Highlighting the Threat of Circumferential Stress Corrosion Cracking (CSCC) with Advanced Inline Inspection Tools

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Abstract

Axial stress corrosion cracking (SCC) has been a known threat for many years. SCC has been found in many pipelines that are susceptible based on material, stress, and environment and are especially prevalent in high pressure gas lines. In-line inspection tools leveraging technologies such as ultrasonic crack detection and electromagnetic acoustic transducer are designed to detect and size crack anomalies inclusive of SCC. However, in more recent years, circumferential stress corrosion cracking (CSCC) has been found in both gas and liquid pipelines as the result of complex loading states (axial, bending, and combined), creating a more complex stress state than that resulting from pressure alone.

To manage this threat, several operators have adopted into their integrity management plans magnetic-based combination tools that incorporate inertial measurement units (IMU). These tools enable operators to combine data sets, allowing the assessment of multiple signals. When analyzed together, these signals can help accurately identify and characterize CSCC, as well as rule it out when it is not present. This paper highlights the use of an existing commercially available ILI tool without any modifications to look for CSCC by using the multiple data streams such as geometry, metal loss (axial, circumferential and spiral), low field magnetic response, internal/external proximity sensors and IMU bending strain.

This paper will present the development of the CSCC model, its application to real pipeline data and some field data feedback.

Introduction

Propagating progressively over time, circumferential stress corrosion cracking (CSCC) is a known threat to the integrity of buried oil and natural gas pipelines. For the most part, CSCC has been detected coincidentally through direct assessment of stress corrosion cracking (SCC) and other threats [1]; previous research focused on improving susceptibility modeling, data collection, monitoring and mitigation.

Although catastrophic failure is rare, CSCC has increasingly drawn the attention of the pipeline operators and regulators. The publication of API 1176 [2], originally published in 2016, significantly influenced how the industry addresses SCC by providing a clear framework for pipeline integrity management. The pending 2nd edition of this document is anticipated to provide similar frameworks for the management of CSCC anomalies, increases awareness of CSCC, promotes a risk-based approach to pipeline inspection, and provides detailed inspection guidelines. API 1176 further addresses the susceptibility of pipelines to SCC, emphasizing the selection of resistant materials, the need to minimize residual stresses during manufacturing and installation and the use of appropriate coating materials to protect the pipe from corrosive environments.

Despite these efforts, the industry lacked a way to prioritize CSCC threats using conventional in-line inspection (ILI) technology. Early research into the efficacy of combining data from existing multiple ILI tools yielded a prioritization model for potential CSCC defects, including those undetected by conventional magnetic flux tools. The original model has demonstrated a 75% true positive success rate [3].

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Understanding CSCC

To better understand CSCC, it's helpful to compare it to axial SCC, which is more widely recognized in the industry. Both are environmentally assisted cracking that can propagate progressively over time, driven by a combination of three simultaneous conditions: material susceptibility, exposure to active corrosion and tensile stress. Susceptible materials include pipeline steel (e.g., low carbon steel), and corrosion often occurs where the pipeline coating has degraded or been compromised. Specific to CSCC development, experience has shown a special susceptibility of tape wrap failures. A key difference is the source of the stresses that drives the development of SCC versus CSCC. This difference results in the different cracking orientation.

For example, the driving stress for axially oriented SCC is predominantly a result of the internal pressure. The pressure of the product flowing through the pipeline creates hoop stress. When the stress exceeds a threshold estimated to be around 60% of the specified minimum yield strength (SYMS) [2], it can lead to the initiation and propagation of a colony of axial cracks perpendicular to the direction of the primary stress. Some operators have documented pipe that have SCC where the calculated stress due to pressure is less than 60% SYMS, although it’s unclear if other contributing factors and loading may have been in play.

By contrast, when present, external loads beyond the loading posed by the internal pressure alone may result in a complex stress state, with the predominant direction of the stress with an orientation other than circumferential. SCC cracking that develops in the presence of the complex stress state results in CSCC, which is characterized by circumferential or helical cracks. The additional external loading sources may include residual stresses from pipe manufacturing, girth welding, pipeline construction and maintenance, cold bend locations, and geohazard location. While bending strain associated with geohazards had been assumed as a primary contributor to CSCC development for many years, recent work has stated that tension and compression loading during pipeline construction and/or settling are two of the most common additional loading conditions resulting in CSCC development [4].

Detection Technologies

Pipeline inspection technologies such as ultrasonic (UT) and electromagnetic acoustic transducer (EMAT) are commonly used to detect and size axial cracks. Typically, these technologies send an acoustic wave circumferentially around the pipe, where they reflect off any axial defects. However, this wave orientation is unable to properly size non-axially, oriented features, especially as they approach a pure circumferential orientation. These technology function best when the features of interest are perpendicular to the direction of travel for the acoustic wave.

To provide context regarding the limitations of magnetic-based technologies, the 2016 Pipeline Operator Forum’s (POF) “Specifications and Requirements for In-line Inspection of Pipelines” distinguishes between "cracks" and "crack-like features" based on their size. A crack is defined as a defect with an opening less than 0.1 mm, while a crack-like feature is larger. MFL technology is typically capable of detecting crack-like features but may not be able to detect smaller cracks [5].

To help operators identify, size and prioritize circumferentially oriented SCC features, T.D. Williamson (TDW) developed a process leveraging existing MDS™ Pro technologies.

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The MDS Pro platform, Figure 1, incorporates multiple ILI technologies on a single inspection vehicle. This integrated approach allows for the cross-referencing of data collected in a single run from different techniques, leading to a more comprehensive understanding of the pipeline's condition. MDS Pro technologies include:

- *Axial magnetic flux leakage (MFL)* detects volumetric metal loss, mill anomalies and extra metal within the pipe wall, measuring changes in the magnetic flux leakage field. Circumferentially oriented metal loss similar to that associated with CSCC, will result in a strong response in this technology.
- *Spiral magnetic flux leakage (SMFL)* uses a spiral magnetic field to detect and size longitudinal defects. Combined with the results of the axial MFL data set, this data helps differentiate circumferential from axial metal loss features.
- *IMU (XYZ)* provides high resolution mapping of pipeline routing, useful for locating and assessing bending, both intentional and unintentional, in the pipeline. This technology is useful for performing post inspection bending strain and line movement analysis.
- *Low-field axial magnetic flux leakage (LFM)* detects changes in material permeability. This technology has proven to be useful for locating potential localized cracking.
- *Geometry or deformation (DEF)* technology provides detailed information about the geometry of the inner diameter of the pipeline. Experience has shown, for larger and deeper CSCC anomalies, they can be detected by DEF as a slight geometric bulge in the pipe wall.
- *Internal/External Discrimination (IDOD)* technology identifies the location of metal loss anomalies as either internal surface or external surface.

Figure 1: Example MDS Pro system containing SMFL, MFL, LFM DEF/IDOD and XYZ technologies.

History of CSCC Analysis Development: Identifying and Prioritizing CSCC Threats

Initial Model Development

Initial development of the CSCC prioritization model began by assessing how existing ILI tools could identify corrosion and loading conditions to infer the potential location of CSCC.

A key of the initial ILI -based CSCC assessment process was investigating location of elevated strain. Bending in the pipeline, either intentional or unintentional, can result in residual stress in the pipe wall, creating tensile strain on the extrados of the bent section. Unintended bending may occur due to land movement, construction loading or operational issues. The location of the unintended bending could be found using inertial measurement units (IMUs) to measure the orientation and curvature of the pipeline. The ILI-based approach of evaluating the risk of CSCC presence could be assessed by evaluating environmental corrosion, and mechanical stresses from bending, to identify regions that are more prone to SCC development.

Figure 2 shows how the interaction of corrosion and bending stress can be used to find regions with elevated risk of CSCC. Specifically, it represents the coincidence of calculated bending strain, the

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orientation of tension in the material fibers and metal loss features identified by the associated ILI MFL technologies.

In Figure 2, the red line (top of image) in the plot is the strain calculated from the MDS™ Pro mapping data. The peak in the red line indicates an area of unintended curvature in the pipe.
The black line (bottom of image) in the plot shows the orientation of the extrados of the curvature.

Finally, the purple triangles (symbols) represent areas of metal loss detected and identified by the axial MFL and SMFL datasets.

From this figure, we can identify that there is an area of elevated bending strain with coincident corrosion that is located on the tension side of the bending. Given the stress induced by the bending exceeds the hoop stress applied by the internal pipeline pressure, SCC cracking is initiated, but propagated in a circumferential direction, rather than in the typical axial orientation.

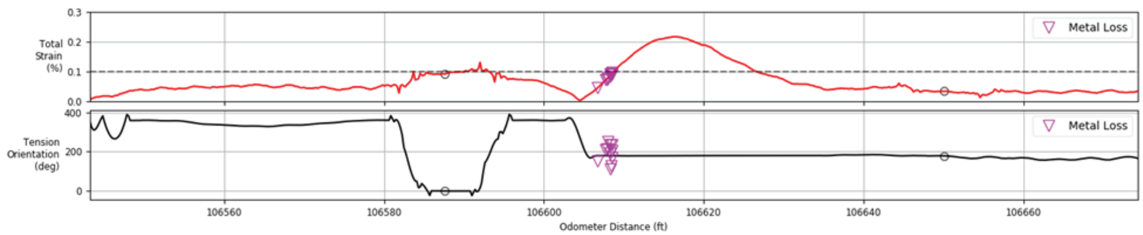

Figure 2: Calculated strain due to unintended curvature (top line), tension orientation of the curvature (bottom line) and the orientation of metal loss (symbols) plots for an area of unintended curvature.

Another key aspect for identifying and sizing CSCC anomalies is the characterization of the orientation of the metal loss anomaly itself. Because magnetic discontinuity are detectable with openings as small as 0.1mm (0.004"), circumferentially oriented crack-like indications can be detected by MFL technologies. Conversely, axially oriented crack-like indications can be detected by SMFL technologies. Leveraging the presence of both technologies on a single tool train, ILI tools allow for characterization of both axial and circumferential crack-like indications, and the ability to differentiate one from another (Figures 3 and 4).

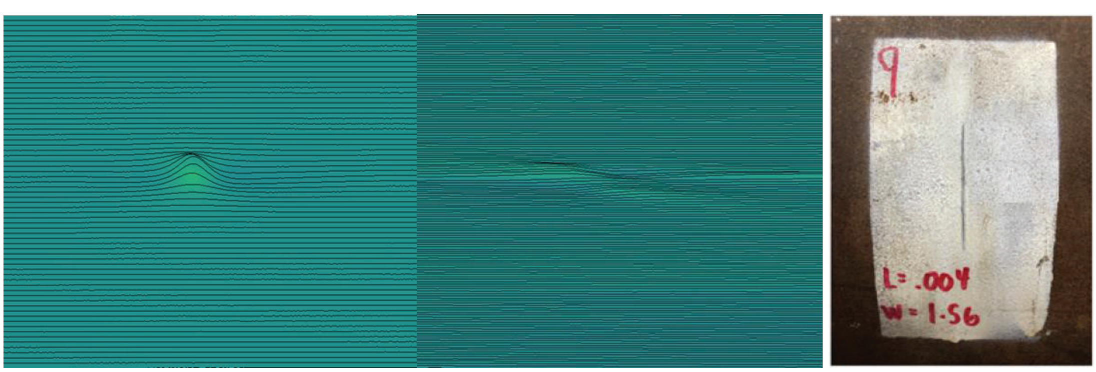

Figure 3: MFL response for the axial (left) and spiral (center) field directions for a circumferentially oriented crack-like (0.004" L x 1.17" W x 0.26t D) feature. Actual feature image (right). The axial field MFL detected a circumferential crack-like feature, but the SMFL detection is muted.

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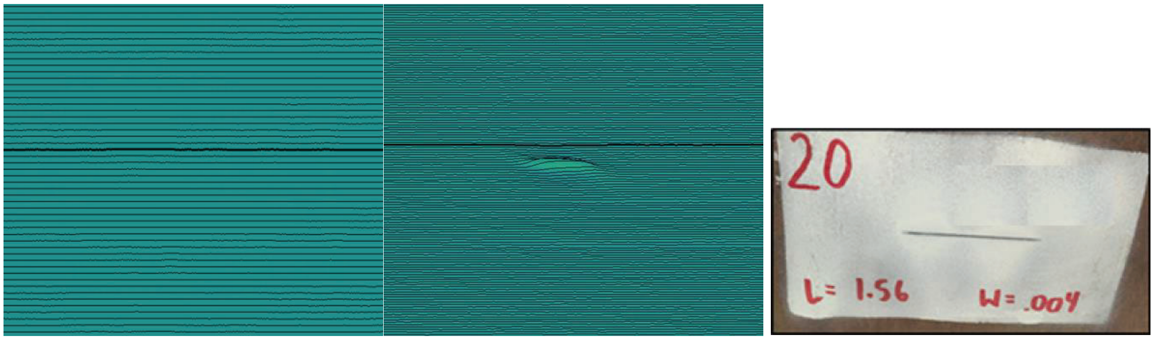

Figure 4: MFL response for the axial (left) and spiral (center) field directions for an axially oriented crack-like (1.56” L x 0.004” W x 0.25t D) feature. Actual feature image (right). The SMFL technology detected an axial crack-like feature that was invisible in the axial field direction.

The initial model relied on characterizing the orientation and overlaying the corrosion features on bending strain profiles helped identify areas where corrosion coincided with areas of unintended curvature. The result of this early model was a classifier that produced high, medium and low likelihood classification results.

Developing a Scoring Model Methodology

For the next iteration of CSCC assessment, a scoring method was developed to classify circumferential crack-like features from general volumetric geometries. By analyzing the rate at which the MFL signal data changed, analysts can classify the general shape of the corrosion. A sharp, narrow peak in the signal indicates a crack-like, more critical feature while a broader peak suggests a volumetric defect. This approach builds upon the visual classification developed in the initial model, resulting in more consistent results.

Figure 5 shows two examples of the first order axial derivative profiles for two different metal loss features. The left profile is a 0.004”-long circumferential slot (something like Figure 3 above) feature while the right is a 1.0”-long pitting (volumetric) feature. Both features have similar signal peak amplitudes but the rate at which the signal rises and falls differentiates the two.

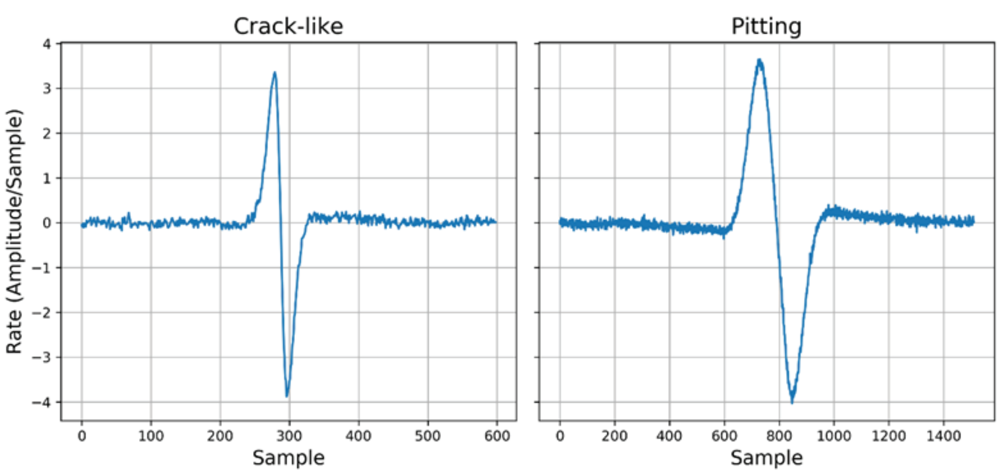

Figure 5: Comparison of the first order derivative profiles for two different POF geometries, crack-like and pitting

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Leveraging the characteristics of the rate of rise/fall rate for a metal loss anomaly, a score was generated to group metal loss anomalies based on 'sharpness'. Figure 6 shows a comparison of metal loss geometries and the calculated score for each feature sorted descending by highest score. The separation between crack-like and volumetric features provides a simple way to classify individual metal loss signatures.

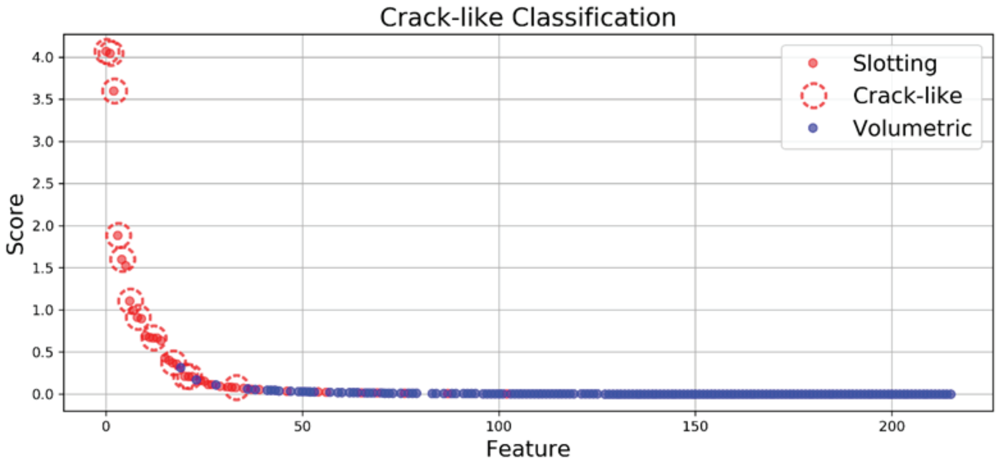

Figure 6: Comparison of circumferential slotting, circumferential crack-like and volumetric feature scores

Adding LFM Technology to Enhance Identification

Adding LFM data to the assessment process proved a key enhancement to the CSCC characterization process. LFM data, which is typically utilized to characterize pipeline material from manufacturing processes, welding, operational stresses and other factors, has demonstrated a unique response near CSCC anomalies. It seems the LFM data responds to localized permeability changes due to localized stress associated with cracking. Including the LFM response in the CSCC characterization process has helped achieve a substantial increase in true positives and a significant decline in false positives rates during reporting.

Since the industry has documented instances of CSCC occurrence outside the expected elevate strain location associated with geohazard, the addition of the LFM data to the assessment process has facilitated continued success locating and characterizing CSCC anomalies.

The Updated Assessment Process

In summary, the updated CSCC prioritization process involves:

- Assessing and scoring signal specific characteristics (MFL, SMFL and LFM)
- Associating the orientation of tension in the pipe wall, if curvature is present
- Additional scoring takes accounts for changes from previous ILI results, line movement analysis results, coating type and conditions.
- Assigning priority, and providing a cumulative final scoring

The Results

Figure 7 outlines a real-world example of CSCC classification from ILI data, despite being located in the long seam. The axial MFL data indicated a circumferentially oriented anomaly, with two strong,

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short and wide responses. Conversely, coincident weak response in the SMFL data indicates the metal loss anomaly is likely crack-like and circumferentially oriented. SMFL data also confirms the long seam location. In addition, the LFM response is disproportionate to the typical LFM response that would be expected for the documented MFL response. This disproportionate, high amplitude LFM response suggested a permeability change, likely the result of local stress associated with cracking.

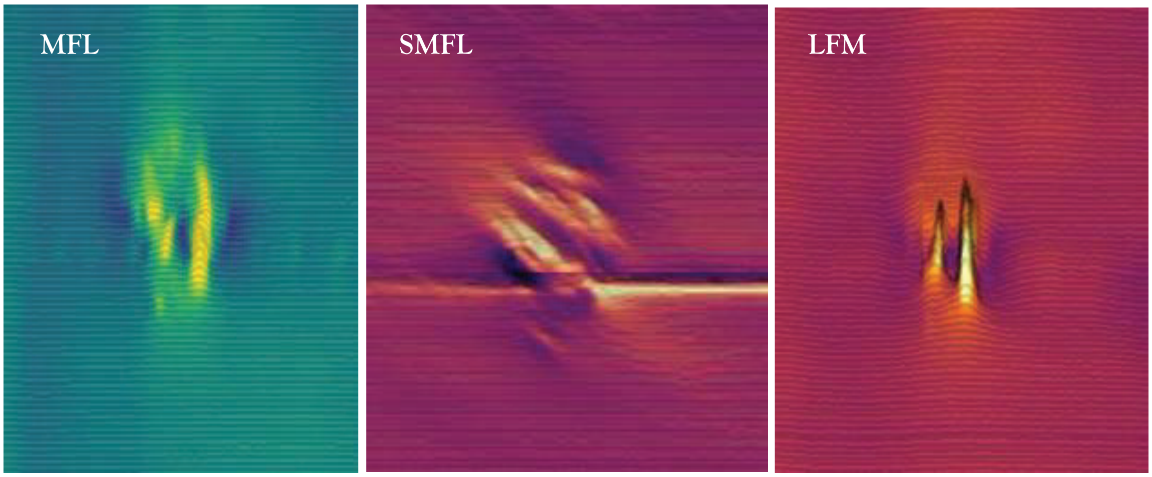

Figure 7: Data collected from MFL (left), SMFL (center) and LFM (right) using the MDS Pro ILI platform.

Figure 8 shows the as-found anomaly in the field, two CSCC anomalies in close axial proximity to one another, coincident with the two peaks seen in the ILI data in Figure 7.


Figure 8: As-found CSCC anomalies for the ILI data shown in Figure 6.

Conclusion

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Many pipeline operators have been on a journey in recent years as they have researched and implemented techniques for managing CSCC anomalies. TDW CSCC assessment techniques have grown right alongside these operators. Early CSCC assessment techniques focused techniques to assess and characterize areas of unintended bending in the pipe.

More recent findings by operators have indicated that while unintended bending can contribute to CSCC generation, many CSCC features are being found outside of the detectable pipe bending regions. The updated CSCC characterization process leverages additional data sources, including LFM technology, to accurately detect and size CSCC anomalies.

Today, the latest CSCC characterization model leverages information from MDS Pro datasets and other observations indicating that:

- A strong LFM response disproportionate to the normal MFL response is a positive indicator of localized cracking.
- Unintended bending and pipeline movement can produce strain to activate CSCC.
- While elevated bending strain is often associated with CSCC, it isn't required for identifying or classifying such defects.
- Significant CSCC anomalies produce a distinct profile in IDOD data.
- Significant CSCC anomalies also result in bulging that can be detected with DEF technology.
- New or rapidly growing anomalies may signal the development or significant progression of cracks.

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