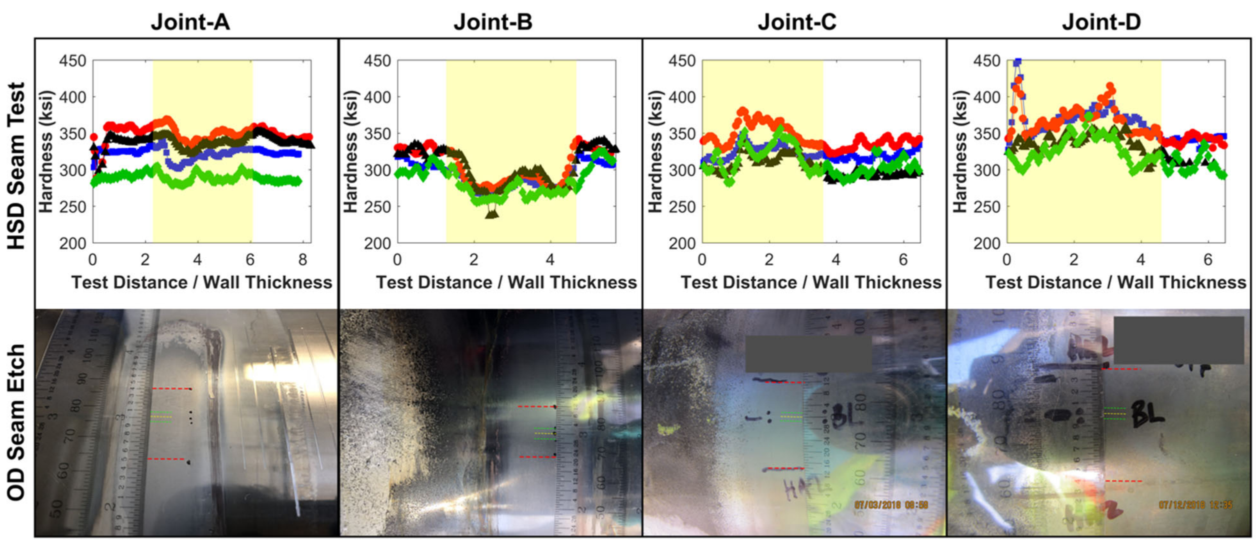

Fig. 14: Field data collected from selected assessments. The HSD seam tests in the first row have the HAZ shaded in yellow, and the measured hardness for each of the 4 styluses are shown in different colors. The OD seam etches on the bottom row show the extents of the apparent HAZ in red, the bondline in yellow, and an inner-HAZ is shown in green.

Conclusions

This paper describes a new methodology to quantitatively classify different longitudinal seam types for steel pipelines. This approach is based on the combination of multiple NDE techniques to assess changes in the steel microstructure, hardness, and chemistry as a result of different welding processes used during manufacturing. Multiple classification models have been parameterized through a database of known seam-welded pipe joints, and the procedures and predictive models have been used on more than 100 in-ditch assessments. From this, the following is concluded:

- **Flash-welded and SAW pipes are identified by the external reinforcement**: Visual examination of the seam for the presence of weld reinforcement allows for identifying flash-welded or SAW pipes. Flash-welded pipes have a square cross-section and SAW pipes have a rounded profile. HSD tests have also been performed across the seam for additional information, such as predicting tensile properties of the filler weld metal in SAW joints.

- **Measurements of the etched apparent HAZ provide valuable information for classifying ERW seams**: From the analysis of the available pipes in a known database, quantifiable criteria have been established for classifying seam types based on the width of the apparent HAZ. HF pipes yield a narrow HAZ, HFN pipes are significantly wider, and LF pipes lie in-between. Additionally, asymmetry in the HAZ with respect to the position of the bondline provides an additional confirmation of HFN pipes.
- **HSD tests provide unique data on changes in material properties**: A unique capability of the HSD Tester is to quantify changes in local material properties as a test is performed across a longitudinal weld. This allows for the identification of welding processes for LF, HF, and HFN-ERW seams. Weld classification is based on one or more characteristic features of the measured hardness response such as the relative increase in hardness within the HAZ. Tests on ERW pipes show that HFN seams exhibit a limited hardness increase, LF seams typically show a moderate increase in hardness, and HF seams have 1 or more high spikes in hardness. Improper PWHT can also be assessed in some pipes that show a large increase in hardness throughout the HAZ.
- **Longitudinal seam type can be classified by combining multiple NDE techniques**: Classifying seams is challenging, especially for ERW pipes where the traditional destructive method of etching the seam cross-section is not always conclusive. The approach detailed in this paper has been developed through an extensive assessment of known pipe joints. Measurements and observations from different techniques are systematically compared to assess their ability to differentiate between different seam welding processes. Seam properties can vary significantly, and the consideration of multiple parameters allows for more accurate and reliable seam type determination. The effectiveness of this method is dependent on the proper execution of these procedures during in-field assessments.
- **Validation database**: The current methodology and criteria for determination of seam type is based on a weld database of 32 ERW pipes, 17 SAW pipes, and 20 flash-welded pipes. Additional field assessments have been performed on hundreds of pipe joints, but this data would only be included the seam database for calibrating classification models if there is an opportunity to verify the NDE prediction with a destructive metallographic examination of the pipe cross-section at the seam. As more samples are added to the population of seam-welded joints, the confidence and accuracy in seam type determination will continue to improve.
- **Extending to a quantitative index of seam toughness**: The classification detailed in this paper provides important information on the welding processes used to manufacture the pipe joint and on potential seam risks that are considered through integrity management programs. In the future, the etched HAZ width and HSD seam test can be combined with additional NDE methods to develop a regression correlation with an index of seam toughness, such as Charpy V-notch energy. These additional considerations include microscopy across the welded seam to observe microstructural phases, grain size and orientations, chemical composition of the steel, and details of the pipe vintage and grade.

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