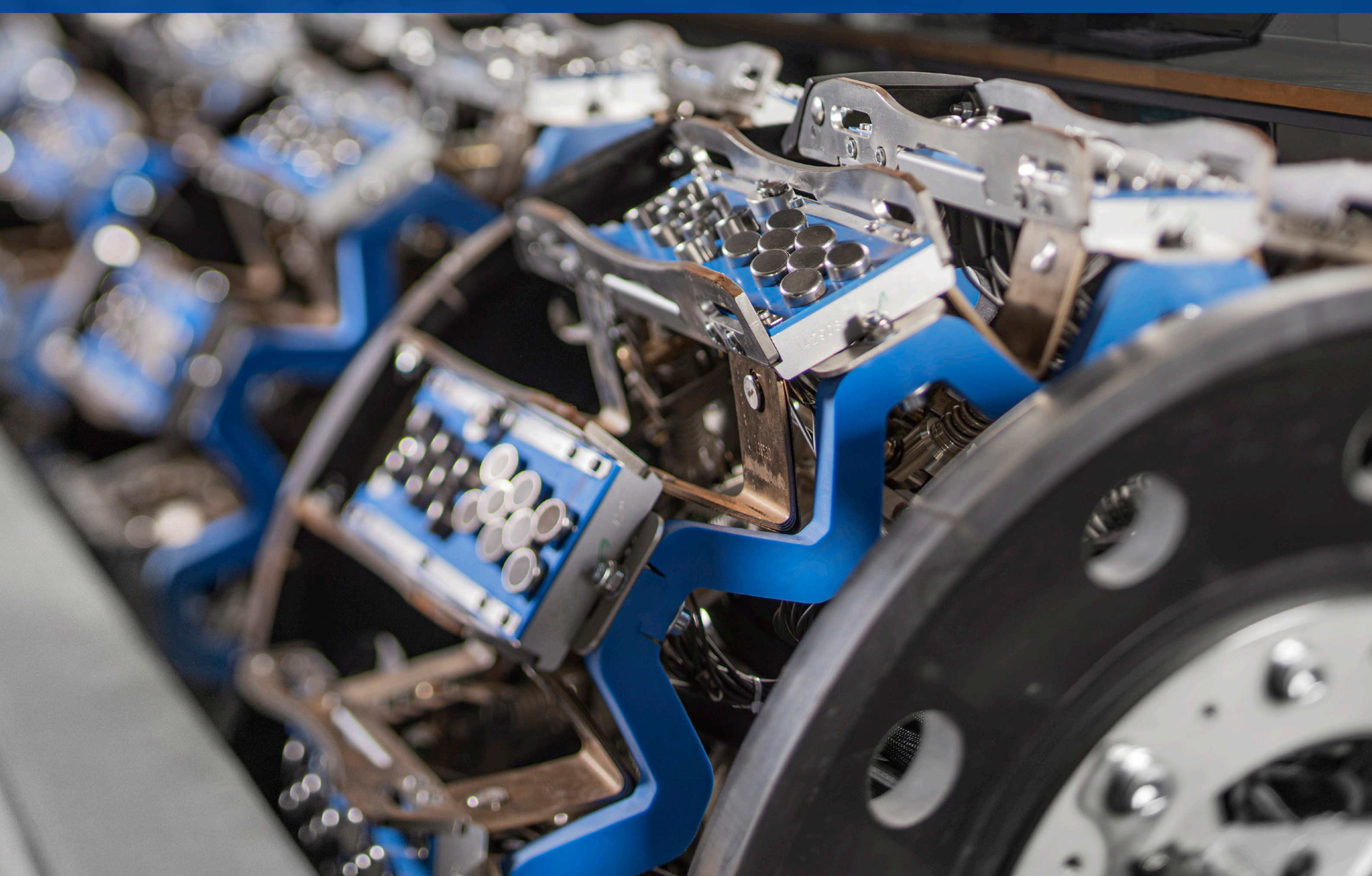
White Paper

Detecting and Identifying Complex Cracking in LF-ERW Pipe



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Detecting and Identifying Complex Cracking in LF-ERW Pipe

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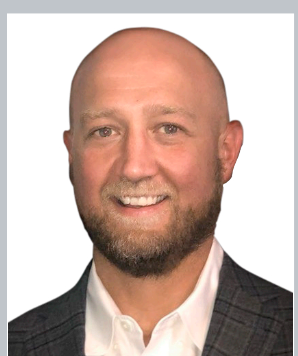

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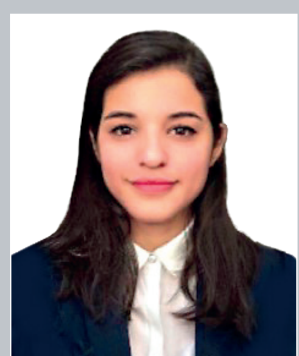

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Abstract

Pipeline operators employ various strategies to ensure the operational safety of their pipeline systems. A crucial element of this strategy involves inline inspection (ILI) and non-destructive examination (NDE). However, what happens when all available evidence points to a systematic limitation in the performance specification of these systems? How can the operator utilize this data within their Integrity Management Program (IMP)? Lastly, can this data be effectively utilized to derive new rules and analysis processes?

NDT Global, in collaboration with Phillips 66, has been tasked with investigating, documenting, and delivering a novel approach to identifying crack complexity, specifically hook cracks, within a population of previously detected and undersized features. Currently, there is no ILI tool available in the specific required diameter in the market that meets the requirements or performance specifications necessary to provide essential information for engineering assessments and the proper ranking of such features.

The primary objective of the research and validation is to develop an approach that provides a systematic method for identification and, potentially, improved depth sizing. These critical attributes can then be effectively used for engineering calculations, priority ranking, and risk mitigation activities.

This innovative approach incorporates years of accumulated knowledge from other pipelines to develop a systematic analysis approach. Additionally, it involves the calibration of this approach through collaboration with the operator, utilizing advanced in-ditch NDE techniques, and potentially employing destructive testing during lab testing.

This paper is a summary of the research and collaboration between NDT Global and Phillips 66.

Introduction

Pipeline operators use different approaches, often in combination, to ensure the safe operation of an asset. Axial Crack ILI together with in-ditch non-destructive examinations (NDE) are common techniques that pipeline operators utilize to ensure the integrity of their assets.

Axial cracking is the predominant form of cracking found in pipelines; detection and sizing of such planar linear imperfections using Ultrasonic Pulse Echo technology has been a proven methodology for more than 25 years. Nevertheless, characterization and sizing of features that have a tilt from the radial direction i.e., 'hook cracks' or a skew from the axial orientation could pose a challenge for this technology.

Research and development efforts within the pipeline industry through collaboration between pipeline operators and ILI vendors have put these challenging features as a top priority since accurate detection, characterization, and sizing are required to ensure the safe operation of pipelines globally.

This paper presents a case study in which a high-resolution axial crack inspection yields a considerable number of anomalies showing data signals of complex geometries reported in the longitudinal weld, and the limitations driven by the unavailability of an ILI service suitable for complex cracking i.e., Pitch and Catch, this is mainly due to diameter and wall-thickness restrictions. Through advanced signal analysis, it was possible to work collaboratively to apply pattern recognition based on NDE to better understand the challenging anomalies present in the line. The research and execution of the project was structured in 2 phases:

- Phase 1 – ILI data signal pattern analysis based on NDE results.
- Phase 2 – Validation of Phase 1 categorization methodology with field verification.

Background

In December 2021 a high-resolution axial crack inspection was conducted in a 6" pipeline built pre-1980 from low-frequency electric resistance welded (LF-ERW) pipes. It is important to note that small-diameter pipelines pose difficulties for both ILI and field verification NDE techniques. On the ILI side, in addition, tool mechanical design is limited making Pitch and Catch technique development complex. For NDE, challenges include the combination of a wide heat-affected zone with crack tilt angles, the combination of a small wall thickness with high pipe curvature, and the high number of reflections from impurities within the steel.

Based on the ILI results in-ditch NDE was conducted at dig locations, leading to several anomalies verified in the field as "hook cracks" and 1 as an internal, surface-connected crack.

Measurement principle

Ultrasonic crack inspection tools rely solely on the Pulse-Echo (PE) technique, which uses piezo-electric transducers to generate a 45° shear wave in the pipe wall. This wave reflects off cracks and returns to the sensors. This idealized hit-and-reflection is called the Corner Echo, Figure 1, depicts a schematic drawing of a clockwise (CW) and a counterclockwise (CCW) sensors corner echo between an ideal external crack and the outer diameter. A typical ultrasonic crack inspection uses both CW and CCW sensors. Due to technology own limitations, the PE technique can size cracks with ±10° of tilt and ±5° of skew (Figure 2 for the definitions of tilt and skew).

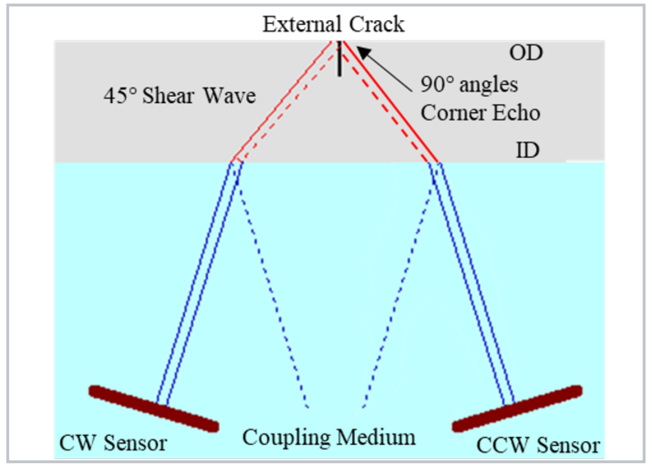

Figure 1 – Schematic of clockwise and counterclockwise UT sensors interacting with an ideal crack. The CW Sensor is transmitting while the CCW Sensor is also in transmission mode (no Pitch and Catch technique).

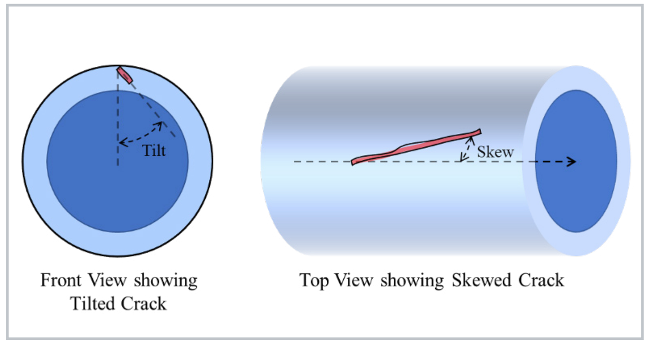

Figure 2 – Schematic of tilted and skewed ideal cracks.

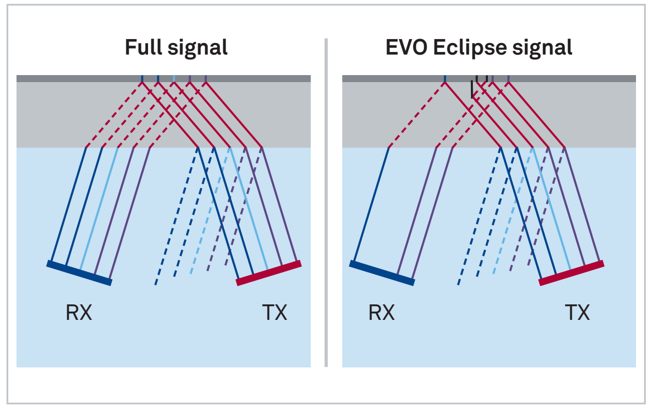

Figure 3 – The Pitch and Catch technology principle. Full signal with no shading (left) and eclipsed signal due to a feature (right). The CW Sensor (Sensor 1) is in receiving mode while the CCW (Sensor 2) is in transmitting mode.

On the other hand, the Pitch and Catch technique (Figure 3) covers a broader range increasing tilt sizing capabilities to ±45°, and ±10° of skew. 'Hook cracks' are an example of tilted cracks where Pitch and Catch technology can help to size when a hook crack lies within the same depth sizing boundaries as tilted and skewed cracks. However, because of the mechanical limitations of the 6" tools, this ILI service was not available.

Non-destructive examination

A typical seam weld inspection involves visual testing and magnetic particle testing on the external pipe surface, followed by ultrasonic testing (UT) based on shear waves i.e., shear wave UT or phased array UT (PAUT). The main interest lies in the latter, due to the cracks potentially being embedded or internal, and the focus on the comparison with the ultrasonic ILI technology.

A shear wave UT (SWUT) inspection requires manually scanning the weld from both sides, using 2 probes with different refracted angles e.g., 45° and 60°. This is a pulse-echo measurement, similar to the In-Line inspection discussed above. The probes are moved in a meandering pattern along the weld to ensure full coverage of the weld and heat-affected zone.

PAUT typically uses sectorial scans, where the angle is electronically modulated e.g., between 40° and 70°. This yields full coverage without varying the distance between the probe and the weld. As a result, the inspection can be automated, and data can be recorded for post-analysis. This works for vertical defects, but there are limitations regarding embedded cracks and planar, but tilted, anomalies with a directional reflectivity. In this case, multiple scans with different probe positions relative to the weld may be required. As a result, the detection of tilted or embedded cracks can depend on the probe's angle for shear wave UT and the probe's position for PAUT sectorial scans (Figure 4).

Anomaly descriptions in NDE reports are often limited to their type and overall dimensions, though in some cases screenshots can be analyzed to determine from which side a crack was detected, and whether it showed different amplitudes or a tilt angle.

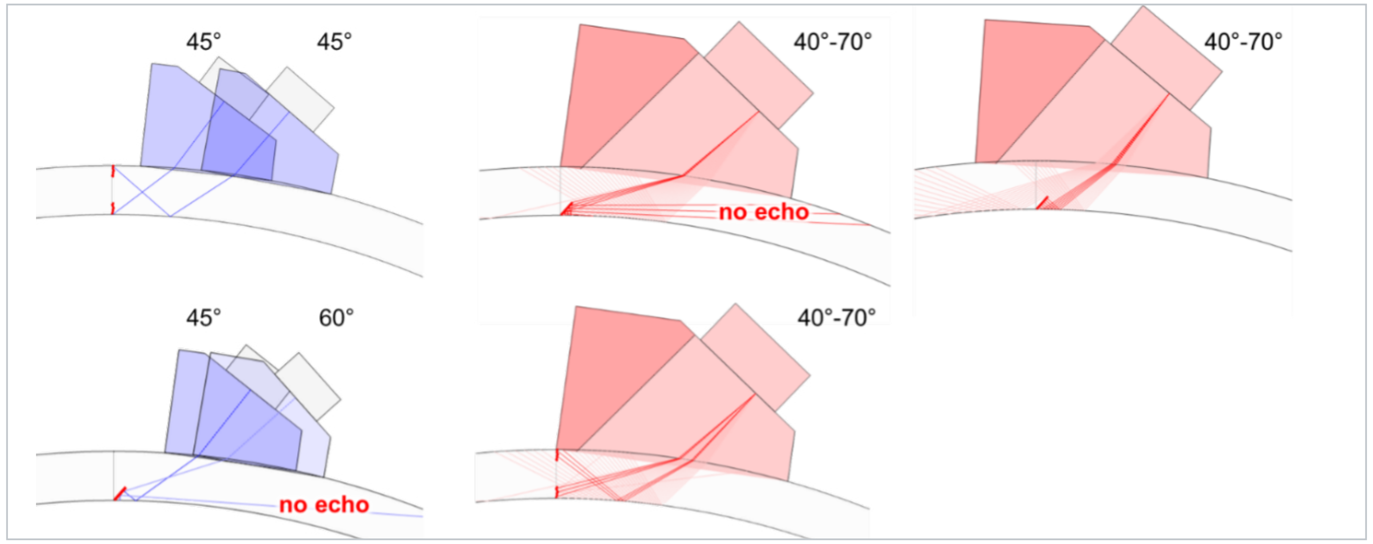

Figure 4 – Sound paths for SWUT (blue) and PAUT (red) for tilted cracks (top) and radial, surface-connected cracks (bottom). Note, that the tilted reflector may be missed depending on the probe's angle (for SWUT) and position (for PAUT sectorial scans), as the reflections are guided away from the probe.

Complex Crack Geometry and the Impact on ILI Data

One type of welding anomaly that poses a threat to LF-ERW seams is the so-called “hook cracks”, which often have the potential to sharpen and fatigue under cyclic loading.

These complex geometry cracks could be caused by separations resulting from imperfections in the edge of the skelp, parallel to the surface, which turn toward the internal or external surface. They could also originate from manufacturing-related anomalies in the bond line (lack of fusion) or cracking in the upset region of the weld, which could grow to trace the flow line and then jump across other plains of inclusions ("stepwise cracking"). Vintage skelps are known to have higher levels of impurities and are more likely to produce hook cracks than modern steels with low sulphur content (API 1176 2016).

Hook cracks are seam anomalies that are not purely radial, and as mentioned before, the crack angle is an important variable in the sizing capabilities of cracks with conventional ultrasonic crack ILI tools. The crack angle is also significant for NDE methods like shear wave UT or phased array UT. Defects with geometries outside of the technique's specifications (i.e., tilted or skewed cracks) are frequently undersized. (Willems et al. 2017 paper concludes that hooked and tilted flaws can affect the sizing accuracy of existing conventional ultrasound crack detection services – typically leading to under sizing of flaws).

Evaluating 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 amplitudes of the reflection from a crack from both sides of the weld behave similarly, then the flaw is radial. When the amplitudes are significantly different or the signal patterns differ, the anomaly can be tilted or might involve some kind of complexity in its geometry. A bond line that is not purely perpendicular to the surface can make the identification of an anomaly type more difficult.

Figure 5 depicts some example pictures of hook crack flaws. The different flaws are grouped in 4 main categories (LeRoy, M. et al. 2020):

- A – Predominantly radial orientation with a small non-radial component at the tip.
- B – Non-radial flaws with additional deviating tip components.
- C – Flaws showing a significant horizontal component, but with a radial surface connected component.
- D – Zig-zag flaws, radial, but with many alternating components in clockwise and counter-clockwise directions.

Phase 1 – Analysis Approach, Pattern Recognition

While doing field verifications for the 6" vintage pipeline with a predominant wall thickness of 0.188", hook cracks were verified in several locations. In-ditch non-destructive examination (NDE) inspections were conducted listing several anomalies verified in the field as 'hook cracks' and 1 internal, surface-connected crack. The corresponding locations were analyzed in the ILI data to determine patterns and identify possible systematic or distinct behaviors across the different flaws.

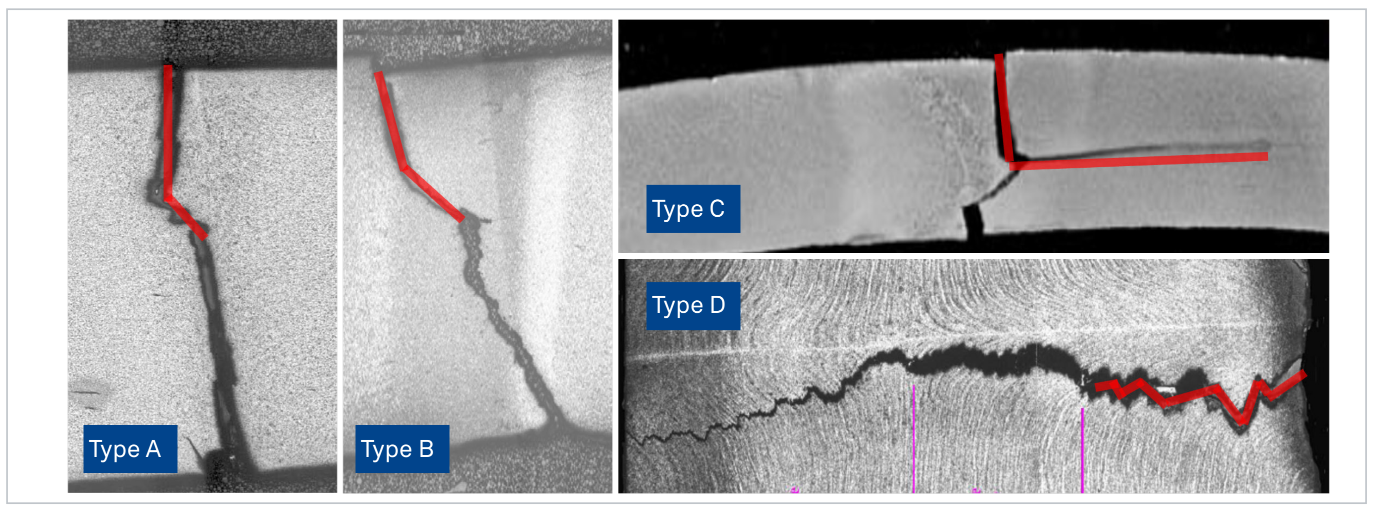

Figure 5 – Sample of hook crack morphologies. Red lines indicate the fundamental crack morphology (Hartl, K. et al. 2021).

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Two different patterns were identified for the hook population:

The first pattern was the expected one, due to the nature of the hook cracks, which are seam flaws that are not purely radial and generally include some parallel to the surface component. With hook cracks, it is expected that ILI data signals would differ between the clockwise (CW) and counterclockwise (CCW) sensors, either in amplitude, signal pattern behavior, or both. Figure 6 depicts an example of a flaw found in the pipeline system and a simulated ultrasonic 45º UT technology sizing it. From the CW sensor perspective, corner echo would be reflected to the transducer, this record would depict a linear indication with high amplitude. However, from the CCW sensor perspective, multiple echoes from the hook component of the flaw would be received by the transducer reflecting from the "hook" component of the crack leading to multiple linear indications that make the data look "cloudy".

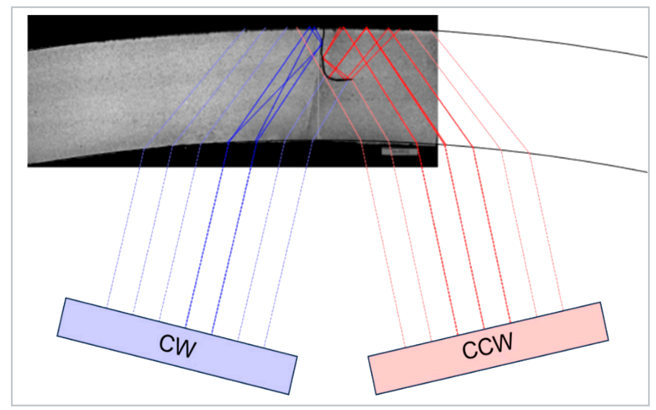

Figure 6 – Scheme of a hook crack detected by clockwise and counterclockwise sensors. Colour lines simulate the sound beam, and the stronger ones indicate reflections from the flaw back to the sensors.

Figure 7 shows a sample B-Scan data of one of the recorded anomalies. Each sensor recordings are colour coded by its amplitude, the darker the higher, this recorded amplitude is depicted in front of their Time of Flight (TOF), from the sensor and back, and the relative distance to the referenced girth weld. The upper left corner shows circled in dark blue the CW sensor recording of a linear anomaly, bottom scans depict circled in red two CCW sensors with cloudy reflections from multiple echoes.

For the second pattern identified, the ILI data signals did not indicate a hook component in the flaw, even though the anomalies were field-verified as hook cracks. In this case, the anomalies show the same signal and patterns in the data recorded from both sides of the weld, however, these indications followed a pattern

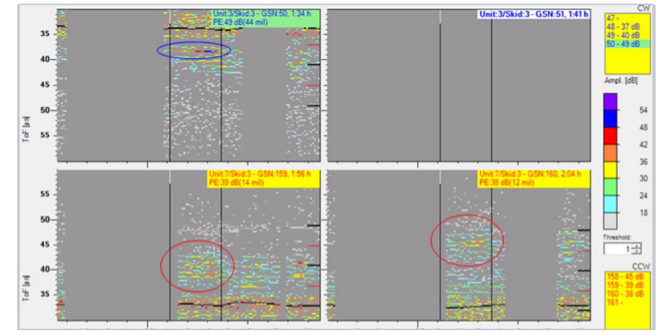

Figure 7 – B-Scan data for a verified hook crack. Upper scans correspond to CW sensors and bottom scans to CCW sensors.

of three linear reflections (as seen in Figure 8 circled in dark blue) close to each other but in different TOF. This signal behavior could indicate some level of complexity in the geometry of the flaws but is not necessarily related to a hook crack.

In addition, a distinct pattern was identified for the internal surface-connected crack that was non-hook-related. The information included in the ILI data shows the expected behavior of a perpendicular surface-connected linear anomaly. Clockwise and counterclockwise sensors captured pulse-echo traveling back from the flaw with similar patterns and amplitudes between the recorded data in sensors across the weld. Similar patterns and amplitudes between opposing sensors indicate a planar surface reflector to the UT beam, which is expected for a non-complex geometry crack. geometry crack.

This pattern recognition methodology generated from the NDE inspected hook cracks was applied to all reported non-repaired anomalies. 35% of the anomalies had signal behavior that matched one of the patterns described above. 14% of the anomalies were considered "likely hook" because their signals matched with the first pattern and 86% were considered "possible hook" because signals matched with the second pattern.

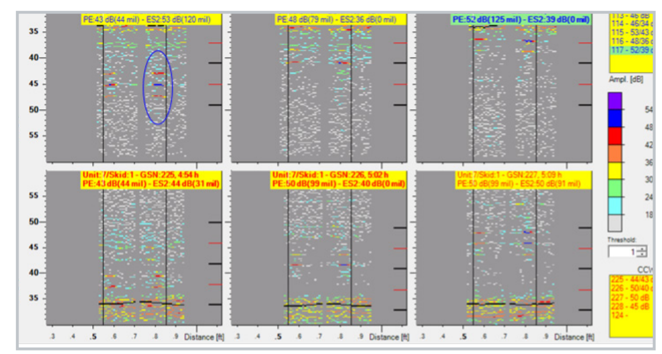

Figure 8 – B-Scan data for a verified hook crack.

Phase 2 – Validation of the Methodology

Of these pattern-matching anomalies, the operator selected 7 for non-destructive examination. In addition to the third-party NDE vendor, NDT Global field experts were invited to assist in the field and evaluate the anomalies. The results of these validationa are displayed in Table 1.

ILI pattern recognition feature type	NDE Feature type
likely hook	hook crack
likely hook	hook crack
possible hook	crack
possible hook	hook crack
possible hook	hook crack
possible hook	crack
possible hook	crack

Table 3 – Overview of the NDE validation

Based on the pattern analysis, all anomalies considered likely to be cracks with hook morphology were verified as hook cracks in the field. Nevertheless, not all anomalies that match the second pattern, which were reported as possible hook anomalies, were verified as hook cracks, 3 of the 5 were verified as internal crack-like anomalies. Consequently, a second signal pattern analysis was performed for these anomalies identifying some differences between the ones verified as hook cracks and the ones verified as common crack-like anomalies.

> **Anomolies verified as hook cracks show the highest recorded alternating amplitudes between the expected external and internal ToF window.**

The second signal pattern evaluation demonstrated that anomalies verified as cracks were consistently reflecting the higher amplitude in the internal or the external Time of Flight expected window, however, the ones verified as hook cracks were showing the highest recorded amplitudes alternating between the expected external and internal Time of Flight windows, evidencing some level of complexity or multiple reflectors.

The complete signal pattern recognition methodology allowed the identification of 22% of hook crack anomalies among the non-repaired reported linear anomalies.

Improved Non-Destructive Examination Approach

The setup used by NDT Global was selected based on the weld geometry with no seam caps, 6.625" diameter, 0.188" wall thickness, and expected hook cracks at or near the weld centerline. To address the above-mentioned shortcomings, the Total Focusing Method (TFM) was used. Thorough testing on the effect of the probe position (relative to the weld) indicated that it was unnecessary to vary it for the given pipe geometry.

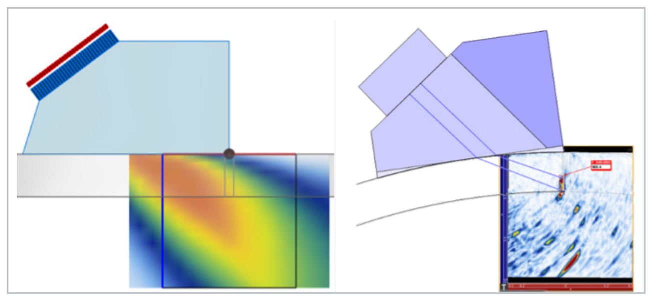

Figure 9 – Left: TFM sensitivity map for the setup using a TT-mode (but neglecting the pipe curvature). Right: Sketch of the probe in 90° skew position and the corresponding T-scan for an internal reflector on the weld centerline. Additional echoes originate from small impurities within the steel.

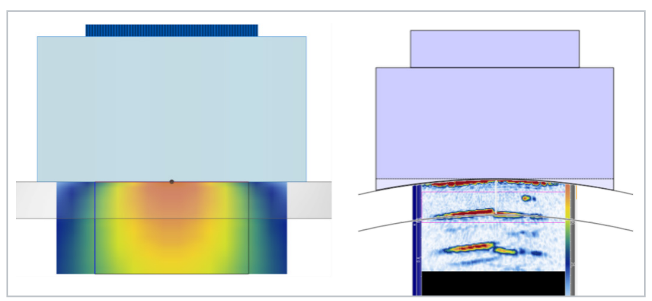

Figure 10 – Left: TFM sensitivity map for the setup using a LL-mode (but neglecting the pipe curvature). Right: Sketch of probe above the seam weld and the corresponding T-scan for a laminar reflector clockwise from the centerline.

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Setup	Equipment		Settings	
TT-mode	Instrument	Eddyfi Gekko 32:128PR	TFM mode	TT
	Probe	Eddyfi 10L32-G1	TFM zone	0.59" by 0.059"
	Frequency	10 MHz	TFM zone offset	0.000"
	# elements	32	# pixels	37,000
	Elevation	0.315"	Pixel size	0.00308"
	Pitch	0.0138"	Aperture	32
	Wedge	G1-i36 COD 6.625"	Probe index offset	0.000"
			Sensitivity calibration	TCG (3/64" side-drill holes)
LL-mode	Instrument	Eddyfi Gekko 32:128PR	TFM mode	LL
	Probe	Eddyfi 10L64-G2	TFM zone	0.79" by 0.47"
	Frequency	10 MHz	TFM zone offset	0.000"
	# elements	64	# pixels	15,000
	Elevation	0.315"	Pixel size	0.00518"
	Pitch	0.0138"	Aperture	64
	Wedge	G2-i0 COD 6.625"	Probe index offset	0.000"

Table 2 – TFM setups for TT- and LL-modes.

Since the cracks were potentially curved sideways and more likely in steel with a higher concentration of inclusions, the weld was also inspected for lateral reflectors and thickness variations.

Different from PAUT, there are no distinct angles for a TFM setup. It uses phased array UT (PAUT) probes, generating a high number of different sound paths between the individual PAUT elements. The inspected area (TFM zone) is represented by a grid, where the signals from all sound paths are merged, based on the wave mode and theoretical travel times for each individual grid cell.

In this case, transversal waves without mode conversions were used (TT-mode). The sensitivity varies within the TFM zone, so the probe position and dimension of the TFM zone were optimized according to the weld geometry and expected anomalies. (Figure 9, left) The resulting setup made it possible to detect and analyze echoes from both internal and external anomalies. Equivalent to a PAUT sectorial scan, the T-scan shows the amplitudes within the TFM zone as colors, and the horizontal and vertical plot axes refer to the distance from the probe (Figure 9, right).

A separate TFM scan was performed with longitudinal waves (LL-mode), with the probe directly above the seam weld, allowing to detect lateral reflectors and thickness variations. Analyzing this first proved beneficial, as it could indicate wall thickness variations or the presence of anomalies such as laminations or weld misalignment which might overwise mislead the analysis of the transversal wave modes. Both a lateral reflector and weld misalignment are visible in the example in Figure 10.

The strong curvature of the 6" diameter pipe mandated curved wedges with the PAUT linear array-oriented circumferentially for both setups. (Even a water box with flexible gaskets would require modifications, as most systems are designed for the linear array-oriented along the pipe axis.) Additional details on the setups for both TT- and LL-mode are given in Table 2.

	Characteristics of hook cracks
A	Diffracted signals from crack facets, following its hooked shape
B	Main echo in different legs (clockwise vs. counterclockwise probe)
C	Lateral components detected with LL-mode
D	Echoes differ between clockwise and counterclockwise probe (or detected from 1 side only)
E	Stacked with or parallel to additional crack indications
F	Multiple hook cracks within the same joint
G	High-density of steel impurities / inclusions in the area
H	Positioned on or near the weld centerline

Table 3 – Characteristics of hook cracks. Note, that other anomaly types can show some of these characteristics as well.

The identification of a hook crack is challenging in thin-walled pipes. It may have some or all characteristics listed in Table 3, though these typically don't prove an anomaly to be a hook crack:

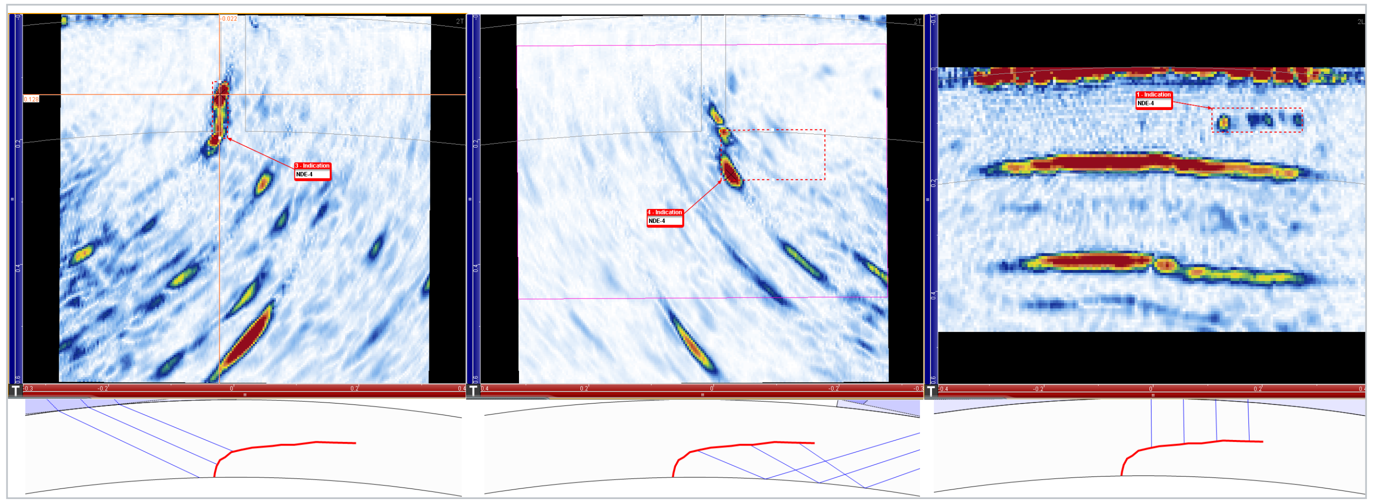

Figure 11 – TFM T-scan images of a hook crack. From left to right: probe shooting clockwise (TT-mode, 90° skew), counterclockwise (TT-mode, 270° skew), and vertical (LL-mode). The sketches below indicate the main direction of the ultrasonic signals.

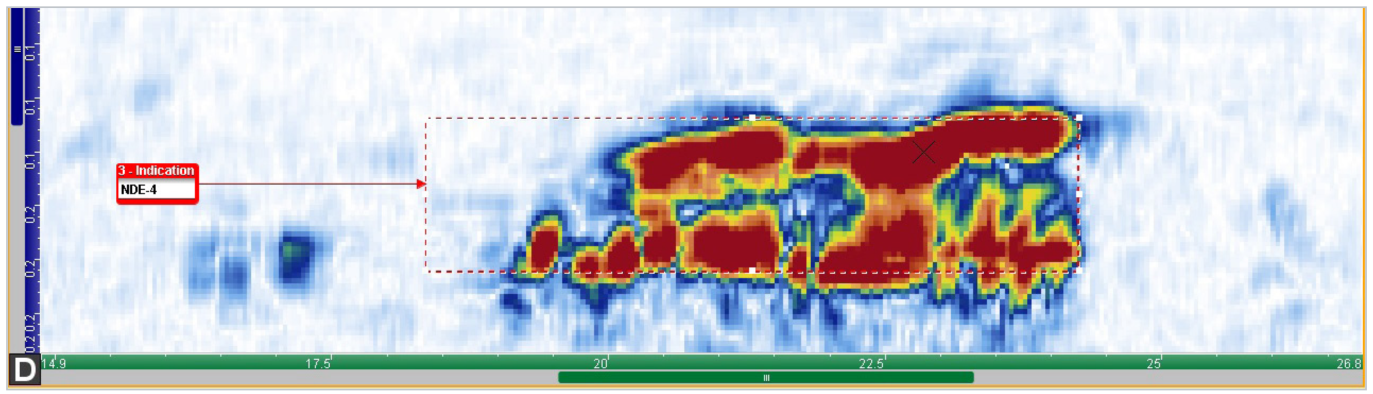

Figure 12 – TFM D-scan from the clockwise shooting probe (90° skew) for the hook crack discussed above.

Figure 11 shows TFM T-scans for a very pronounced hook crack. The clockwise shooting probe shows clear echoes above the inner pipe wall i.e., in the first leg. The probe on the opposite side of the weld shows the main echo below the inner pipe wall i.e., in the second leg, and it even detected hints of its lateral components. The latter became clear indications in the LL mode. Overall, this crack met characteristics A, B, D, F, G, and H from Table 3.

It was also observed that some of the deeper hook cracks showed a plateau in the crack-depth profile. This can be seen in the D-scan in Figure 12, showing echo amplitudes with the vertical and horizontal axes referring to depth below the probe and axial distance along the seam weld, respectively.

If the hooked shape originates from the crack following the steel's grain structure, such a plateau shouldn't be unexpected, and it might be usable as additional characteristic of (deep) hook cracks for future inspections.

Conclusions

Completion of this work highlights the importance of collaboration between pipeline operators and ILI vendors. Having direct involvement with the NDE field procedures leads to a better understanding of the recorded ILI axial crack tool data, deriving improved rules and analysis processes.

Despite the limitations driven by the unavailability of a specific ILI service suitable for complex cracking i.e., Pitch and Catch, the data quality obtained with the high-resolution axial crack inspection allowed through advanced signal analysis the parametrization of the reported anomalies based on NDE and other sources of feedback. Table 4 contains a summary of the parametrization applied for hook crack identification in both, NDE and ILI data.

The utilization of additional analysis methods provides a higher degree of confidence, and when in combination with field validations will better inform decision-making

Hook Crack ILI PE Pattern	Hook Crack NDE TFM Pattern	Shared characteristic	Comment
-	Diffracted signals from crack facets, following its hooked shape	No	Cannot be distinguished in ILI data
Main echo alternating external and internal (different TOF)	Main echo in different legs (clockwise vs. counterclockwise probe)	Yes	Characteristic observable in ILI and NDE
Multiple echoes from its laminar component	Lateral components detected with LL-mode	Yes	Characteristic observable in ILI and NDE
Different echo pattern and amplitude (clockwise vs. counterclockwise sensors)	Echoes differ between clockwise and counterclockwise probe (or detected from 1 side only)	Yes	Characteristic observable in ILI and NDE
Multiple crack indications at different TOF	Stacked with or parallel to additional crack indications	Yes	Characteristic observable in ILI and NDE
Multiple hook crack indications along the pipe joint	Multiple hook cracks within the same joint	Yes	Characteristic observable in ILI and NDE
High density of impurities / inclusions in the pipe joint	High density of steel impurities / inclusions in the area	Yes	Characteristic observable in ILI and NDE
-	Positioned on or near the weld centerline	No	Only in or at long weld is distinguishable in ILI data

Table 4 – Guidance on parametrization ILI vs NDE and their similarities.

leading to a reduction in the number of assumptions, ultimately resulting in better management of the pipelines' integrity. The operator can then utilize this data within their IMP reducing risks and unnecessary digs.

Integrity Management Program Implications

Proper classification and sizing are necessary for any integrity program. In December 2021, Phillips 66 ran a high-resolution axial crack tool on a 6" refined products pipeline. After completing the dig program, it was determined that primarily hook cracks were found on this line and that most were under-called by the ILI tool. After communicating these dig results back to NDT Global and learning of the limitations of available technology to characterize and size hook cracks in a 6" line, a qualitative approach was determined as the best path forward. The deliverables resulted in the qualitative approach were a listing of likely/possible/unlikely hook cracks for features above and below the tool reporting threshold. Unfortunately, sizing cannot be reliably corrected in this approach.

Phillips 66 will be reviewing the provided listing from NDT Global and performing a risk-based assessment to decide which likely/possible/unlikely hook cracks need remediation and include them in their next dig program. These new NDE results (including destructive test results) will be valuable to revalidate the applied parametrization of the anomalies and increase the sample size, to possibly obtain an adapted depth sizing curve applicable to this particular asset.

Abbreviations Summary

Abbreviation	Description
CCW	Counterclockwise
CW	Clockwise
ILI	In-Line inspection
IMP	Integrity management system
LF-ERW	Low-frequency electric resistance welded
LL	Longitudinal-longitudinal (TFM mode)
NDE	Non-destructive examination
PAUT	Phased array ultrasonic testing
PE	Pulse-echo
TFM	Total focusing method
TT	Transversal-transversal (TFM mode)
TOF	Time Of Flight

Table 5 – Abbreviations summary.

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Axial Cracks
Circumferential Cracks
Metal Loss
Geometry Ovalities
Mapping

This paper was published at the 2024 Pipeline Pigging and Integrity Management conference.

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