The Detection and Sizing of Circumferentially Oriented Stress Corrosion Cracking Using Axially Oriented Magnetic Flux Leakage Inspection

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Abstract

Stress corrosion cracking (SCC) is a problematic phenomenon in line pipe as detection by many MFL inline inspection devices is not possible or has such high thresholds of detection it is insufficient to adequately identify threats before the next inspection cycle. In this paper we investigate the use of ultra-high frequency MFL sampling using Hall effect sensors to detect and characterize circumferentially oriented stress corrosion cracking (C-SCC). In pull tests, an axial flux direction magnetizer is used with 2.1 mm (0.083 in.) circumferential sensor spacing and sampling rates up to 4,000 Hz. Minimum detection criteria are estimated using excavated line pipe containing C-SCC, supported by laboratory testing and measurements. This inspection tool configuration proved capable of detecting in a small sample set circumferentially oriented SCC as small as 0.5 inches (12.5 mm) in length and 10% deep[1]. Sizing tests were conducted yielding 80% depth certainty tolerances consistently less than ±20% of wall thickness and 80% circumferential width tolerances consistently less than ±0.6 inches (15 mm).

Background

Colonies of circumferentially oriented Stress Corrosion Cracking (SCC) were coincidently discovered during inline inspection verification digs for a natural gas pipeline. The SCC colonies were located in close proximity to external metal loss anomalies but were not detected by the inline inspection tool. 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 with elevations in excess of 11,400 ft above sea level. At the time of discovery, the most severe indications were cut out for a third-party laboratory to conduct an examination to characterize the anomalies. The results of the examination confirmed the presence of near-neutral pH circumferential stress corrosion cracking. A subsequent selective digging program was established through which additional locations of circumferential SCC were identified. These indications, which were not detected by inline inspection, were subsequently cut-out for testing purposes.

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 [1]. Circumferential SCC (C-SCC) occurs when longitudinal stress, typically from ground movement or localized bending, is the major stress component. Circumferential SCC is near neutral to high pH [2] [3] and is typically trans-granular in nature [1].

Since the major stress that results in C-SCC is longitudinal or along the axis of the pipeline, critical defects are typically greater than 80% of wall thickness and hydrostatic testing, which increases hoop stress, is not an effective method for detection [1]. Hence the use of axial flux MFL with a high sampling rate is now considered as a possible solution.

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[1] Depth based on laboratory metallography results [3].

Figure 1: Circumferential Stress Corrosion Cracking (C-SCC) in a Natural Gas Pipeline

For this testing, a standard 6-inch axial flux (AMFL) inspection tool is used that is reliably capable of sampling frequencies up to 4,000 Hz[2]. Hall effect sensors are oriented to capture the axial component of the magnetic flux leakage field. Axial flux is used due to the predominantly circumferential orientation of the excavated cracking samples. Sensors are arranged circumferentially at 2.1mm (0.083 inch) spacing. Dual flux, which also incorporates a circumferential flux magnetizer (CMFL), is used to correlate sensor responses. In a similar strategy presented in [4], this is to better discern between C-SCC and 3-dimensional (volumetric) metal loss.

Pull tests were conducted at various speeds up to 9 mph (4 m/sec). This results in axial flux sampling densities ranging from 300 to 600 samples per square inch depending on tool speed.

Detection in AMFL Data

Due to its predominant circumferential direction, C-SCC proves to be readily visible in axial flux MFL (AMFL) but not in circumferential flux (CMFL) data. Figure 2 shows this to be true for indications C5, C6-A and C6-B. Note that C6-C was not visible in the AMFL data, suggesting a lower threshold on detection whereas C6-A and C6-B at 14% and approximately 0.5 inches (25.4 mm) in circumferential width were visible. See Table 1 for size details.

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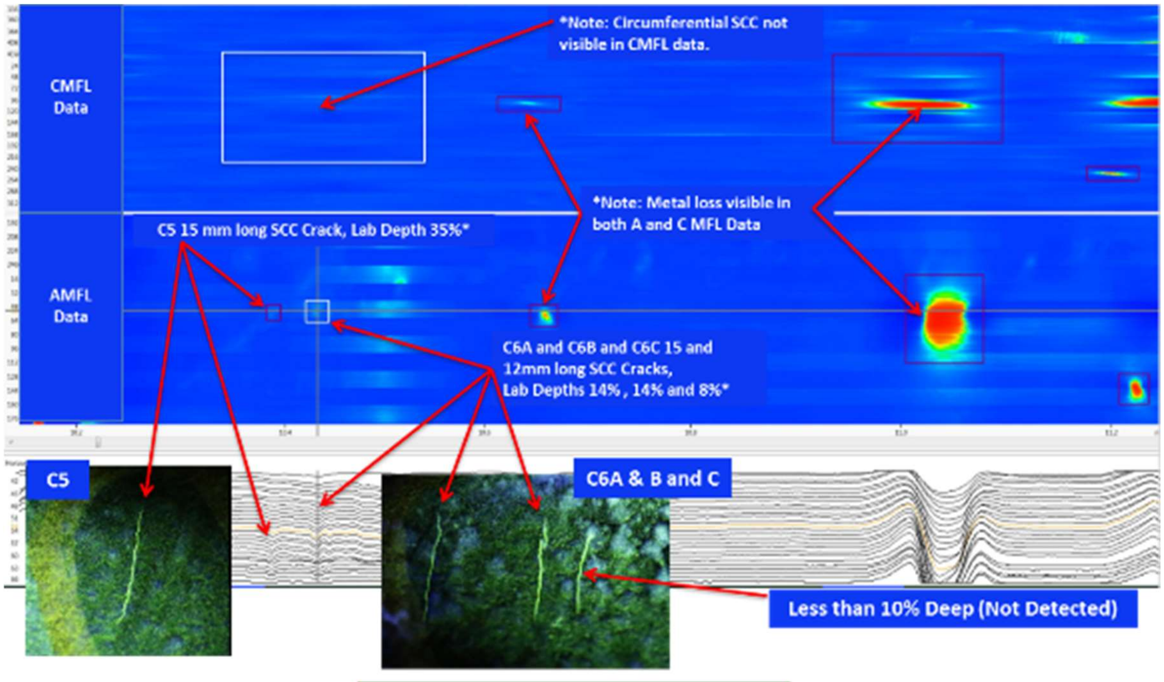
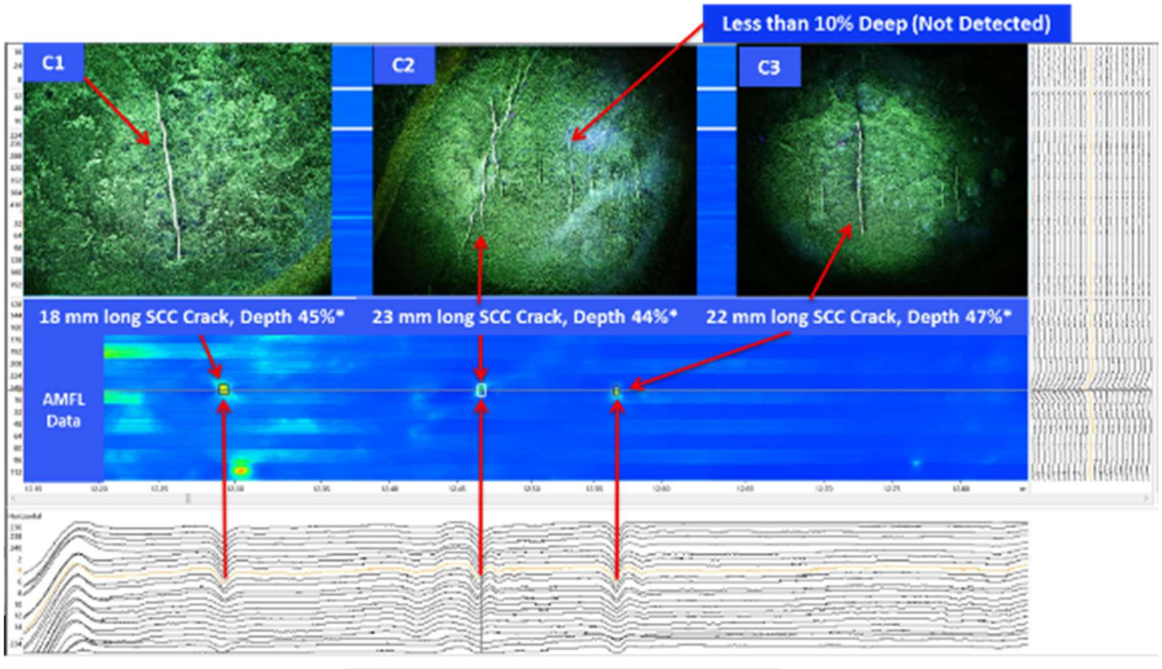
[2] This sampling frequency is possible for dual flux (both axial and circumferential flux magnetizers) inspections. Higher frequencies are possible when solely using axial flux.



* Depths shown from lab results

Figure 2: Detection in dual flux data

In Figure 3, a small example of C-SCC that is less than 10% of wall thickness deep was not visible alongside deeper examples, again suggesting a lower threshold on detection between 10% and 20%. It is expected that reliable reporting of C-SCC would begin at 0.8 inches (20.3mm) and 15 to 20% of wall thickness deep.



* Depths shown from lab results

Figure 3: Detection in AMFL data

Non-Destructive and Metallography Testing

Nine (9) samples were cut from the excavated pipe sections for a third-party laboratory to conduct non-destructive and metallography examination. Item C4 was an axially oriented flaw and not applicable to this study and so is not in Table 1. To determine locations of C-SCC, fluorescent magnetic particle inspection (FMPI) testing was used. Samples were then mounted in Bakelite, ground, and polished in accordance with standard ASTM E3-17. These specimens were then observed using 50X magnification light microscopy.

The following is a summary of these results. Third-party observations are shown in pink, where in-house observations are in green. Where the third-party laboratory could not measure circumferential width due to the cutting of sample coupons, the in-house measurements are substituted for sizing tests.

Crack No.	Third-Party Measured Nominal (in)	Third-Party Measured Depth (in)	Third-Party Actual Depth (%)	Third-Party FMPI Circ. Width (in)	Third-Party Crack Opening T (μm)	Third-Party Crack Opening T1 (μm)	Third-Party Crack Opening T2 (μm)	Mean Crack Opening (μm)	Detected by AMFL
C1	0.193	0.087	44.9%	0.687	160	40	20	73	Yes
C2	0.197	0.087	44.0%	0.911	230	30	50	103	Yes
C3	0.193	0.091	46.9%	0.861	70	40	70	60	Yes
C5	0.189	0.067	35.4%	0.591	70	40	60	57	Yes
C6-A	0.193	0.028	14.3%	0.591	140	80	210	143	Yes
C6-B	0.193	0.028	14.3%	0.472	260	230	180	223	Yes
C6-C	0.193	0.016	8.2%	0.394	30	10	30	23	Yes
C7	0.193	0.051	26.5%	0.264	160	140	320	207	No
C8	0.193	0.047	24.5%	0.902	70	10	80	53	Yes
C9	0.209	0.083	39.6%	0.551	60	30	50	47	Yes

Table 1: Circumferential SCC third-party testing summary

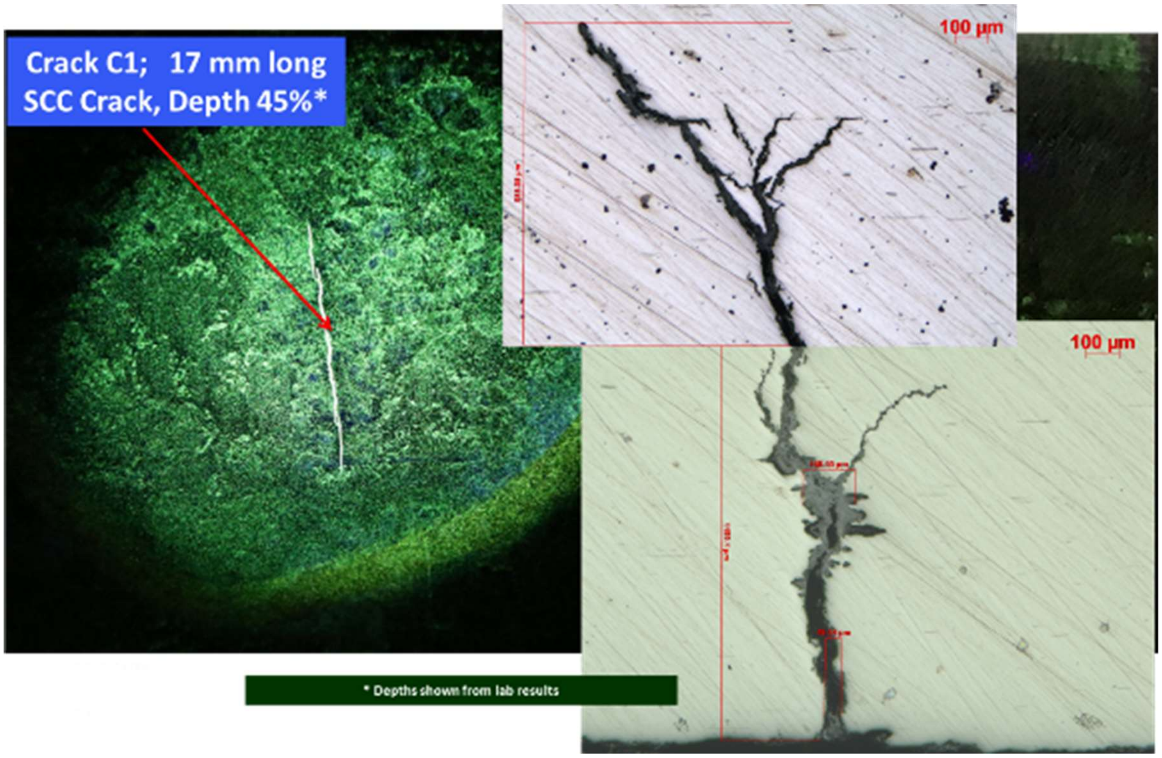


Figure 4: Excavated C-SCC (C1) 0.7 in (17 mm) long by 44.9 % wall thickness deep.

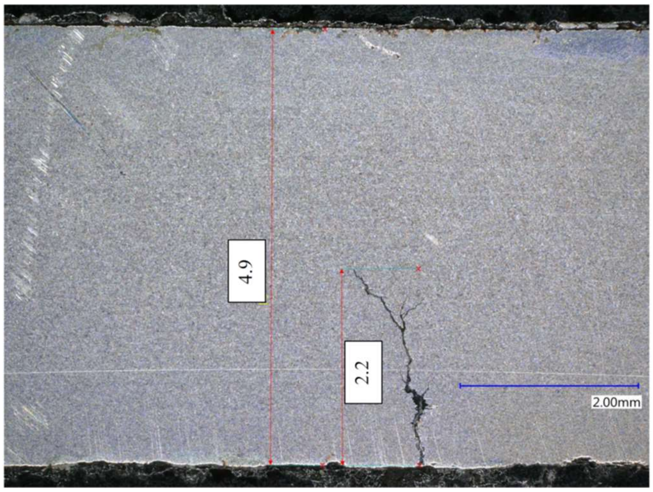


Figure 5: C1 showing relationship to full wall thickness (dimensions shown in mm).

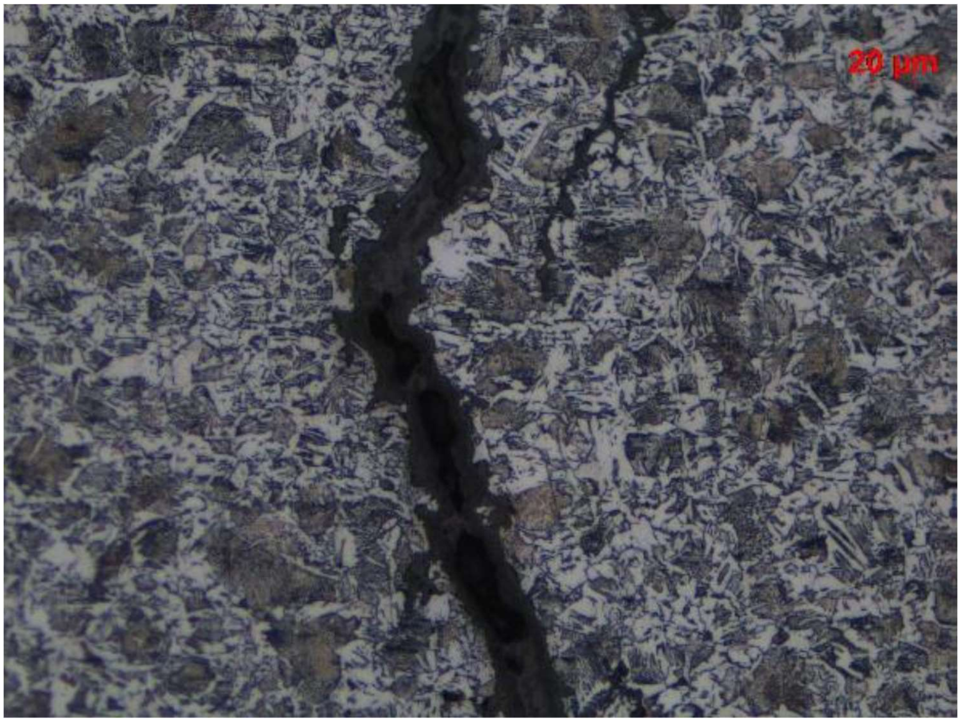


Figure 6: Microstructure of C1.

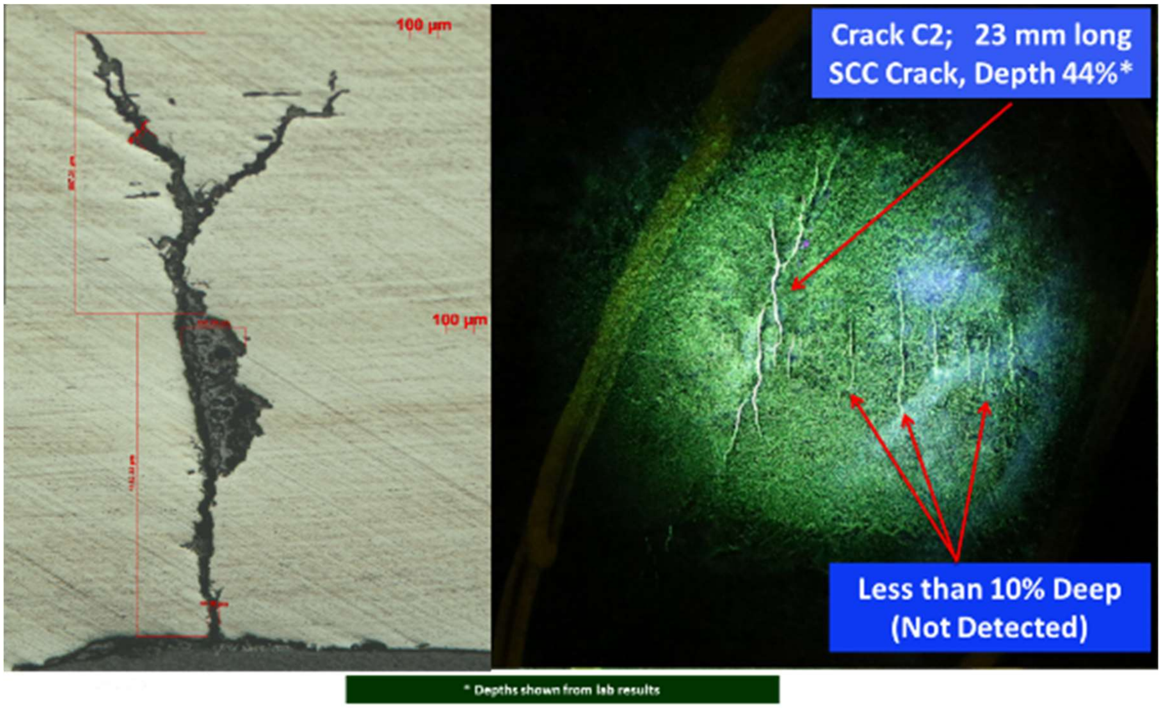


Figure 7: Excavated C-SCC (C2) 0.9 in (23 mm) long by 44.0 % wall thickness deep.

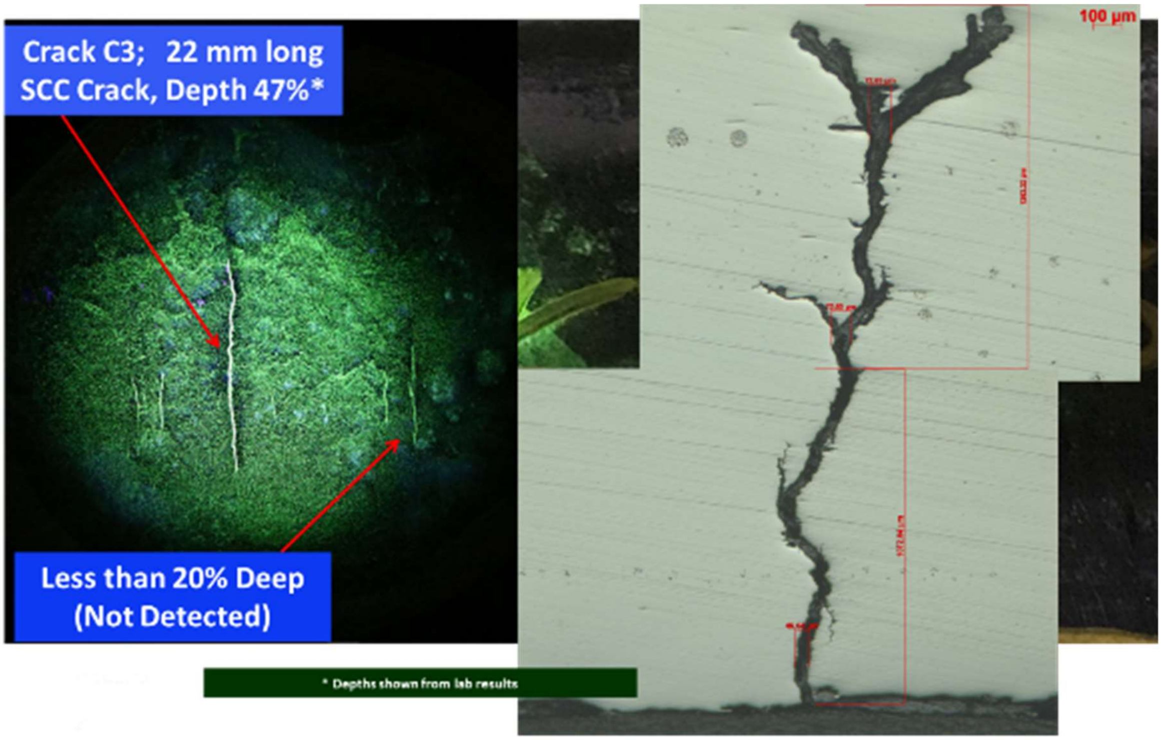


Figure 8: Excavated C-SCC (C3) 0.9 in (22 mm) long by 46.9 % wall thickness deep.

Sizing Pull Tests and Results

Pull testing was performed using both single (axial only) and dual (axial + circumferential) flux configurations of a standard inline inspection device. Pulls varied in speed from 1 to 9 mph (2.2 to 4.0 m/sec). The results shown are from the dual flux configuration with sampling rates of 2000Hz for one set of tests and a 0.040 inch (1mm) fixed distance sampling rate for the other set. From the 10 pull tests, C-SCC Id's C1 to C3, and C6-A, were visible and measurable in 10 of 10 pulls. Ids C6-B and C8 were visible in all but measurable in only 9 of 10 pulls. C6-C was visible but not measurable for any pulls. C7 was not visible for any pulls. Although at a substantial depth of 26.5% of wall thickness, C7 was only 0.264 inches wide in the circumferential direction. Lastly, C9 was visible but not measurable in any pulls due to a nearby flange adversely affecting the signal.

Due to a lack of test flaw examples similarly dimensioned as C-SCC, a standard sizing model designed for general volumetric corrosion was used to assess the MFL signals. The narrowest circumferential slotting in this training set was 0.280 inches (7.1 mm). In the following unity plots, 80% certainty tolerance estimates (the two-sided tolerance where the frequency of prediction errors is 80%) are calculated by estimating the error probability density function and integrating between ±10% and ±20% depth error[3]. An alternate certainty measure based on counting the number of estimated depths with errors within the specified error tolerance limits is also given.

The results shown in Figure 9 show a ±20% tolerance at a certainty of 80%. Stated another way, the estimated error tolerance from these results is ±17.4% 80% of the time.

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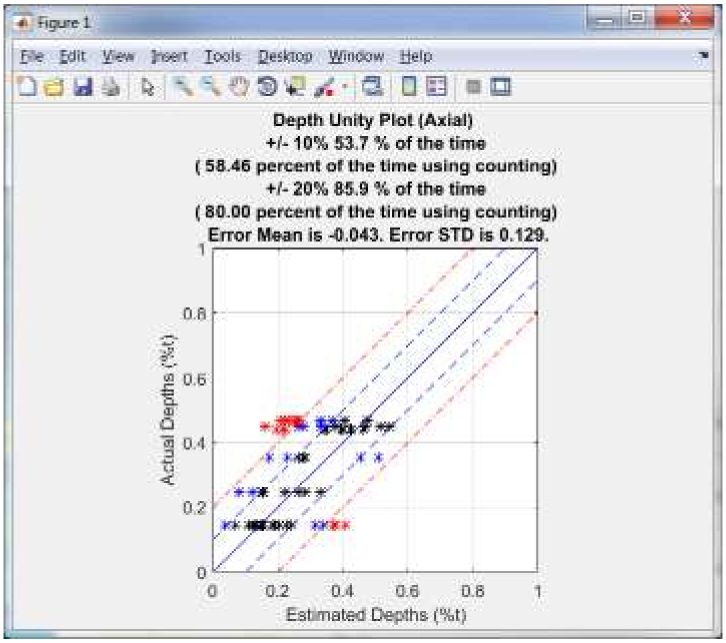
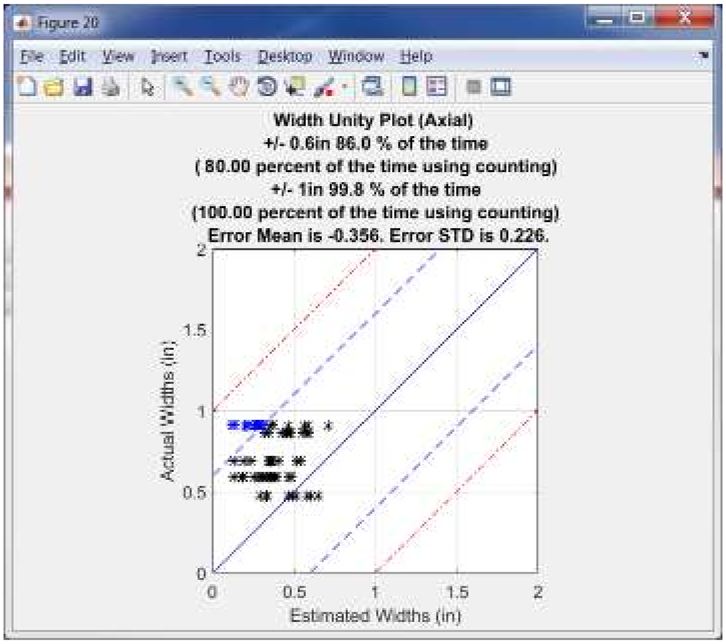
[3] Prediction error is assumed to be Normally distributed.



Depth Unity Plot (Axial)
+/- 10% 53.7 % of the time
(58.46 percent of the time using counting)
+/- 20% 85.9 % of the time
(80.00 percent of the time using counting)
Error Mean is -0.043. Error STD is 0.129.

Figure 9: Depth unity plot for axial data

Circumferential width estimates shown in Figure 10 yields a ±0.6inch (15 mm) tolerance that exceeds the 80% certainty guideline, or ± 0.546 inches 80% of the time. Note the tendency to underestimate width using the current (volumetric corrosion) training set.



Width Unity Plot (Axial)
+/- 0.6in 86.0 % of the time
(80.00 percent of the time using counting)
+/- 1in 99.8 % of the time
(100.00 percent of the time using counting)
Error Mean is -0.356. Error STD is 0.226.

Figure 10: Width unity plot for axial data

Discussion

The reported depth and width estimation results from the use of a standard sizing model that does not include any training for circumferentially oriented crack-like items are a promising sign.

Expanding the training flaw set to include C-SCC like items should improve characterization accuracy. Note that tests were conducted while the test pipes were not under any stress that might normally increase the crack opening. This too could affect the overall detection and sizing capabilities and must be accounted for in subsequent developments.

Estimated depth sizing accuracy is within the initially targeted ±20% with 80% certainty, showing some promise of improvement with expanded training. The width estimation accuracy is approximately ±0.6 inches (15 mm) with 80% certainty. There is a bias to underestimate this dimension, possibly due to previously mentioned limitations in the sizing training set.

There is insufficient data to readily determine a probability of detection (POD). Using the small data set at hand implies an 90% POD[4] at 0.5 inches (12.5 mm) and 20% of wall thickness deep for a 0.200inch (5.1mm) wall thickness. Further testing with a more complete test set including more pipe wall thicknesses and circumferentially oriented crack-like items is required to adequately quantify this metric.

As previously mentioned, the use of auxiliary sensor data can enhance the identification of possible C-SCC. To this end, IMU data can be used to determine areas of high longitudinal stress, allowing analysis to be concentrated to susceptible sections of pipeline. Further, correlating axial flux direction MFL signals with corresponding circumferential signals will increase the likelihood of a correct identification of C-SCC indications. This can be accomplished using a combined axial-circumferential (dual) flux inspection, or by running two separate inspections.

Conclusions

Detection of circumferential stress corrosion cracking (C-SCC) begins at approximately 0.5 inches (12.5 mm) circumferential width and 15% of wall thickness deep[5]. Reliable reporting of C-SCC begins at approximately 0.6 inches (15 mm) circumferential width and 20% of wall thickness in depth. This is shown in a 0.200inch (5.1 mm) wall thickness and within velocity ranges up to 8.8 mph (4 m/s). The expected wall thickness range for reliable detection is 0.144 to 0.280 inches (3.7 to 12.7 mm). The minimum average crack opening consistently detected in this test set is 50 µm (0.05 mm or 0.002 inches).

Sampling frequencies maintained at 4000Hz would ensure a maximum 0.040inch (1.0mm) sampling at the maximum speed tested. Maintaining a sampling distance of between 0.020 to 0.040 inches (0.5 to 1.0mm) are expected to be the minimum sampling conditions.

Depth sizing verifications to date show a ±20% tolerance within 80% certainty. Circumferential width estimations show a ±0.6 inches (15 mm) within 80% certainty. This could be improved with additions to the sizing training set to include more C-SCC-like items.

Axial MFL at a high sampling frequency must be used to detect and characterize C-SCC. Auxiliary sensor information from circumferential MFL must be used to discern between C-SCC and 3-dimensional metal loss. Further, using IMU information to locate areas of possible high axial (longitudinal) stress can further enhance the ability to locate C-SCC.

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[4] Consistently visible in 9 of 10 specimens for this data set.

[5] Note that a small sample size prevents a more accurate claim statement.

Acknowledgements

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Further thanks as well go to Acuren for the metallurgical microstructure and microscopy results that supplement Novitech's in-house efforts to characterize provided test specimens.

References

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