A case study in the detection and sizing of circumferential stress corrosion cracking

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Abstract

Circumferentially oriented stress corrosion cracking (CSCC) can occur in an operational gas or liquid pipeline when the tensile axial or longitudinal stress exceeds hoop stress [1] [2] [3]. Possible sources of axial stress include but are not limited to bending stresses, soil movement, construction practices, and thermal expansion. When this situation is coincident with a corrosive environment, say where the pipeline coating is damaged or cathodic protection is compromised, CSCC can occur. Since CSCC is not readily detectable using many ILI technologies, current practices for dealing with CSCC take a direct assessment approach, using protocol driven priorities for excavation where conditions are conducive to CSCC.

In this paper we expand on experiences stemming from investigations in direct detection and sizing of circumferential stress corrosion cracking (CSCC) using axially oriented magnetic flux leakage (MFL) with very high sampling rates as reported in [4]. Using in-house developed methods in tandem with criteria summarized in [2], [5] and [6], data from inline inspections including axial MFL (AMFL), transverse or circumferential MFL (CMFL), geometry, and inertial measurement unit (IMU) were searched and screened for possible CSCC. Integrity excavation findings resulting from this reporting were then compared with reporting to gauge accuracy in both identification and characterization of CSCC. These integrity excavations were in a natural gas pipeline located in mountainous topography, lending to a higher probability of CSCC. Results are summarized detailing reporting identification and sizing accuracy, with a synopsis of next-steps for this ongoing research project.

Introduction

After discoveries documented in [4], an inline inspection was planned on a pipeline that was highly susceptible to Circumferential Stress Corrosion Cracking (CSCC). The subject pipeline was constructed in 1965 of 6.625-in OD x 0.188-in WT, Grade X42 line pipe and is located in an area of rugged mountainous terrain. The inspection was conducted in late summer and one validation excavation, a 130 ft cut out covering 18 CSCC indications, has been completed. Although additional validation excavations are planned, at the time of the writing of this paper only one validation excavation was able to be completed due to the weather conditions and the resulting short construction season impacting the subject pipeline.

Stress corrosion cracking (SCC) is a form of environmentally assisted cracking and in general is the result of both stress and environmental and chemical conditions including pH, in a material that is susceptible to cracking [2]. CSCC occurs when longitudinal stress, typically from ground movement or localized bending, is the major stress component. CSCC Susceptibility factors as outlined in [1] and [2] are:

- Coating type that is prone to failure, allowing for a corrosive environment
- Proximity to previously discovered CSCC or SCC
- Year of construction
- Construction season (as an indication of temperature during construction)
- Age of pipe (higher incidence of CSCC in 30 to 50 year old pipe)
- Terrain with elevation changes
- Pipe grade
- Pipe diameter
- Wall thickness

There are inline inspection technologies available to detect circumferentially oriented cracks like CSCC (shear wave UT or EMAT) but the accuracy, reliability, and feasibility of these technologies when specifically reconfigured for this application is not well known [6]. Even with ILI options, many procedures for identifying CSCC rely heavily on identifying areas of susceptibility and completing excavations in these areas. This type of assessment identifies sites where high axial stress coupled with poor or failed coating is possible. This satisfies two of the major conditions that are conducive to CSCC; a corrosive environment and high axial/longitudinal stresses. The remaining conditions for CSCC are then pipe material characteristics; whether the pipe metallurgically is prone to cracking. This last condition can have much to do with historical manufacturing practices, which is why the age of the pipe is considered a susceptibility factor. Figure 1 shows the interaction between these required conditions, and the relationship between CSCC and axially oriented Stress Corrosion Cracking (SCC).

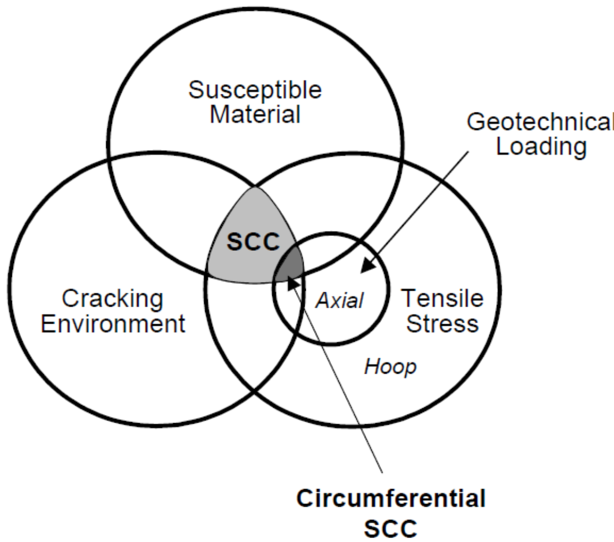

Figure 1: Canadian Energy Pipeline Association (CEPA); "Stress Corrosion Cracking Recommended Practices, 2nd Edition", December 2007

Conducting excavations based on areas of CSCC susceptibility alone can be successful at identifying locations of CSCC. However, conducting a sufficient number of excavations to quantify the threat and confirm that the worst indications have been excavated can prove extremely challenging if not infeasible. Remote, mountainous or hilly terrain where CSCC is often found present significant challenges for conducting excavations and areas of high elevation associated with mountainous terrain can have a very limited construction season.

The circumferential orientation of this type of anomaly makes consistent detection by conventional crack detection methods unreliable. Axially oriented MFL is a more suitable inspection technology, but state-of-the-art electronics are unequal to the task of achieving a suitably high sampling rate for consistent detection. As a solution to these hurdles, we present Axial MFL (AMFL) inline inspection tools with ultra-high sampling rates up to 8,000 Hz. The target sampling distance is in the millimetre or sub-millimetre range (less than 0.039 inches). Using this technology, coupled with other inspection technologies and ranked susceptibility factors, a system for identifying CSCC is developed.

Direct ILI Detection vs. Multi-input Susceptibility Factor Protocol

As previously discussed, current CSCC identification methods rely heavily on non-ILI data information with little to no support from ILI data sources at all. Current and under development ILI technologies have been identified as solutions for CSCC detection, but at this point are unproven [6]. For the time being, it is evident that a protocol driven identification procedure is still the most effective way to identify probable locations for CSCC. To paraphrase this discussion; The current state-of-the-art ILI in general cannot solely be relied upon for effective CSCC mitigation.

This begs the question then, why ILI at all? The answer to that lies in the feasibility or lack thereof of conducting a sufficient number of excavations to quantify the threat and confirm that the worst indications have been repaired, particularly in terrain that is susceptible to CSCC. If ILI technologies can progress to the point of consistent and exhaustive detection for critical CSCC, benefit can result. A further step would be for ILI to identify intermediate risk CSCC, creating a benchmark for ongoing monitoring. This then defines the goals of this ongoing research and development project.

Regardless the success of current ILI technology research and development, if the onus were to shift from ranking CSCC susceptibility factors to direct ILI detection, the former will always be part of the analysis procedure regardless the efficacy of the latter.

Expanding and Ranking CSCC Susceptibility Factors

Using susceptibility factors listed above, expanding them to include factors from ILI data and setting into a preliminary ranking[1], the following are compiled and listed from most to least important for CSCC:

- Signal is evident in Internal Depth Detection™ (IDD) sensors[2]
- An area of bending strain
- Not detected by Micron Circumferential MFL
- Low length to width ratio
- Thin wall thickness
- Signal amplitude in Micron Axial MFL sensors
- Extreme terrain
- Poor coating or CP condition
- Poor ground stability
- Field verification history

Figure 2 shows these susceptibility factors in graphic form. Green items are factors from ILI data, and amber items are pipeline operator supplied.

[1] Based on ongoing Data Analyst input and Excavation results.
[2] IDD sensors are used for both internal/external discrimination and as an indicator of very deep external indications.

Parameter
AMFL Signal Amplitude
AMFL Signal L to W Ratio
Not Detected by CMFL
IDD Detection (Deep OD Crack)
IMU Bending Strain
Wall Thickness
Terrain Profile
Coating and CP conditions
Ground Stability
Field Verification History

Figure 2: CSCC Susceptibility Factors. Green Items – ILI, Amber – Pipeline Operator

At the time of writing, this list is still in a subjective state and will be under further development. Refinements and numerically encoding the ranking will take place when a suitable database of CSCC has been compiled.

Applying Susceptibility Factors to Data Analysis

For the ILI survey described in subsequent sections, possible CSCC indications were identified using the following procedure:

1. Review IMU data, looking for elevated bend stress levels.
2. Reviewing AMFL data in these areas, look for evidence of failed coating.
3. At an appropriate zoom level, look for evidence of bending in the AMFL data.
4. Zooming in, look for possible CSCC in the AMFL data.
5. Is the length to width ratio small?
6. Review IDD signal. Estimate probability of CSCC vs. internal corrosion.
7. Locate any possible CSCC in CMFL data, noting whether any indication is evident.
8. Size using existing AMFL procedures[3].
9. Rank probability of CSCC using the following classification scheme.

CSCC indications were classified and reported in the following way:

> Narrow Circumferential Feature A (NCF A)—Narrow circumferential defect that is likely to cause a failure mechanism for the pipeline in the future. The term "Probable Circumferential Stress Corrosion Crack Indication" is a synonym used to describe this type of an anomaly. This type of anomaly has most of the attributes associated with CSCC (near-by corrosion, located on or near the outside of an area with bending stress, relative thin wall thickness, a pipeline history that shows susceptibility to CSCC, short length, high width/length ratio, visible with AMFL but not CMFL).

[3] AMFL sizing was used in the absence of any controlled examples of CSCC, and as such was only used as a severity ranking.

Narrow Circumferential Feature B (NCF B)— Narrow circumferential defect that is likely to cause a failure mechanism for the pipeline in the future. The term "Possible Circumferential Stress Corrosion Crack Indication" is a synonym used to describe this type of an anomaly. This type of anomaly has some of the attributes associated with CSCC (near-by corrosion, located on or near the outside of an area with bending stress, relative thin wall thickness, a pipeline history that shows susceptibility to CSCC, short length, high width/length ratio, visible with AMFL but not CMFL).

Narrow Circumferential Anomaly (NCA)—Narrow circumferential defect that is unlikely to cause a failure mechanism for the pipeline in the future. This type of anomaly may have one or two of the attributes associated with CSCC, (near-by corrosion, located on or near the outside of an area with bending stress, relative thin wall thickness, a pipeline history that shows susceptibility to CSCC, short length, high width/length ratio, visible with AMFL but not CMFL), but not enough to suggest the possibility of CSCC.

Another aspect of this work is whether the IDD sensor response can be an aid to depth characterization in the absence of a validated sizing model. Current results do show the use of IDD sensors can be an indication of CSCC severity; a possible effective tool for prioritizing integrity excavations. This alone would be a significant aid to CSCC mitigation efforts. Further research will be directed beyond the qualitative characterization to one that is more quantitative. The sampling frequency for IDD sensors is the same as that of the AMFL, so that can be deemed as adequate. The other factor is sensor spacing which is in the current case 0.409 inches (10.4 mm) compared to 0.083 inches (2.1 mm) in the case of AMFL. This will be the subject of future investigations as to whether the IDD sensors are used for identification only or as part of a characterization model.

Integrity Excavations and NDE Results

A target integrity excavation site was chosen based on CSCC susceptibility factors and frequency of ILI analysis calls. Choosing a site with highly ranked susceptibility factors increases the chance of discovering more low level CSCC that may not be identified by ILI analysis, helping set probability of detection levels. Figure 3 shows an elevation plot for the test ILI inspection, including the approximate location of the validation excavation in an area of known historical earth movement.

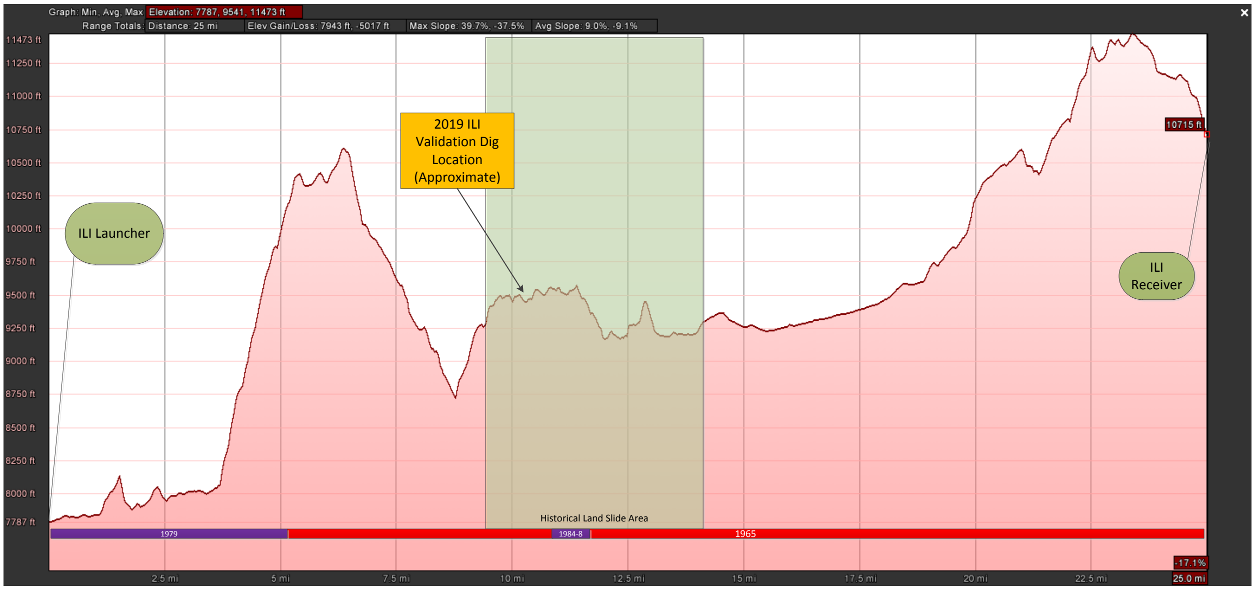

Figure 3: ILI Inspection Information

Figure 4: Examples of Terrain Where Circumferential SCC was Found.

Feature ID	Weld ID	Tool Speed (ft/s)	Reported Feature Type	NDT Group Field Measured (%)	Width measured in the Field (in)	Odometer (Center/Deepest) (ft.)	Orientation (Center/deepest)	Delta from Seam Weld (degrees)	Seam Orientation	Comments
NR1	1312			34%	0.4	57453.524	05:43	17.5	06:18	Not Visible in ILI Data, below detection threshold on circumferential width
NR2	1312			38%	0.4	57454.440	05:54	12.0	06:18	Not Visible in ILI Data, below detection threshold on circumferential width
NR3	1312			15%	0.3	57455.378	05:57	10.5	06:18	Not Visible in ILI Data, below detection threshold on circumferential width
4481	1312	7.9	NCF-B	74%	1.7	57456.360	05:46	16.0	06:18	As identifed in AMFL ILI run. Visible in IDD Sensors.
NR4	1312			36%	0.4	57458.160	06:49	15.5	06:18	Not Visible in ILI Data, below detection threshold on circumferential width
NR5	1312			34%	0.4	57458.351	05:54	12.0	06:18	Not Visible in ILI Data, below detection threshold on circumferential width
NR6	1312			17%	0.2	57459.174	05:54	12.0	06:18	Not Visible in ILI Data, below detection threshold on circumferential width
NR7	1312			15%	0.1	57459.486	05:47	15.5	06:18	Not Visible in ILI Data, below detection threshold on circumferential width
NR8/4484	1312		Metal Loss	54%	0.9	57460.470	05:54	12.0	06:18	Reported as Metal Loss ID 4484, confirmed as CSCC. Interference in IDD signal.
4485	1312	8.6	NCA	36%	0.9	57461.480	05:36	21.0	06:18	As identifed in AMFL ILI run
NR9	1312			13%	0.2	57461.645	05:47	15.5	06:18	Not Visible in ILI Data, below detection threshold on circumferential width
4486	1312	8.7	NCA	44%	1.0	57462.550	04:37	50.5	06:18	As identifed in AMFL ILI run
4488	1312	8.8	NCF-B	100%	1.2	57471.780	04:22	58.0	06:18	As identifed in AMFL ILI run
4489	1312	8.8	NCF-B	65%	0.8	57472.110	05:34	22.0	06:18	As identifed in AMFL ILI run
4491	1312	8.8	NCF-B	76%	1.5	57472.290	03:35	81.5	06:18	As identifed in AMFL ILI run
NR10	1312			34%	0.3	57472.343	02:58	100.0	06:18	Not Visible in ILI Data, below detection threshold on circumferential width
4498	1313	7.9	NCF-B	100%	1.1	57521.530	07:45	19.0	08:23	As identifed in AMFL ILI run
4499.1			Metal Loss - Cluster			57521.770	08:09	7.0	08:23	Visible in AMFL. Weak IDD signal. Reported as Cluster (Corrosion) ID 4499. No NDT measurement.
4499.2						57521.780	08:08	7.5	08:23	Visible in AMFL. Weak IDD signal. Reported as Cluster (Corrosion) ID 4499. No NDT measurement.
4499.3						57521.900	08:23	0.0	08:23	Visible in AMFL. Weak IDD signal. Reported as Cluster (Corrosion) ID 4499. No NDT measurement.
4503	1313	7.7	NCF-A	90%	1.9	57525.850	07:57	13.0	08:23	As identifed in AMFL ILI run. Metullurgical test specimen.
4504	1313	7.7	NCF-B	61%	1.0	57526.580	08:02	10.5	08:23	As identifed in AMFL ILI run
4505	1313	7.5	NCF-B	100%	1.0	57531.280	08:01	11.0	08:23	As identifed in AMFL ILI run
4506	1313	7.5	NCF-B	56%	0.8	57531.640	08:07	8.0	08:23	As identifed in AMFL ILI run
4507	1313	7.5	NCF-B	65%	0.8	57531.980	09:01	19.0	08:23	As identifed in AMFL ILI run
NR11	1313			27%	0.3	57532.061	08:17	3.0	08:23	Not Visible in ILI Data, below detection threshold on circumferential width
NR12	1313			36%	0.3	57533.000	08:10	6.5	08:23	Not Visible in ILI Data, below detection threshold on circumferential width
4509	1313	7.3	NCF-B; adjacent to GW	52%	1.4	57536.940	04:38	112.5	08:23	As identifed in AMFL ILI run
4511	1314	7.3	NCA; adjacent to GW	100%	3.1	57537.380	06:26	34.5	05:17	As identifed in AMFL ILI run
4513	1314	7.3	NCF-B	100%	2.1	57539.800	05:33	8.0	05:17	As identifed in AMFL ILI run
4515	1314	7.3	NCF-B	100%	1.6	57540.580	04:51	13.0	05:17	As identifed in AMFL ILI run
NR13	1314			29%	0.3	57541.551	05:20	1.5	05:17	Not Visible in ILI Data, below detection threshold on circumferential width
NR14/4516	1314		Metal Loss	54%	0.8	57542.510	05:20	1.5	05:17	Reported as Metal Loss ID 4516, Confirmed as CSCC. Barely visible signal in IDD Sensors.
NR15	1314			17%	0.2	57542.670	05:20	1.5	05:17	Not Visible in ILI Data, below detection threshold on circumferential width
NR16	1314			42%	0.5	57542.713	04:26	25.5	05:17	Not Visible in ILI Data, below detection threshold on circumferential width
NR17/4517	1314		Metal Loss	73%	0.9	57543.444	05:27	5.0	05:17	Visible in Axial and IDD. Reported as Metal Loss (Corrosion) ID 4517. Confirmed as CSCC
NR18/4518	1314		Metal Loss	52%	0.8	57545.406	05:23	3.0	05:17	Visible in Axial and IDD. Reported as Metal Loss (Corrosion) ID 4518. Confirmed as CSCC
4519	1314	6.7	NCA	N/A	Corrosion	57559.520	04:09	34.0	05:17	Reported as NCA. Corrosion found.
4522	1314	6.6	NCA	57%	0.7	57570.410	04:46	15.5	05:17	As identifed in AMFL ILI run. Metullurgical test specimen.

Table 1: Excavation Results

Excavation Examples

The following figures are examples of excavated features identified as CSCC.

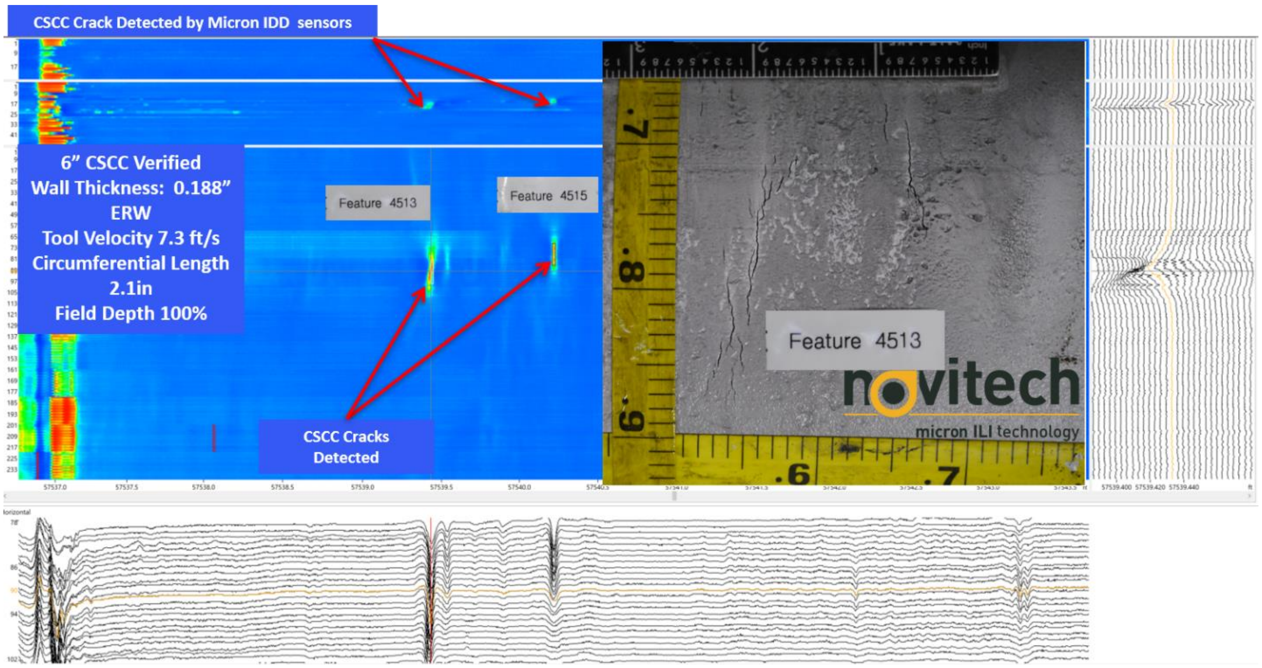

Figure 5: Features 4513.

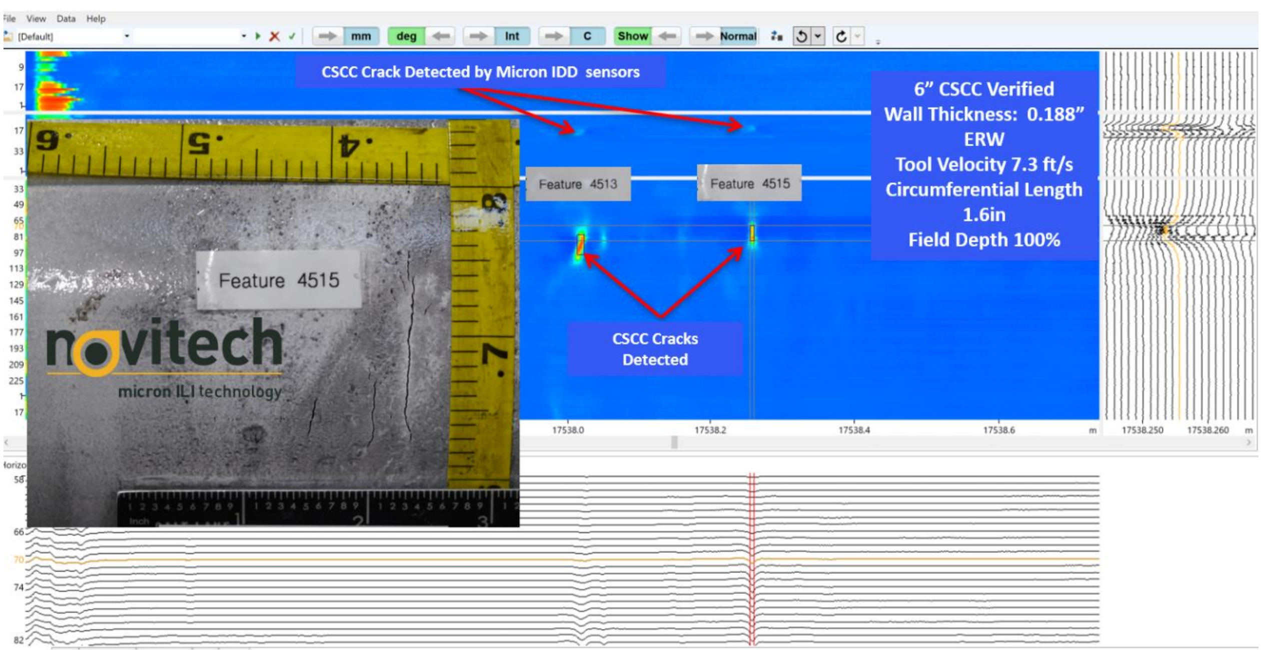

Figure 6: Feature 4515.

Figure 7: Feature 4485

Metallurgical Results

Two sections of pipe with CSCC feature Ids 4503 and 4522 were submitted for third party metallurgical testing. The following excerpt from the final report confirms stress corrosion cracking.

> "The cracks on both pipes exhibited a transgranular, branched morphology consistent with stress corrosion cracking (SCC). In particular, sodium and sulfur were detected within the cracks., Sodium and sulfur-based compounds are known to cause SCC within carbon steels, yet other compounds which may cause cracking cannot be detected by EDS[4] (i.e. ammonia)." [7]

Each ILI identified feature is broken down to separate cracks in the colony. The depth accuracy for "Company 1" NDE PAUT is +11.9% for feature Id 4503 and +5.3% for feature Id 4522. The depth accuracy for "Company 2" NDE PAUT is slightly more reasonable at +10.3% for feature Id 4503 and + 2.0% for Id 4522. These results do however show a trend to overestimation and an error variance that may well exceed industry perception.

Note that the circumferential dimension of Id 4522 reported by NDE is a composite of both cracks in the colony. Due to the merging of ILI indications caused by signal spread (see Figure 14), an ILI characterization would do the same.

[4] Energy Dispersive Spectroscopy.

Pipe No.	Feature Number	Crack Number	NDE PAUT Measured Depth Company 1 (%)	NDE PAUT Measured Depth Company 2 (%)	NDE Measured Nominal (mm)	NDE PAUT Company 1 Measured Depth (mm)	NDE PAUT Company 2 Measured Depth (mm)	Lab Measured Maximum Depth (mm)	Lab Actual Depth (%)	Lab MPI Circ. Length (mm)	NDE MPI Circ. Length (mm)	Lab Crack Opening at ID Mouth (mm)	Lab measured wall thickness (mm)	Lab Comments and Description
1	4503	1	91.5%	89.9%	4.78	4.4	4.3	3.8	79.6%	44.5	48.3	0.094	4.8	Stress-corrosion crack, caustic likely primary corrosion agent responsible
		2			4.78			1.5	31.4%	10.8		0.018	4.8	
		3			4.78			2.0	41.9%	15.7		0.039	5.0	
2	4522	1	66.0%	56.4%	4.78	3.1	2.7	2.6	54.4%	14.4	17.8	0.069	5.0	Stress-corrosion crack, caustic/sulfur or complex product likely primary corrosion agent responsible
		2						2.9	60.7%	14.0		0.073	5.0	

Table 2: Metallurgical Results for Ids 4503 and 4522

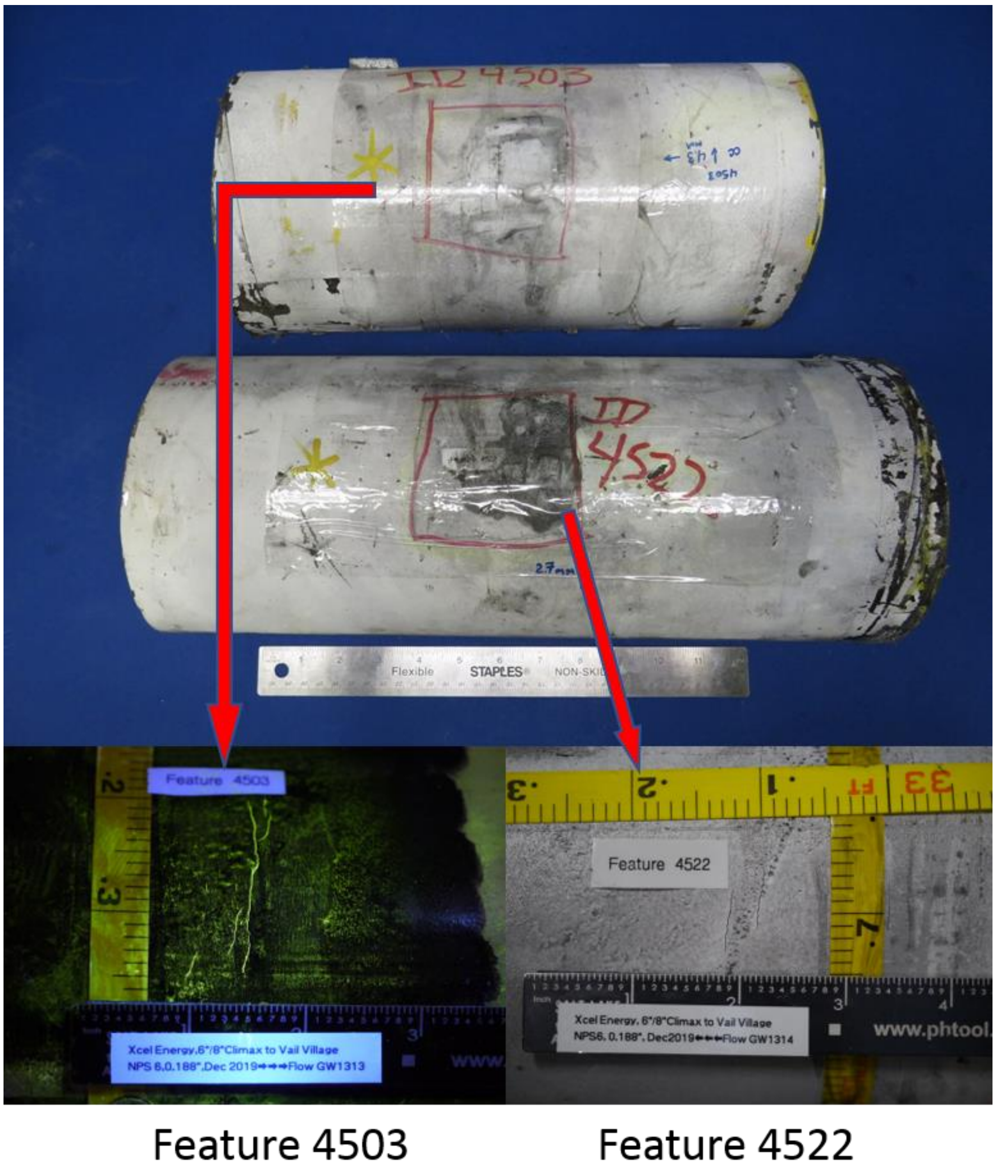

Figure 8: Specimens for Metallurgical Testing

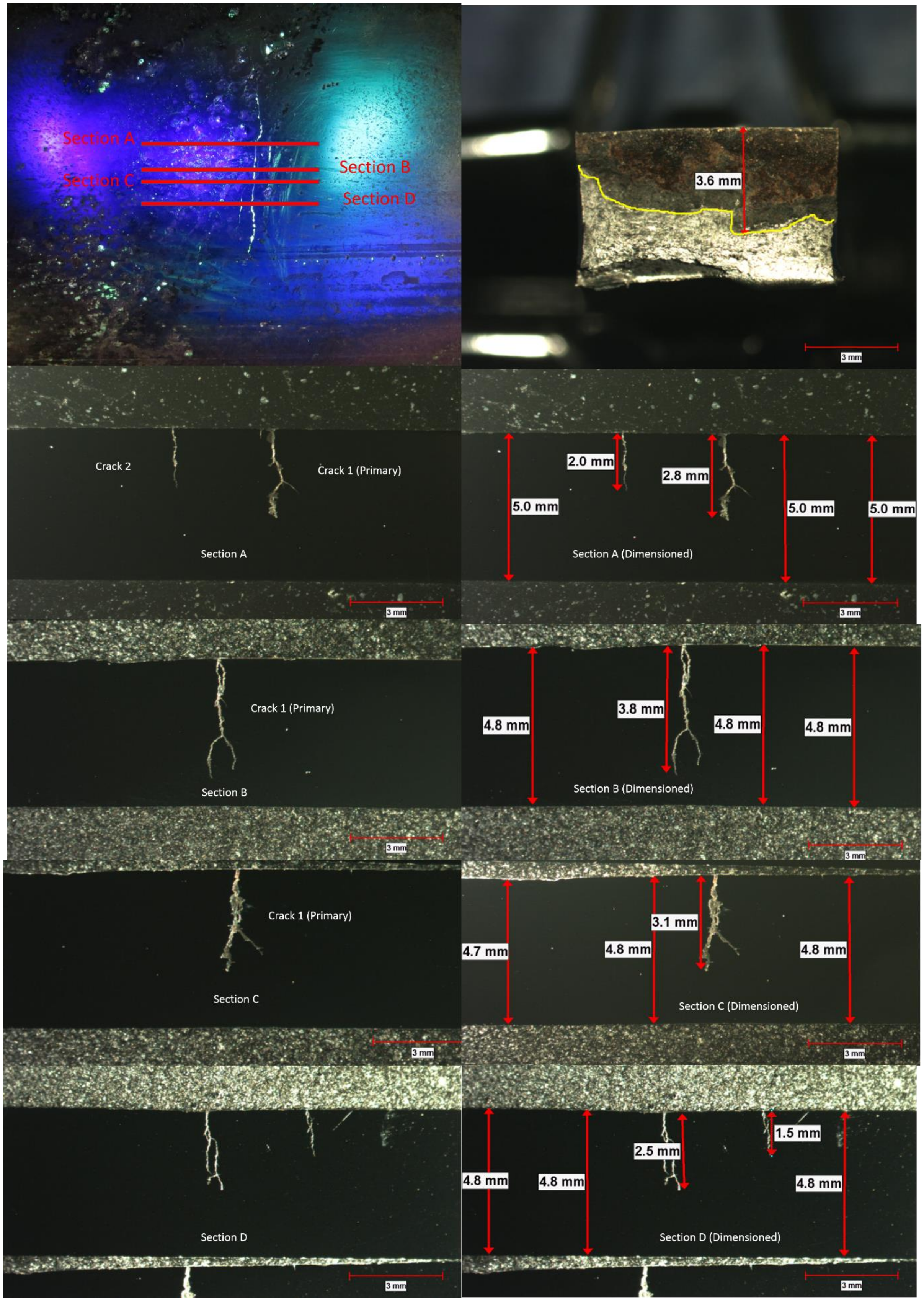

Figure 9: Macrographs Displaying Cross Sections from Feature 4503

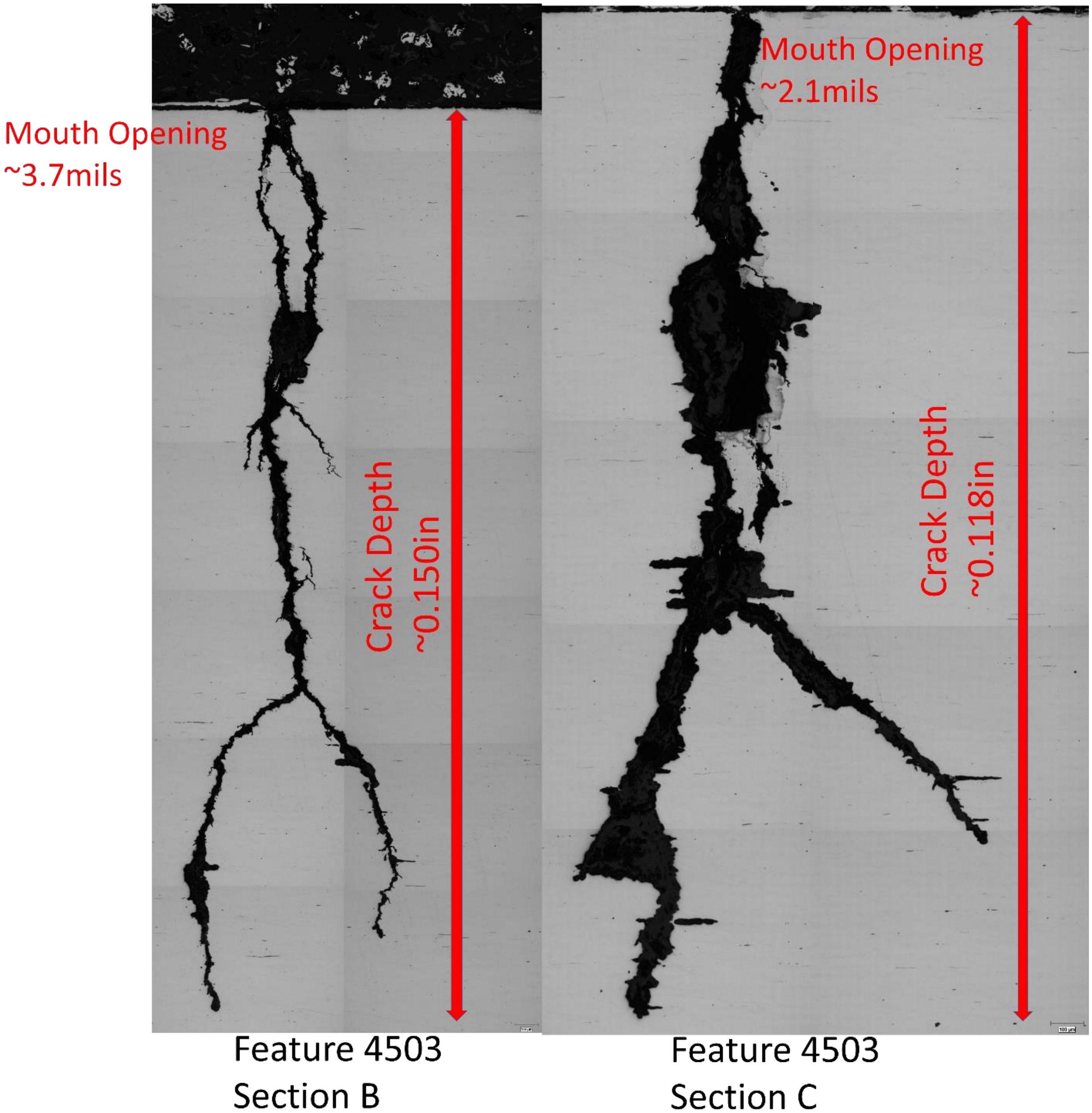

Figure 10: Micrographs of Cross Section Feature 4503 (Main Crack).

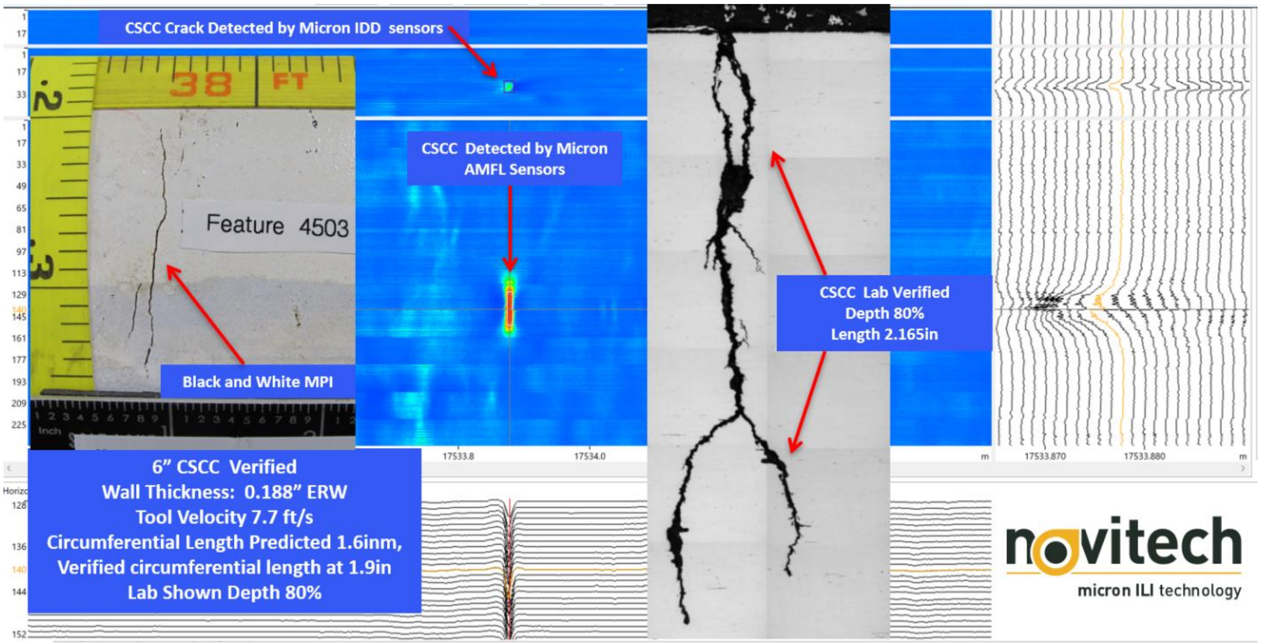

Figure 11: Metallurgically Tested Feature 4503 Data

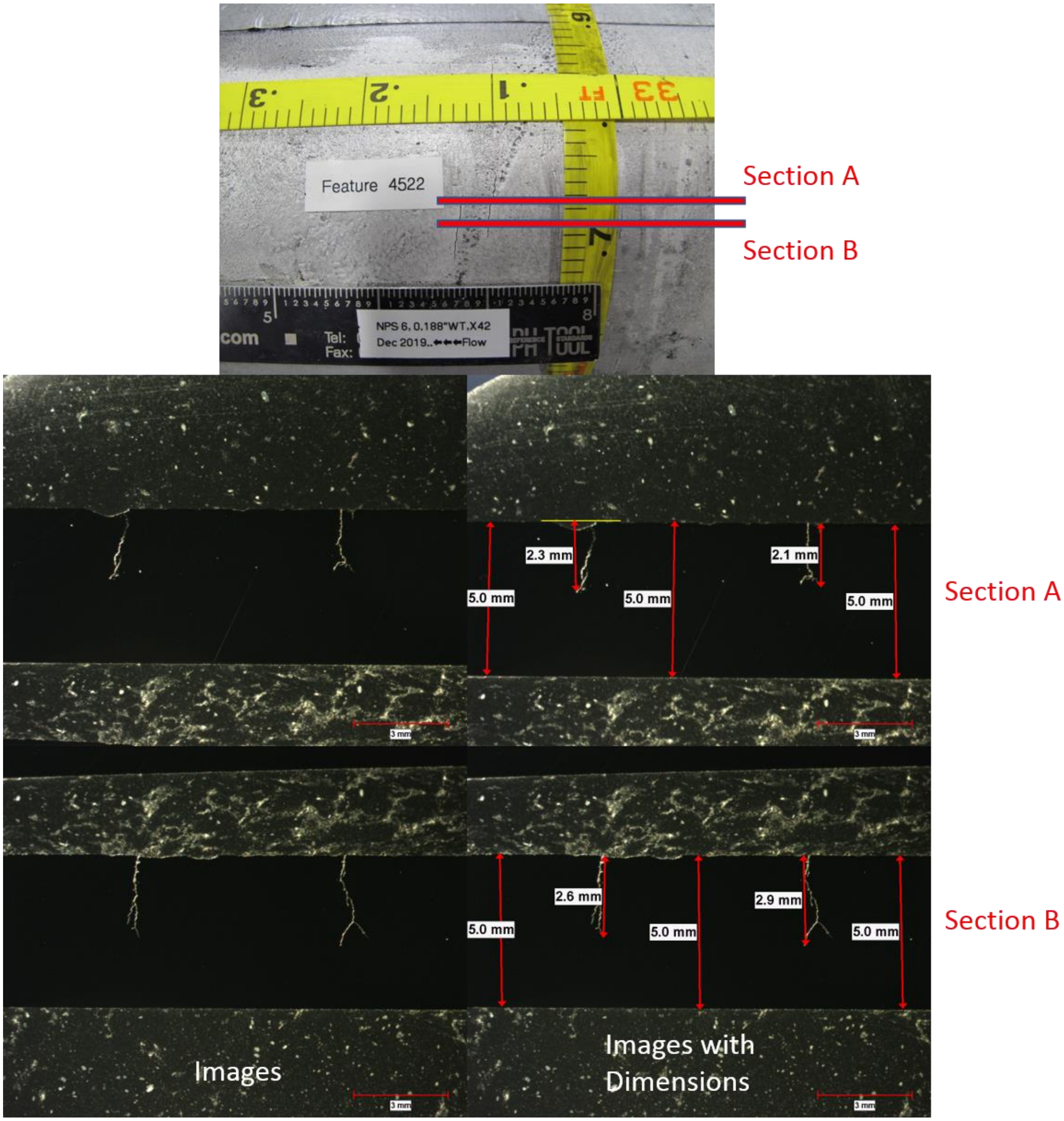

Figure 12: Macrographs Displaying Cross Sections from Feature 4522

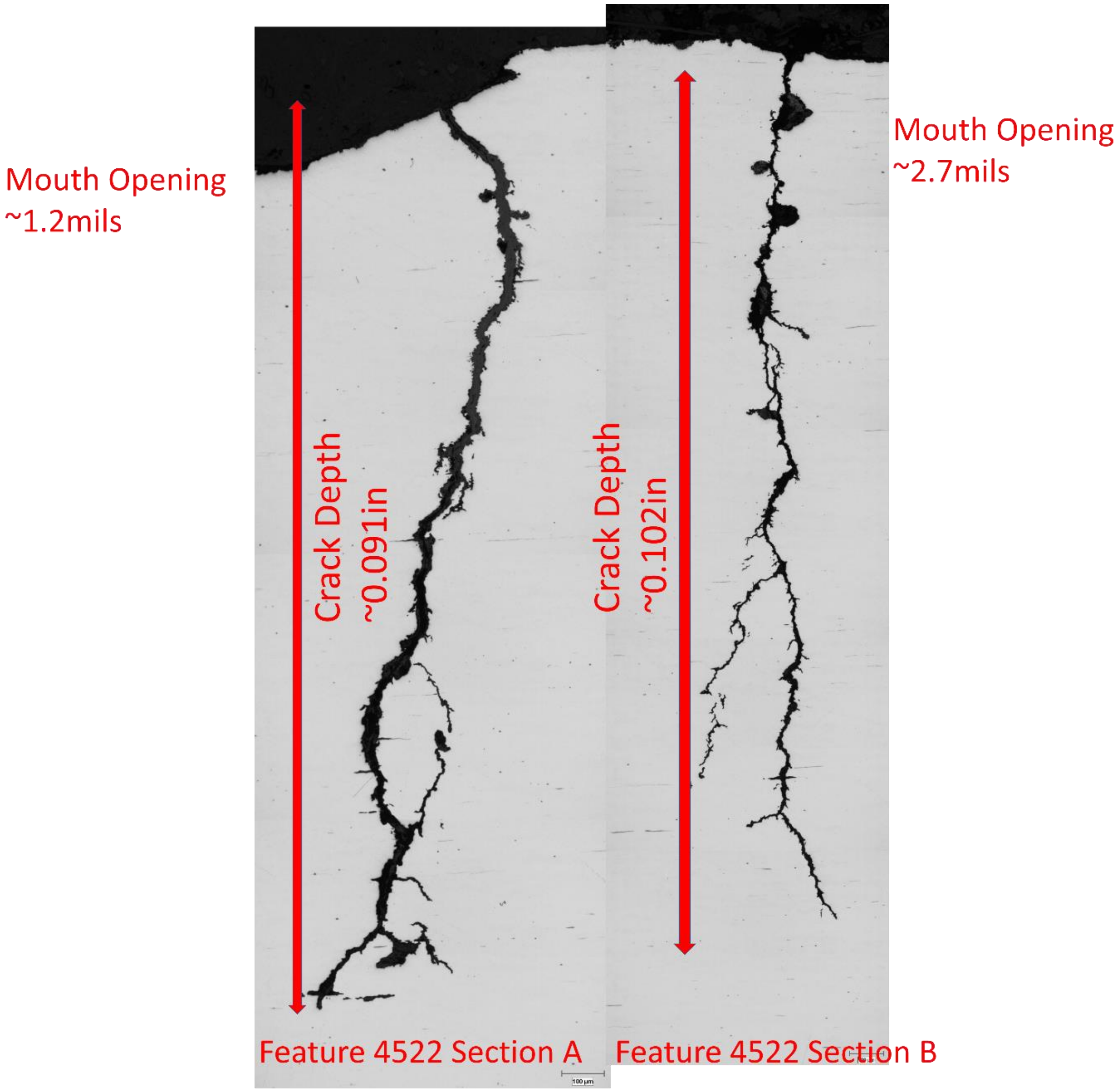

Figure 13: Micrographs of Cross Section Feature 4522.

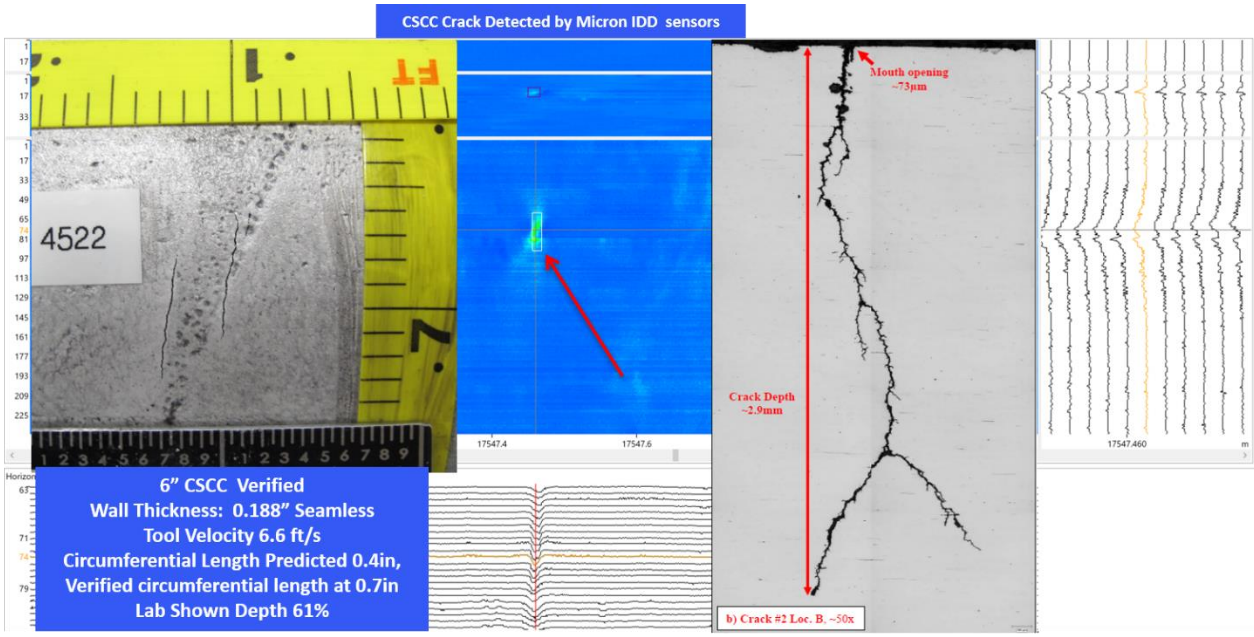

Figure 14: Metallurgically Tested Feature 4522 ILI Data

Detection Accuracy

Reviewing the NDT results in Table 1, it is shown that features with a circumferential width greater than about 0.7 inches (18mm) are detectable in both AMFL and IDD data. Those less than this are not visible or measurable in one or both sensor types. Of this group, the shallowest indication is measured as 36% (ID 4485 at 0.9 inch (23 mm) circumferential width). This implies that these two thresholds must be surpassed before consistent detection can be achieved.

Assuming these thresholds remain over further excavation verifications, and characterization methods prove to be repeatable, guidelines for CSCC monitoring via ILI can be developed.

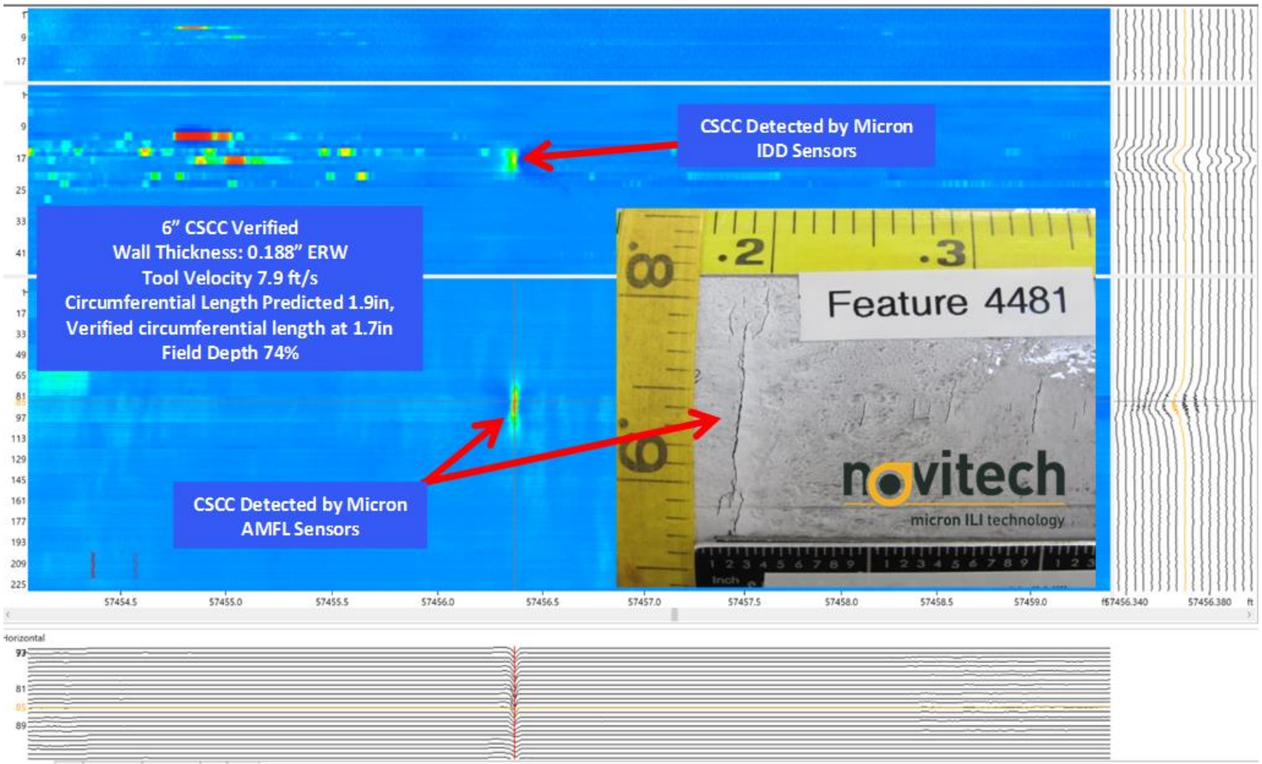

Figure 15: Feature 4481

Unreported or Mis-Characterized CSCC

Apart from CSCC features that were not visible in sensor data, there are a number that were visible in AMFL and sometimes IDD sensor types, but unreported (3) or mis-characterized (12). The 12 CSCC features mis-characterized as corrosion were either by direct reporting error (9) or by omission (3)[5].

There were 12 CSCC features that were reported as corrosion. Two examples of this are NR8/ID 4484 and NR14/ID 4516[6]. Data for NR8 shows an indeterminate signal in the IDD sensors; noise due to possible debris. Data for NR14 shows a faint but clear signal in the IDD sensors. Both features were measured at 54% deep, supporting that a meaningful IDD detection threshold is possible. If future developments support a depth threshold for visibility in the IDD array, at the very least a severity indicator can be implemented to guide integrity excavation priority. As previously noted, the shallowest confirmed CSCC was Feature ID 4485 at 0.9 inch (23 mm) circumferential width and 36% of wall thickness depth (Figure 6). The development of characterization algorithms would further enhance ILI effectiveness by the introduction of depth monitoring over a series of ILI inspections.

[5] The assumption is that the omitted indications were thought to be due to corrosion, but with depth below the reporting threshold.
[6] NDT technicians worked from a list of reported CSCC that did not include reported corrosion, so their identification "NR" (Not Reported) is in their reporting.

That this happened can be explained by reviewing CSCC susceptibility factors. Many unreported or mischaracterized CSCC were in areas where axially oriented stresses are not evident. This observation leads to some questions about how industry accepted susceptibility criteria are applied. Even in locations where field bends are evident, CSCC did not develop where perceived stress patterns would dictate. This questions the assumption that axial stresses can be determined from bend information derived from IMU data.

There was one false CSCC positive in the excavation, Feature Id 4519 which was reported as a Narrow Circumferential Anomaly (NCA or low probability CSCC) 0.9in long by 2.3in wide by 16% deep. The median sample spacing at this item is 1.1mm (0.042in), with a tool velocity of 2.0 m/sec (6.6 ft/sec). This anomaly is at a field bend, satisfying one of the ranked susceptibility factors. Figure 16 shows that there is no indication showing in the IDD data for this item, lowering the probability that this is CSCC. An image of the excavated pipe and ILI data is shown in Figure 16.

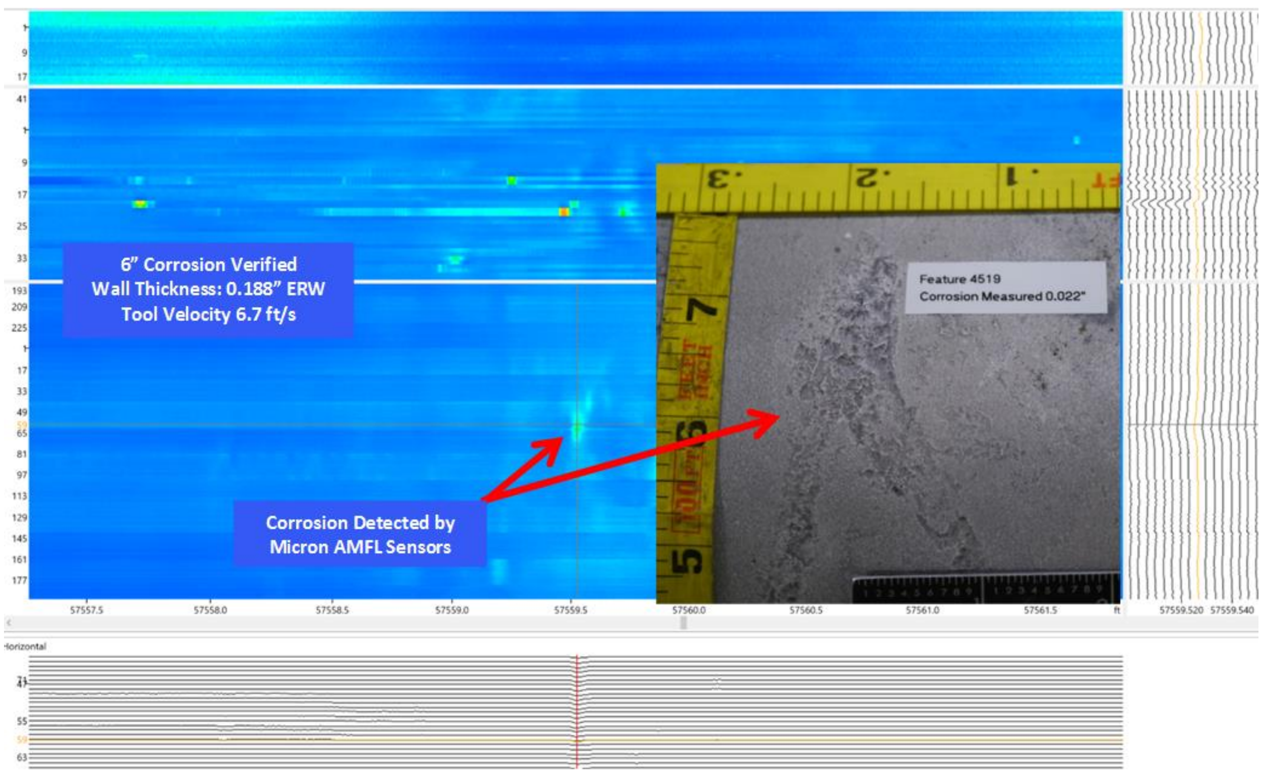

Figure 16: Feature 4519. Corrosion called as Low Probability CSCC.

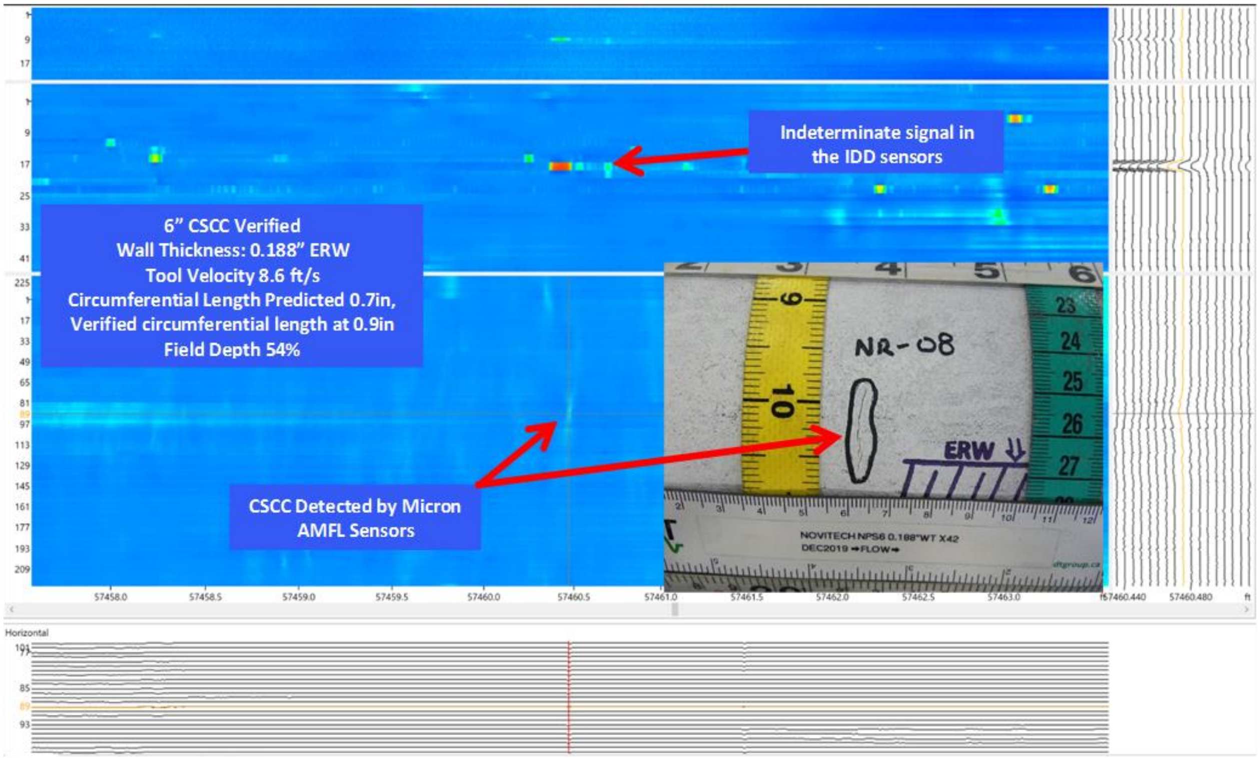

Figure 17: Mis-classified Feature NR8/4484.

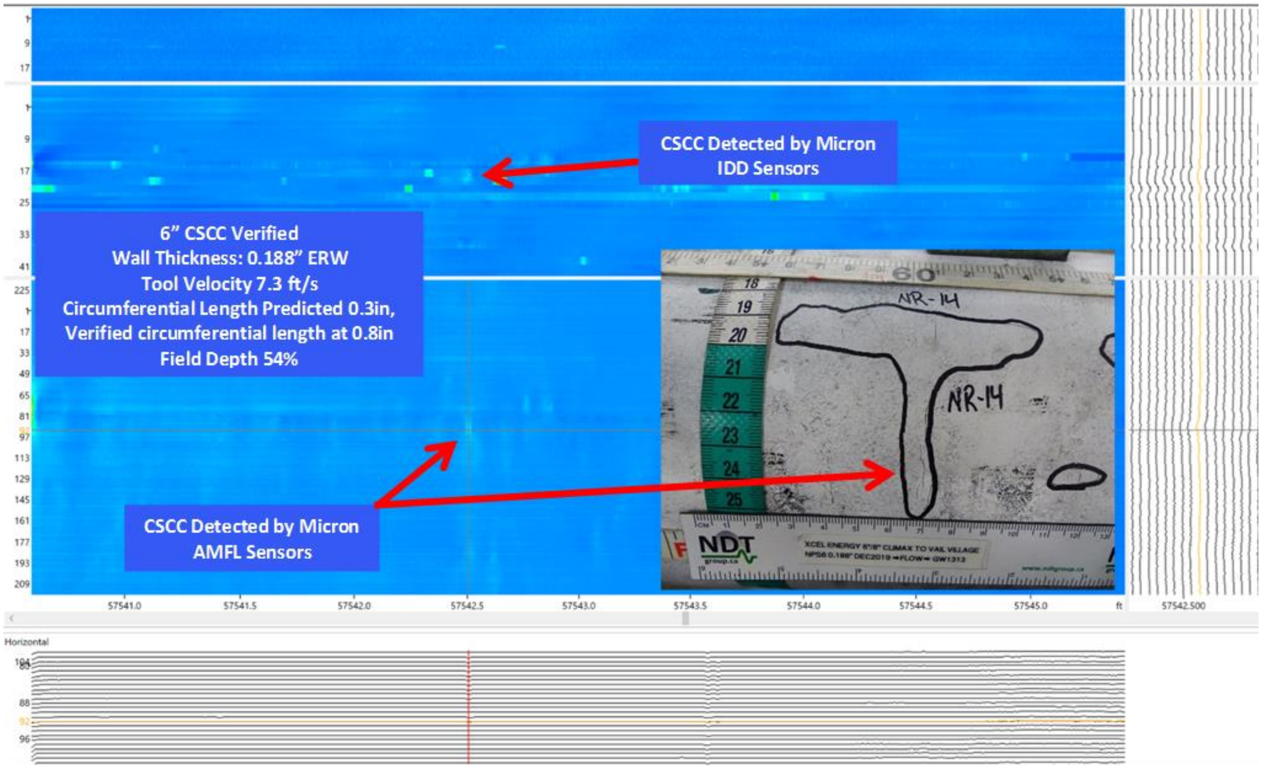

Figure 18: Mis-classified Feature NR14/4516.

Characterization Accuracy

In the absence of a suitable database of CSCC signals with known dimensions, a sizing model based on axial MFL was used. This was meant to assign some semblance of severity to the identified CSCC features. Since the model was not valid for CSCC, depth estimates are not reported here.

Pull Testing

In-house pull testing on excavated pipe sections was conducted at the Novitech facilities. At CSCC locations, indications in the Micron IDD data were evident, showing that the relief of inline stresses did not adversely affect detectability. Further work on IDD signal repeatability and determining the usefulness of this sensor system for CSCC characterization is ongoing.

Discussion

As discussed in the Introduction, this is research documentation for an incremental process, shifting the significance of procedurally identifying locations for probable CSCC based on susceptibility factors to a more direct identification based on ILI sensor technology. Although incomplete, this research effort has made significant steps towards this goal.

With the improvement of ILI technologies to detect CSCC, there is also a paradigm shift towards analysing the entire pipeline with CSCC as an objective target as opposed to specific sites identified by susceptibility-based procedures. As aforementioned, susceptibility-based procedures cannot be abandoned completely.

Until this paradigm shift is more complete, ILI community research efforts will continue to focus on susceptibility-based processes and procedures. Although not the primary subject for this paper, efforts in this direction remain important and imperative.

IDD Sensors as an Indication of CSCC Severity

The interesting development brought to light during the post-analysis of this ILI inspection is the strength of identifiable signals in the IDD sensors for deeper CSCC. These signals were not evident in previous pull tests in excavated pipe with known CSCC. Subsequent pull testing of excavated pipe show signals in the IDD data at CSCC, indicating that removing stresses on cutting and excavation did not affect crack openings enough to prevent detection.

This next example shown in Figure 19 (Feature 4488) shows a peak-to-peak amplitude that is more than the amplitude of that in the AMFL data. As the Hall effect sensors are oriented to measure the radial component of the flux leakage field, the bipolar nature of the signal is evident.

In the short-term the existence of this signal will serve as an indication of CSCC severity. Future research will focus on if this will help refine depth and length characterization. Feature 4488 was measured for depth using phased array ultrasound at 100% of wall thickness.

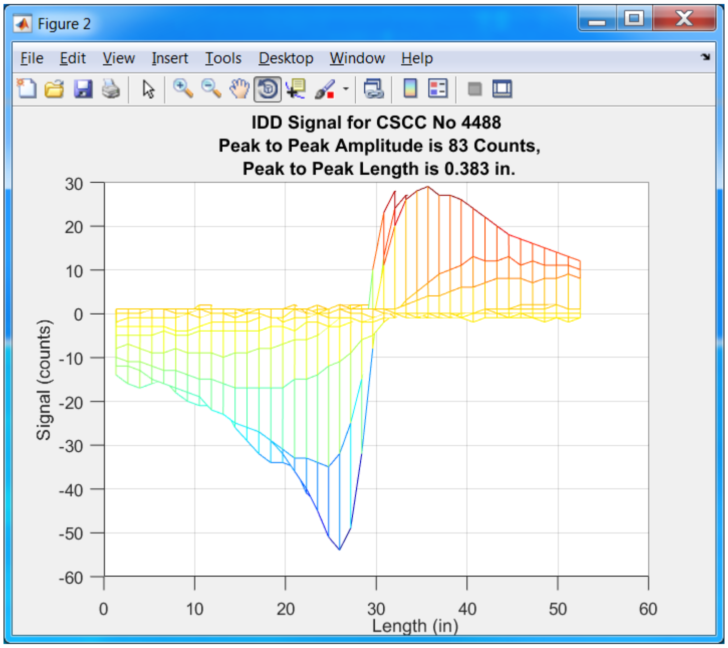

Figure 19: Typical IDD Signal for CSCC (Feature 4488)

CSCC Near or at Long Seam Welds

Of the 42 reported CSCC, 33 were within 30 degrees (1 hour) of the Long Seam Weld, and 37 of 42 were within 60 degrees (2 hours). Many of these indications are not in any areas of perceived stress as indicated by CSCC susceptibility factors. This suggests the possibility of metallurgical factors rising from manufacturing processes that could make the pipe steel more prone to cracking near the long seam weld. Another possibility is that many of the seams in the case of this excavated pipe were near the 6:00 o'clock orientation, increasing susceptibility to corrosion. It is still unknown why most of the excavated CSCC are located in this way.

Inspection Tool Set-up is not a One-off Configuration

The inspection ILI tool is not specific to CSCC and is fully operational for other feature types normally associated with axial flux MFL.

Conclusions

This paper partially documents an ongoing research and development process aimed at the reliable detection and characterization of Circumferential Stress Corrosion Cracking (CSCC). At this stage, there is much more progress on detection than characterization.

A procedural paradigm shift has started whereby more emphasis is put on ILI data for CSCC detection with lesser emphasis on CSCC susceptibility factors. Procedurally this means searching the entire ILI data set for CSCC then checking for susceptibility factors as opposed to only reviewing ILI data in areas of high CSCC susceptibility. CSCC susceptibility factors as before are used to aid in final feature classification. The weighting of CSCC susceptibility factors will be the subject of ongoing research, with the possibility of encoding these rankings to estimate a probability of CSCC. This can be done by developing Bayesian techniques that take advantage of any dependencies that may exist between certain susceptibilities.

Visibility of CSCC in micron IDD sensors can be used as a severity indicator, with this visibility starting at 35 to 40% of wall thickness depending on indication width (circumferential width). Based on these excavations, a minimum CSCC depth and circumferential width can be set at 40% of wall thickness and 0.7 inches (18mm) in circumferential width.

At this point in time, our current sensing systems cannot detect smaller/shallower CSCC, particularly those with limited circumferential width. High sampling rates that result in a sub-millimetre range sampling distance (less than 0.039 in) are not enough for detection of these indications.

A test set of CSCC is required for the development of sizing models.

The long seam weld may be a susceptibility factor for the formation of CSCC. The predominance of confirmed CSCC features in the vicinity of the ERW weld show this may be the case. This could be due to stresses introduced to the steel by the ERW manufacturing process during the time period the pipe was manufactured. Another possibility is that many of the seams in the case of this excavated pipe were near the 6:00 o'clock orientation, increasing susceptibility to corrosion. Again, the actual cause for the majority of CSCC being located in this way is not known.

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