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IN-LINE INSPECTION IN LIEU OF HYDROSTATIC TESTING FOR LOW FREQUENCY ELECTRIC RESISTANCE WELDED PIPE

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ABSTRACT

Hydrostatic testing is a costly, operationally-impactful method of verifying seam integrity in low frequency electric resistance welded (LF-ERW) line pipe. Pipeline operators seek an alternative seam assessment method that provides a sufficiently conservative integrity assessment without the potentially negative impacts of hydrostatic testing. As in-line inspection (ILI) and field nondestructive evaluation (NDE) improve, pipelines that have been historically hydrostatic tested can now use ILI to ensure operational integrity. The improved ILI technology assessed in this work is an enhanced ultrasonic crack ILI tool with higher circumferential resolution and finer axial sample intervals. Magnetic ILI data from previous assessments is used to assist in anomaly identification. In addition to utilizing NDE technologies such as phased array, the emerging full matrix capture (FMC) imaging method that quantifies the size, position, and orientation of seam weld anomalies was examined. This paper discusses the work performed to ensure the efficacy of the improved ILI and NDE methods to accurately detect and quantify all anomalies that could possibly fail a hydrostatic test. An early step in the process was removing three sections of pipe from service for technology calibration and assessment. Each spool was examined with ILI technology in a pump-through facility, inspected using many NDE methods and then destructively tested. These results were communicated to ILI analysts and used to calibrate and improve the interpretation of the inspection results. Then the pipeline was inspected as part of the scheduled integrity assessment. Using field evaluation of anomalies detected by ILI, pipes were selected for removal from service to examine destructively. This paper presents the inspection and destructive testing results in addition to prognosis for the use of the ILI in lieu of hydrostatic testing for LF-ERW pipe.

INTRODUCTION

For many pipelines built from pipe with a low frequency electric resistance weld (LF-ERW) that transport liquid products, managing the threat of cracks in the seam weld is an essential part of an overall integrity management program. A common method for managing this threat is hydrostatic testing. With the improvements to ILI technology, pipeline operators may have more efficient and effective approaches to detect, assess, and identify cracks and then repair those needing remediation to ensure safe pipeline operation.

Hydrostatic testing has some well-known technical limitations. The main limitation is that hydrostatic testing only identifies cracks that fail during the test. Any crack or other flaw that has a failure pressure greater than the test pressure will not be discovered. For example, short, deep cracks, which inherently have high failure pressures, can go undetected with hydrostatic testing. With hydrostatic testing, the operator will not gain additional knowledge of the possible number and locations of cracks that did not fail during the hydrostatic test. In some cases, cracks close to failure can extend in size during hydrostatic testing; this larger crack has a greater potential to grow to a critical size before the next scheduled hydrostatic assessment or can even fail at a pressure lower than the hydrostatic test pressure known as a pressure reversal.

ILI has the potential to overcome some of the technical limitations of hydrostatic testing since it can detect cracks smaller than the critical size. But for ILI to be a successful replacement for hydrostatic testing, all anomalies greater than critical size must be detected and identified for remediation. While the improvements in ILI technology make this an attainable goal, the successful implementation of an integrity management program to use ILI in lieu of hydrostatic testing is dependent on understanding the types and dimensions of crack-like flaws that could fail, the probability that they are present in the pipeline, and the potential for any existing cracks to grow to failure given the operating parameters. A process for verifying ILI results to ensure the pipeline is adequately assessed for cracks is outlined in American Petroleum Institute (API) recommended practice (RP) API RP 1176 [1]. This paper describes an implementation of a process for integrating many data sets to provide the confidence that ILI can be used to assure the integrity of a pipeline.

NOMENCLATURE

API – American Petroleum Institute
CFF – Chilled forced fracture
CMFL – Circumferential MFL
EDM – electrical discharge machining
ERW – Electric resistance weld
FMC – Full Matrix Capture
ID – Inner or inside diameter
ILI – In-line inspection
IWEX – Inverse Wave Extrapolation
KMAP™ – Kinder Morgan assessment protocol
LF-ERW – Low frequency electric resistance weld
MFL – Magnetic flux leakage
NDE – Nondestructive evaluation
OD – Outer or outside diameter
PA – Phased Array UT
RP – Recommended practice
SMYS – Specified minimum yield strength
TFM – Total Focus Method
UC – Ultrasonic crack ILI
UCh – High resolution ultrasonic crack ILI
UCx – Extra high resolution ultrasonic crack ILI
UT – Ultrasonic

BACKGROUND

Any welding process may produce anomalies which over time could impact weld integrity. LF-ERW seams are a common long seam type for line pipe manufactured from the 1930s through 1970[2]. This welding process has a well-documented history of anomalies [3-5]. The two types of seam weld anomalies that have most commonly caused seam failures were hook cracks and cold welds[1]. A cause of failure is the enlargement of hook cracks by pressure-cycle-induced fatigue. In-service leaks from short cold welds, sometimes referred to as penetrators, cannot be prevented by hydrostatic testing and it has been reported that testing may have contributed to such leakage [3].

API RP 1176 recognizes that ILI for detecting and sizing cracks is more challenging than ILI for metal loss. Each crack ILI inspection has unique factors, including:

- Potentially multiple known or suspected cracking threat(s)
- Pipe characteristics including steel vintage and manufacturing technique
- Crack ILI history of the specific line
- Level of inspection validation
- Specific capability of the ILI technology
- Method of field NDE or other in-situ crack measurement
- Operational history of the pipeline

API 1176 provides many recommendations for assessing these factors. An example implementation of these general recommendations for using ILI to assure integrity is provided next.

CRACK ILI VERIFICATION PROCESS

Collecting, reviewing and integrating many data sets are needed to provide the confidence that ILI can be used to assure the integrity of the pipeline. The pipeline operational history that includes anomalies that may have caused a release, either in service or during a hydrotest, is the first data set that should be reviewed. Destructive testing is strongly recommended in API RP 1176 to confirm anomaly type, size and time dependency; actual pipe properties can also be determined which can help provide a better assessment of criticality for anomalies identified in the ILI report. The results of previous ILI crack integrity assessments should be collected in a manner that enables efficient correlation with the most recent test results. These data are used to select an appropriate ILI tool to assess the pipeline for cracks. Ensuring the ILI tool has performed adequately is an essential part of the process. Calibration features such as electrical discharge machining (EDM) notches can provide an assessment of the general ILI tool performance and illustrate potential limitations in the data collection and analysis. In-the-ditch NDE being used for the evaluation plays an important role for discrimination and sizing of selected anomalies, both cracks and other features. One added challenge when verifying with NDE results is that measurement error and

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[1] While cold weld and lack of fusion are used interchangeably in the industry, cold weld is the term that appears in API BULL 5T1 Imperfection and Defect Terminology and will be used in this paper.

NDE inspector capability can make it difficult to quantify performance. Integrating these results can provide confidence that the ILI inspection can be used in place of a hydrostatic test in future integrity assessments. To demonstrate the validity of the process, hydrostatic testing can be used. This could initially require a test of the entire pipeline, but could over time focus on high-risk segments (based on anomaly density or potential for crack growth due to fatigue). The goal can be to eliminate hydrostatic testing as confidence in the process increases.

Data Collection, Review and Integration

The subject pipeline was constructed with LF-ERW pipe made in 1956 by Republic Steel. A common assumption is that the weld bondline is straight and perpendicular to the inner and outer surfaces. This is a logical assumption, since it is likely that an equal amount of steel is displaced for each plate edge when the two square plate edges are forced together and the welding current is applied. This straight, perpendicular geometry is common for nearly all high frequency (HF) ERW welds and many low frequency welds. However, for this pipe, the bondline can be curved as illustrated in Figure 1. The figure also shows a crack that was broken open by impact after being cooled in a liquid nitrogen bath. This hook crack was connected to the inside diameter (ID) (bottom of the image) and followed the flow lines through a third of the wall thickness. The chilled forced fracture (CFF) portion of the break is nearly perpendicular to the OD surface.

The crack surfaces that are not purely perpendicular to the surface affect the crack sizing capabilities of liquid coupled ultrasonic ILI and many field NDE methods such as shear wave and phased array ultrasonic methods. Typically, with ultrasonic inspection techniques, the crack sizing is based on the amount of sound energy returning from the crack that is converted into signal amplitude by the ultrasonic transducer. The term corner echo or corner trap is used to describe the path of the sound energy from the ultrasonic transducer to the corner between the crack and the surface of the pipe and back to the transducer. When the bondline deviates from purely perpendicular, the amplitude of the signal returning for a crack is reduced. Since the amplitude is a function of angle and the angle is not known, crack sizing will be less accurate. This could even lead to non-detection of flaws as the reflected energy may be too low to be considered for data storage or not reported as the size may be below reporting threshold. Interrogating cracks from both sides of the weld provides some insight into the possibility that cracks are at an angle. It is generally assumed that when the amplitude of the reflection from a crack from both sides of the weld are nominally equal, then the flaw is a cold weld; when the amplitudes are significantly different, the anomaly is a hook crack. A bondline that is not purely perpendicular to the surface can make the identification of anomaly type more difficult.

Other data that are useful to collect are actual yield strength and toughness data. The strength for the pipe being studied consistently tested greater than the API 5L specified minimum yield strength (SMYS). These properties were measured using more than a hundred pipes removed from service for many reasons including class changes and hydrostatic test failures. The 99th percentile minimum yield strength was 7.4 ksi above SMYS. The toughness was 31.8 ft-lbs, which is good for this vintage. Both of these values were used to assess the pipeline anomalies which reduced conservatism.

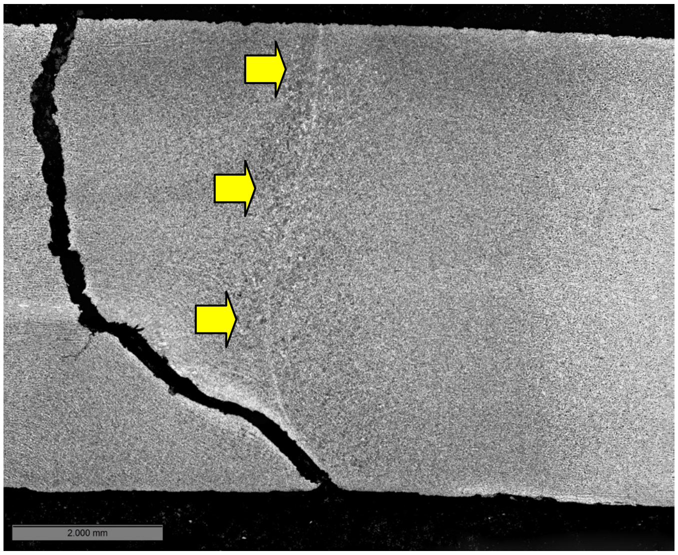

Figure 1. Curved ERW bondline in Republic ERW pipe.

The pipeline has been subjected to many integrity assessments. The year, plus or minus one depending on segment and assessment types were:

- Hydrostatic testing: nine covering the entire pipeline with the three most recent in 2004, 2008, 2013
- Geometry: 2004, 2008, 2013
- Mapping: 2014
- Magnetic Flux Leakage (MFL): 2004, 2017
- Circumferential MFL: 2009, 2013
- Kinder Morgan Assessment Protocol (KMAP™) examination of CMFL data: 2013
- UT crack tool: 2013, 2018

There is a detailed leak history of this pipeline that goes back to the installation in 1958. Nearly all of the releases from this pipeline were hydrostatic test leaks or ruptures and were the result of seam anomalies. The investigation of the seam leaks and splits showed that anomalies that failed were either a hook crack or a cold weld, with nearly equal probability of occurrence. As for recent in-service releases, one leak has occurred on this pipeline after both the 2004 and the 2010 hydrostatic tests. There have not been any leaks or ruptures since the 2013 hydrostatic test. The leaks have been the result of short cold welds, one inch (25mm) or less in length often called penetrators. Detection of this type of anomaly is difficult with either hydrostatic testing or ILI [1]. The recent improvements in data recording technology translate to finer axial sample intervals and enable the detection of shorter anomalies such as penetrators. If penetrators are a significant cause of leaks on a particular pipeline, the use of UC tools with finer axial sample intervals coupled with running the ILI tool at slower product speed could improve the detection of this anomaly type.

The well documented hydrostatic test history makes this pipeline an excellent candidate for management using ILI. While the hydrostatic tests exposed a handful of anomalies each time, this can mainly be attributed to high test pressure, typically greater than 95% of SMYS. Only four of the anomalies that failed showed fatigue growth. There is a high potential that the hydrostatic testing may cause more harm than the operational cycles as the few cycles at high pressure may have caused the cold weld oxide layer to begin to break down and the hook cracks to grow. This was part of the motivation to investigate the use of ILI in lieu of hydrostatic testing.

Integration of Current and Prior ILI Results

Aligning the ILI calls in a common database can be helpful when attempting to determine whether an ILI indication is crack or geometry variation in the seam. Circumferential MFL has the capability to reliably detect non-injurious geometric anomalies such as trim variation in the seam weld. This technology can also detect hook cracks that have an appreciable length, depth, and crack opening. Detection reliability is better for hook cracks open to the internal surface of the pipe. In general, ID and OD cracks are equally likely hence pipeline operators should review results to ensure an appropriate number of ID and OD cracks are identified [1]. Circumferential MFL is less reliable at detecting cold welds since the opening is typically negligible.

Aligning the data can help in the identification of the anomaly type. A crack-like indication from CMFL or KMAP and an ID indication from the UT crack tool results with divergent signal amplitudes form the clockwise and counter-clockwise sensors indicates that the anomaly is likely an ID hook crack. An indication of a seam variation such as poor trim or plate mismatch in the UT crack tool data can be confirmed by a corresponding indication in the CMFL or KMAP results. Other examples will be provided when specific anomalies are discussed later in this paper.

Calibration Spool

The use of calibration spools containing simulated crack-like features is referenced in API RP 1176. Specifically, EDM notches that have known lengths and depths can be used as initial indicators of ILI tool performance. These notches typically have less complex geometries than actual crack-like features, so they should not be used to replace validation with actual flaws. However, they can be used as for initial screening to determine the rate of detection and length and depth accuracies of ILI technologies in comparison to stated specifications. Additionally, installing a calibration spool in-situ gives results under actual inspection conditions and removes biases associated with flow loop testing [11].

The ILI vendor and pipeline operator collaborated to develop a framework for the use of calibration spools that would provide an initial indicator of tool performance, confirm data analysis parameters, and identify limitations of the UT crack tool platform. This included a statistically-valid methodology for sizing verification of ILI-detectable features, challenging vendor specifications using out-of-specification features, and utilizing known features provided by the ILI vendor to calibrate the analysis parameters.

An iterative analysis approach was implemented where the ILI vendor first analyzed notch-like features without any specific knowledge of dimensions or orientation. After blind analysis, the pipeline operator provided a sample set of actual feature sizes and locations to assist the ILI vendor with calibration. This led to a complete reanalysis of the calibration spool, applying enhanced sizing to deep (>120 mil) features. Ultimately, the ILI vendor was able to meet or exceed the stated detection and sizing specifications; the pipeline operator utilized the analysis as an initial validation of the rate of detection and length and depth sizing for the ILI tool.

ILI Tool

The ILI tool type used in this study was a 12" NDT Global EVO Series 1.0 UCh tool. Like other shear wave UT crack ILI tools, this tool requires a liquid medium between the sensor and the pipe and is referred to as a liquid-coupled angle beam ultrasonic tool. In recent years, UT crack tools have achieved significant measurement resolution enhancements

Recent developments in ultrasonic crack detection tools focused on two areas. The first area of development is operational aspects such as maximum inspection speed, capability to inspect pipelines with high attenuation media and/or slow speed of sound as observed in condensates or LNGs [6,7]. The second area of development is resolution and measurement enhancement for crack detection tools. Figure 2 depicts a comparison of sensor arrangement for a conventional UC tool and a high resolution UCh tool. The number of sensors is doubled, consequently the sensor track spacing in the circumferential direction is reduced to 5.0 mm (0.20 inch).

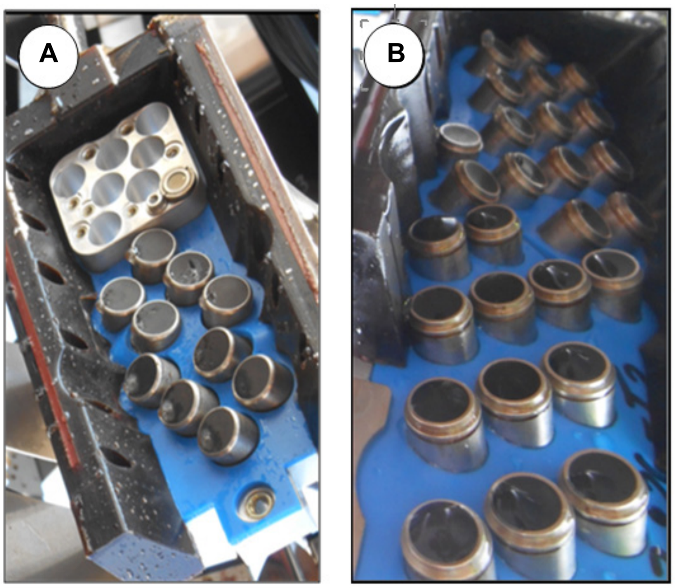

Figure 2. Picture of conventional UC (A) and high resolution UCx (B) sensor arrangement.

As briefly described above, the detection and sizing capabilities of ultrasonic shear wave crack detection tools utilized the reflected energy of flaws. To achieve a homogeneous sensitivity distribution over the entire pipe surface, the number of sensors, sound beam characteristics and pipeline geometry (diameter and wall thickness) and even the ultrasonic properties of the product must be considered. A simplified example of the benefit of increasing the circumferential resolution for crack detection tools is shown in Figure 3. The variation of sensitivity over the circumference varies within a certain range. Conventional tools typically allow a variation of approximately -6dB at the maximum, whereas the increase of sensors reduces this variation by design down to -3dB. Consequently, flaws which are measured with high resolution tools show less variation in amplitudes; subsequently depth sizing will be more accurate than conventional crack detection tools. This effect becomes obvious with data collected in a pump test at the ILI vendors' test facility. Identical spools with natural SCC colonies were tested with three different circumferential sensor resolutions: UC (10mm), UCh (7mm) and UCx (5mm). The effect in repeatability and consistency of signal responses for the repeated measurements is clearly visible. Conventional tools achieve a variation of approximately 6dB (as illustrated in Figure 4). High resolution UCx tools reduce the variation to less than 3 dB, and in this example only 2.4dB.

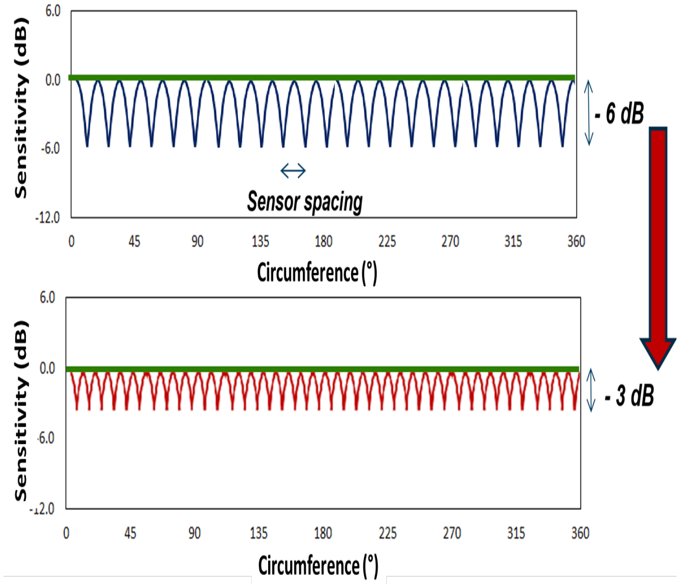

Figure 3. Sensitivity distribution over circumference with increasing sensor density.

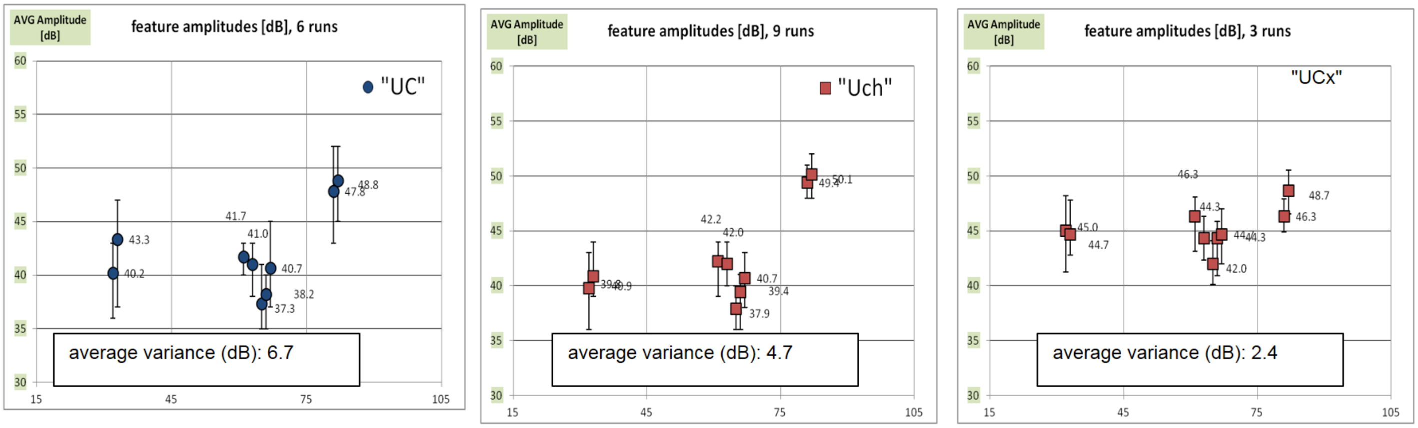

Figure 4. Variation of amplitudes for repeated measurements of natural SCC fields with different sensor resolutions (10mm, 7mm and 5mm).

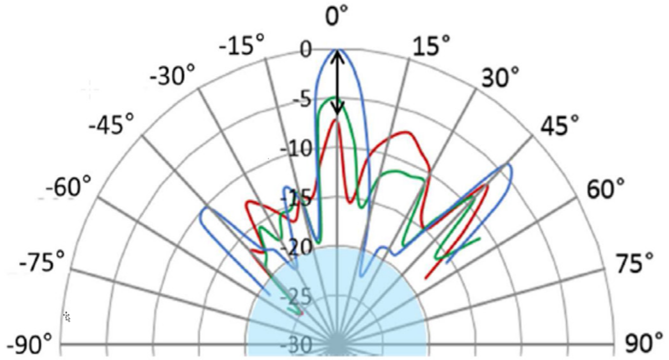

Figure 5. Signal response based on simulations for three crack geometries as a function of tilt angle.

Depth determination methods for cracks that are skewed or tilted with respect to the outer surface were improved by numerical simulation of ILI sensor response to seam anomalies. Simulations with in-house 3D finite difference software and a commercial software package were conducted to quantify the effects of tilt angle, skew angle, size, and shape of flaws on the detection and sizing potential. Figure 5 depicts the effect of tilt angles for three simplified crack morphologies. The pure notch provided the largest signal, while the more natural crack geometries have smaller maximum signal amplitudes. The radial notch also has the strongest decrease when the crack is tilted by approximately 30º. More natural cracks show in general a reduced amplitude level (approximately 50% of notch amplitude for radial orientation), but the decrease is not as significant for different tilt angles. As a simple explanation, the rough and facetted crack profile always has a surface oriented in a direction to produce some reflection that would reach the sensor. Additional parameter studies and results can improve depth determination [8].

Field NDE Tool Verification

Two common in-the-ditch inspection methods were used to detect and quantify anomalies on the pipeline, magnetic particle inspection (MPI) and phased array (PA) ultrasonic testing. Two recognized limitations of ILI tool verification using field NDE is the measurement error of the inspection technology and the capability of the inspector making the NDE measurement. These inspection methods were used for the general assessment of ILI tool performance and confirmation of the location of anomalies for cutouts and destructive testing. The capability of an emerging ultrasonic imaging technique was also evaluated by comparing the output to ILI and destructive testing results.

Ultrasonic imaging using full matrix capture (FMC) is an in-the-ditch NDE technique based on capturing a matrix of full waveform data by firing each individual element and recording all the individual array elements; repeating this for all the elements results in a matrix of A-scans of 128 firing elements by 128 receiving waveforms for a total of 16,384 waveforms. An image is produced from the acquired FMC by processing these data using a method such as the total focusing method (TFM). In contrast to beam forming as used by PA inspection, imaging approaches based upon FMC enable focusing at every point in a region of interest. Although TFM is evolving as the descriptor for image processing techniques using DMC data, there are actually several methodologies. The method used in this study for image processing is Inverse Wave Extrapolation (IWEX). IWEX linearizes the image processing algorithms and as a result can process up to 13 different modes simultaneously and overlay them into an image. Each mode represents an image determined by numerous skips off the ID or OD surfaces. The advantage of multiple modes is that some are better at imaging the ID surface, some are better at imaging the OD surface, others are better at imaging the crack-like flaws, and others can be used for corner reflections or tip diffraction detection. The advantage of using multiple modes is that they help in determining the orientation of the flaw with respect to the surface because different modes are capable of imaging different inclinations to the OD or ID surface. In addition, different complementary modes are needed for tip diffraction signals used for sizing the flaw. [9]

IWEX and other TFM methods find their origin in the application field of seismic exploration, where recorded subsonic wave field data are used to reconstruct structures and layers in the subsurface in the search for oil and natural gas deposits. The image processing techniques in seismology are usually referred to as migration methods, but are very similar to TFM and IWEX data processing. With the introduction of ultrasonic array technology and advancements in computing processing power, the principles of seismic processing can be applied in real time to ultrasonic frequency FMC datasets. A goal of IWEX imaging is to produce images capable of detecting, discriminating, and sizing crack-like features such as cold welds, surface breaking hook cracks, and fatigue cracks. These images can be used to discriminate these crack-like features from indications such as non-surface breaking upturned fiber indications, poor trim, offset plate edges, laminations and inclusions [10] which are more likely to be non-injurious. In mapping these anomalies, the goal is to size accurately enough to qualify ILI tools used for crack inspection.

Destructive Testing

While the hydrostatic test history provided details on anomalies that could fail, additional information on anomalies that were detectable by ILI but small enough to pass a hydrostatic test was needed. Understanding the detection and sizing capability of the ILI tools and field NDE is needed to better understand the safety margin associated with the inspection method. Based on prior ILI inspections, three pipe samples were removed from the pipeline and prepared for inspection. These pipes had over 20 anomalies based on the 2013 ILI examination and other ILI inspections. The pipes were assessed with IWEX and PA after they were cut out. Then, they were tested by the ILI vendor in a pump test facility. After the results were presented, anomalies were chosen for destructive testing. Two criteria were used to select anomalies for CFF. The first criterion was a common approach of selecting the anomalies with the largest size as determined by the inspection method. The second criterion was to choose anomalies where the estimated sizes had some ambiguity to even an experienced analyst, such as multiple signals or significant difference in the automatic depth estimate from one side or the other. Selected results from the more challenging category are provided next.

Error! Reference source not found.6 shows a hook crack that is nearly perpendicular to the surface on the left edge and at about a 45-degree angle on the right edge. This depth as determined by CFF was 0.04 inch (1mm) for the open hook crack and a 0.02 inch (0.5mm) segregation band for the left side expanding to 0.04 inch (1mm) for the open hook crack and 0.04 inch (1mm) segregation band for the right side. The profiles for the crack generated by the UT crack tool and IWEX inspection methods are in close agreement. This anomaly was particularly difficult to size because of the difference in the amplitude of the signals for transducers sending ultrasonic energy in the clockwise or counterclockwise direction. It was not clear whether the segregation band was intact or cracked during the inspection making absolute determination of accuracy debatable.

Figure 7 shows a hook crack which formed from a sloping lamination; this anomaly was 40 percent deep at the ID on the left edge and approximately mid-wall at the right edge. This hook crack was nearly perpendicular to the surface at the OD of the surface and quickly changed parallel to the surface near the mid-wall. The metallograph of the CFF is shown in Figure 8. This metallograph also shows the ERW electrode contact points with a benign planar anomaly on the left. The magnetic particle inspection detected both the hook crack and the contact mark. In the absence of a hook crack or well-defined trim, contact marks such as these can be reported by field NDE as cold welds unless properly characterized by the ultrasonic NDE method. The IWEX imaging of this anomaly showed a good correlation of length and depth and clearly identified the contact mark. The UT crack tool length correlated well but the depth was generally underestimated. For this anomaly, the ILI tool recorded signals from many sensors for both sides of the weld, but the geometry of this anomaly caused amplitudes to vary. While this anomaly visually appears to be significant, it passed 9 hydrostatic tests and did not show any signs of growth by fatigue.

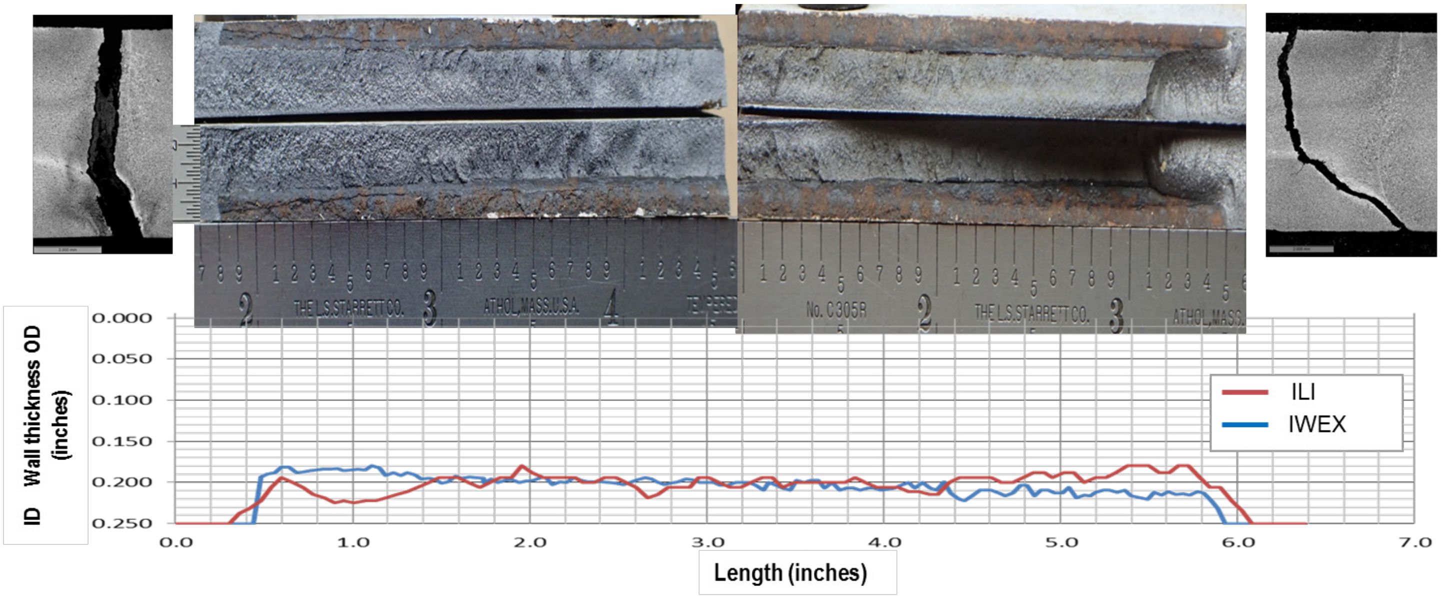

Figure 6. A hook crack that is nearly perpendicular to the surface on the left edge and at about a 45 degree angle on the right edge.

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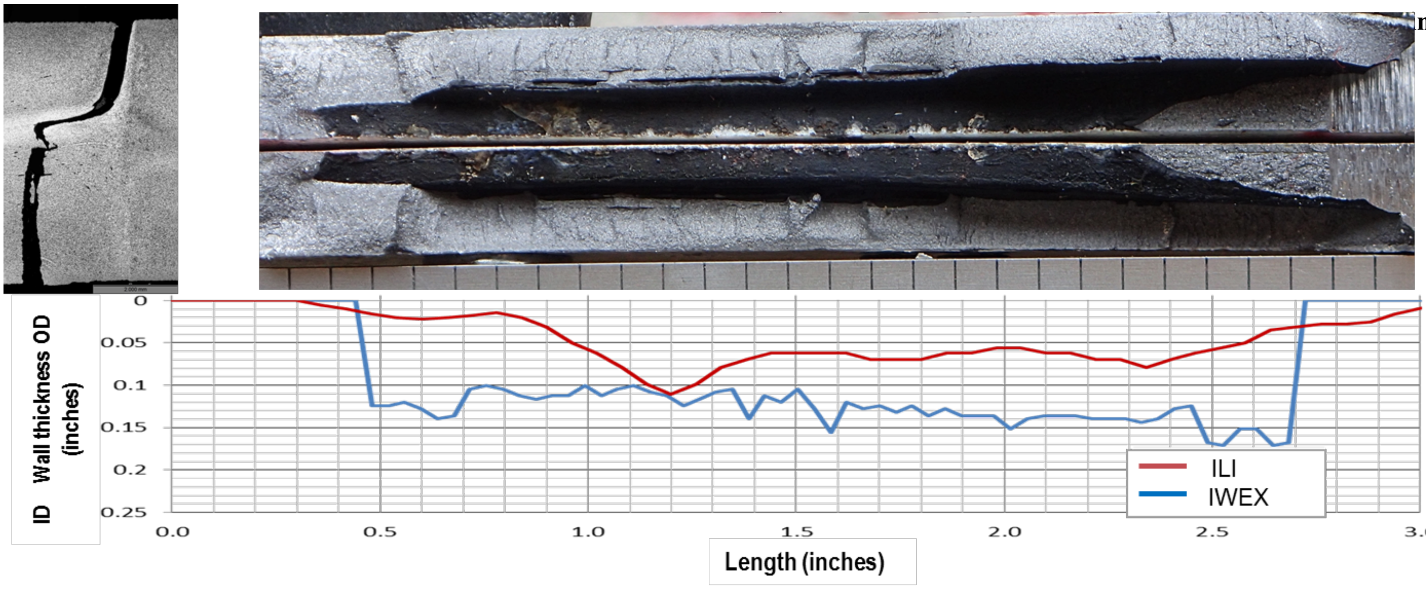

Figure 7. Hook crack that formed from a sloping lamination.

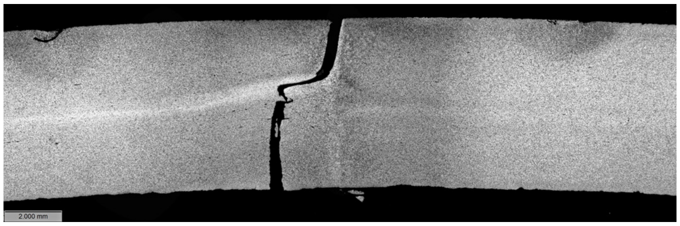

Figure 8. The metallograph of the hook crack opened by CFF with fracture surfaced mated.

Some unusual anomalies in the seam were detected by ILI of NDE methods that typically do not impact integrity nor would they be detected by a hydrostatic test. One such feature is a forked lamination with a distorted seam shown in Figure 9. For this anomaly, the midwall lamination was exposed on one plate edge. When the two plates were forced together to form the ERW weld, the steel from the solid plate edge flowed into the lamination. This anomaly was over a foot (30cm) in length. At the upstream edge of this anomaly, a hook crack that broke to the ID formed. In 2013, UT crack tool inspections by two vendors identified the entire anomaly as a hook crack. The most recent inspection with the higher resolution UT crack tool correctly identified the midwall feature and the hook crack separately. The IWEX image of this anomaly, shown in Figure 10, shows the midwall lamination and the crack tip diffraction signals from the ends of the forked lamination. It also shows that the anomaly does not extend to the ID or OD of the pipe. Again, this anomaly passed 9 hydrostatic tests and did not show any signs of growth by fatigue.

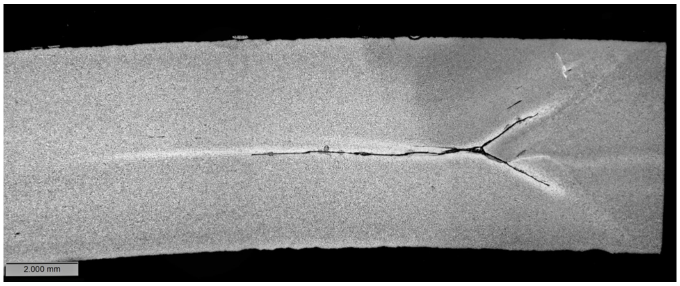

Figure 9. Forked lamination with distorted seam.

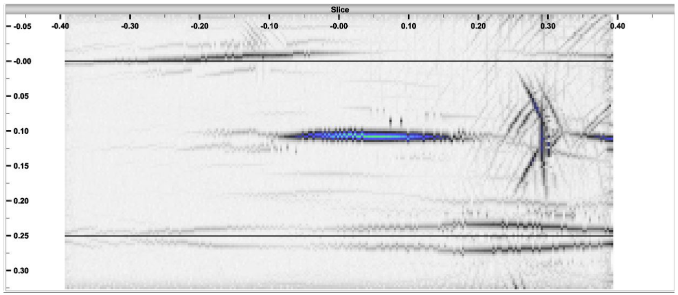

Figure 10. IWEX image of forked lamination.

Another seam weld anomaly that typically does not impact integrity, nor would it be detected by a hydrotest is shown in Figure 11. This is a tapered wall thickness variation anomaly that abruptly stops creating a notch-like anomaly. A cross-section is shown in Figure 12. This anomaly could be treated as a metal loss anomaly since one edge is sufficiently abrupt to cause a signal using ultrasonic inspection approaches, but not sharp enough to create a stress concentration sufficient to cause a crack to form and grow. The grain structure shows this anomaly was present when the plate was rolled. The object that

Figure 11. Image of the ID of a wall thickness variation anomaly.

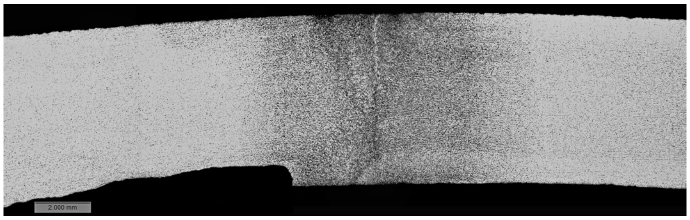

Figure 12. Cross-section of a wall thickness variation anomaly.

was rolled in may have fallen out during the pipe forming process since the bondline of the weld seam deviates at the ID. The UT crack ILI tool detected this anomaly with a significant signal from one side, and almost nothing from the other side. Another occurrence of this benign anomaly was found in a different pipe sample. Therefore, since additional anomalies of this benign type could occur in this pipeline, interpretation methods that correlate other ILI data to identify the metal loss component would help avoid unnecessary excavations.

Using Destructive Test Results in ILI Interpretation

After the ILI of the entire pipeline in late 2017, the destructive testing results were helpful in selecting anomalies for additional assessment. These anomalies were investigated either by excavation and field NDE assessment or cut-out and destructively lytesting. The destructive testing showed that anomalies that had significantly different ultrasonic signal amplitudes for ultrasonic transducers sending energy towards the anomaly from either side of the weld were most likely hook cracks. The cold welds typically had nominally similar ultrasonic signal amplitudes from either side of the weld. Since this anomaly type can grow by fatigue, a lower crack depth threshold could be chosen for these anomaly types over the cold weld anomaly. The one exception to the different amplitude rule indicating a hook crack is the roll-in anomaly. These could be identified by correlating the metal loss ILI results with the crack detection tool results with the presence of the likely hook crack being nearly eliminated when a shallow metal loss anomaly on the ID is detected near the seam. Another way to confirm that an ID crack-like call is a hook crack is by comparing the results from previous CMFL inspections and advanced analyses protocol such as KMAP™ with UT ILI crack calls. If the CMFL or the advanced analysis identified an anomaly in the category as the most crack-like (for example, seam weld anomaly A, level 5), then a UT ILI crack call with significantly different ultrasonic signal amplitudes from either side of the weld are very likely hook cracks. The presence of the hook crack with a large flat top being undersized did raise some concerns. If this anomaly type is a common failure mode in the confirmatory hydrostatic test, a high resolution ultrasonic wall thickness tool may aid in the identification of the anomaly type. By correlating the results of laminations near the seam weld with crack ILI tool results may help identify this certain type of hook cracks that may be missed otherwise.

These rules for characterizing anomaly types will differ by mill and pipe vintage. The combination of destructive testing and careful field NDE will help a pipeline owner to tailor the analysis approach for the anomalies found in the specific pipe.

Confirmation of Results

A hydrostatic test plan was developed to confirm that it is possible to use the crack ILI verification process with destructive assessment and field NDE to improve interpretation of ILI results so that ILI could be used in lieu of a hydrostatic test. The hydrostatic test pressure was greater than 95% of SMYS which was higher pressure than the pipeline had ever withstood. The pipeline was scheduled to be tested after the submission date of this paper, but the results will be presented at the conference.

CONCLUSIONS

Technology improvements make the use of ILI in lieu of hydrostatic testing a viable approach to the integrity management of pipelines. Success is dependent on understanding the types and dimensions of cracks that could fail, the probability that they are present in the pipeline, and the potential that any existing cracks would grow given the operating parameters. Many data sets are needed to provide the confidence that ILI can be used to assure the integrity of the pipeline.

Evaluation of ILI performance must go beyond the verification of the largest anomalies identified in the inspection report. Understanding the types and morphology of cracks that have the potential to grow and affect the integrity of the pipeline is an important process. The approach chosen for this pipeline was to remove pipe sections from service for technology calibration and assessment. The pipe sections were examined with ILI technology in a pump-through facility, inspected with many

NDE methods, and destructively tested. These results were communicated to ILI analysts and used to calibrate and improve the interpretation of the inspection results. The process for fully understanding the cracking threat is pipeline specific and other approaches that can rely more heavily on field NDE are possible. Emerging NDE imaging approaches that confirm crack dimensions can be a useful part of the process. Ultrasonic imaging techniques using FMC data such as TFM or IWEX are becoming commercially available and other imaging techniques are in the demonstration phase such as x-ray computed tomography (XCT). These imaging approaches can augment (and have the potential to replace) destructive examination.

For ILI to be accepted in lieu of hydrostatic testing, all significant anomalies must be found. For some anomalies, where interpretation can be difficult, the use of other ILI data sets and knowledge of the pipeline could help identify anomalies that have a higher potential for being undersized, thus increasing the confidence that all significant anomalies must be found.

In the 20th century, hydrostatic testing was the common method to ensure integrity of pipelines with corrosion, but metal loss ILI has superseded that approach in this century. This work shows the advances in crack ILI and field NDE that could make crack ILI inspection a viable alternative to hydrostatic testing for all pipelines in the near future.

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