Abstract

Near-neutral and high pH Stress Corrosion Cracking (SCC) are the most prominent forms of Environmentally-Assisted Cracking (EAC) in pipelines. SCC remains a threat for safe operation of pipelines susceptible to EAC worldwide and is focused by many studies and industry wide collaborations. Pipeline failures, which had been attributed to SCC occurred first in Canada in 1985. Subsequently SCC has been identified as a possible threat in other countries as well. In South American countries large integrity programs were started in the early 2000, when SCC was becoming a global phenomenon for mainly gas transmission pipelines. Meanwhile a proactive process using high resolution in-line EMAT inspections has been established based on the experience gained in North America. This process supports the early detection of critical SCC incorporated into a tailored program to mitigate the risk of in-service pipeline failures. Actively growing SCC colonies need to be properly addressed before individual cracks coalesce over time which ultimately leads to rapid fracture of the pipe. Management of SCC in gas pipelines includes hydrostatic pressure testing of pipe valve sections, direct assessment of pipe ranked as being susceptible to SCC and smart In-Line Inspection (ILI) tool surveys. The high-resolution Electro-Magnetic Acoustical Transducer (EMAT) In-Line Inspection (ILI) technology has been developed to address the SCC threat. The technology, smart ILI tool data analysis and non-ILI data integration techniques evolved for almost a decade to a process that has been extensively validated. This contribution demonstrates current capabilities of the EMAT technology and associated processes to successfully manage SCC in line pipe. Validation is outlined by results obtained from pipe inspected that is known to have an SCC history. Correlation of EMAT ILI crack calls to non-destructive as well as destructive measurements lead to a comprehensive understanding of the capabilities of the EMAT technology and associated processes.

1. Introduction

In-Line Inspection (ILI) of pipelines by smart tools provides a lot of information to a framework for managing the threat of crack-like defects such as Stress Corrosion Cracking (SCC) [1]. Several technologies based on Magnetic Flux Leakage (MFL), eddy current or ultrasound are applied to address a wide range of different types of defects to support the discrimination and sizing of SCC. However, the most promising technology for direct detection and sizing of SCC has emerged in the past few years. The Electro-Magnetic Acoustic Transducer (EMAT) technology allows for generation of ultrasonic horizontal shear waves in the pipe wall by either of two physical phenomena resulting from alternating currents in a static magnetic field: Lorentz force and Magnetostriiction. The EMAT ILI system is set up to generate ultrasonic waves consisting of lower and higher order modes which propagate in circumferential direction of the pipe wall.

The ROSEN EMAT Crack Detection and Coating Disbondment ILI tool fleet can be applied to detect planar axial anomalies in the pipe wall as well as determine and identify the condition of external pipeline coatings. Figure 1 shows the 24/26” dual diameter ROSEN EMAT ILI tool during the launching process. Current tool fleet covers all pipe diameters ranging from 12 to 48 inch. By the end of 2014 more than 26,000 km (16,100 miles) have been successfully inspected worldwide.
2. EMAT Operating Principle

Figure 2 shows a schematic representation of the EMAT arrangement. A single EMAT probe inspects a small, well-defined area between transducer and receiver. Transmission and reflection signals are captured in time and frequency domain by means of two separate receiver sensors within the EMAT sensor arrangement.

For an EMAT In-Line Inspection tool, sensors are arranged to allow for a high-resolution image of the pipeline. Due to the limited propagation distance of the waves between the measuring elements, this design ensures high signal to noise ratios as a basis for accurate determination of the position and dimensions of features.
Waves which propagate from transmitter to receiver through the pipe wall without hindrance are used to assess the external pipe coating. The ultrasound is attenuated by intact coatings and lower signal amplitude is captured by the receiver. Different coatings can be identified by their characteristic alteration of the frequency signal pattern and characteristic attenuation coefficient of the transmission amplitude. In case of coating disbondment or e.g. coating holidays attenuation is reduced. Pipe anomalies situated in the sensitive EMAT measurement area reflect part of the ultrasonic wave. Information on frequency, time of flight and modes are used for discrimination of cracks and volumetric features and for determination of length and depth of the features. The quality of EMAT signals obtained from crack and coating measurements is supported by the quantification of possible lift-off effects and magnetization measurements. Further details on the concept of the high resolution EMAT technology are described in references [2-4].

3. Data Integration and Analysis

Case studies have been generated by the data acquired from EMAT inspections of two 20” and one 24” natural gas pipelines. Both lines 20” have an SCC and corrosion history. Regulatory requirement was to replace all tape coating installed at welds of a 24” FBE coated gas transmission pipeline. In order to discriminate between tape coated and epoxy coated girth-welds, either direct assessment or EMAT ILI was considered.

Due to the complexity of identification of crack-like defects in pipelines, analysis and correlation of multiple datasets has been carried out on each 20” EMAT ILI indication. Highly effective prioritization has become possible by following a distinct data evaluation procedure based on known SCC susceptibility conditions. Specific pipeline history and operator experiences have influenced the prioritization that has been carefully set-up in terms of rating each single parameter. The overall prioritization of each ILI indication has finally been determined by a weighting process as a final step of the data evaluation.

As described in the previous chapter, the leading dataset used for analysis and anomaly classification is the ultrasonic shear-wave echo reflected by an anomaly situated within the sensitive area of the ROSEN EMAT sensor. Evaluation of echo amplitude, time and frequency balances the classification. In accordance with the requirement of an ROSEN ILI inspection an unambiguous crack-like EMAT signal lead to a corresponding call even if all other datasets do not indicate presence of a crack like feature. This case can easily be explained by taking local variations of the pipeline conditions or limitations of the sensitivity of other datasets into account.

As part of the SCC management approach, predictive soil model categorization allowed for sectioning of both pipelines. The number of potential crack indications detected from the ILI data by the anomaly search algorithm has been determined for areas of interest and correlated to the soil model prediction of pipeline susceptibility to SCC. Verification of sound parameterization at each step of the fully automated data processing ensured highest sensibility and a probability of detection according to published specification.

Prior to the ROSEN EMAT ILI survey a ROSEN circumferential MFL (CMFL) ILI tool was launched to acquire MFL data for correlation of corrosion, prominent crack-like defects and further indications of both pipeline sections. CMFL data are of high interest for detection of corrosion by itself and are of additional value in terms of combined evaluation of EMAT data for identification of crack like features. By accessing both datasets at the same time the discrimination and identification process of each indication is enhanced and supports the prioritization and assessment process.

As described in the previous chapter, the ILI tool comes with an intrinsic transmission dataset of the ultrasonic shear wave generated by the ROSEN EMAT transducer inside the pipe wall travelling to the receiving sensor. The complex variation of the transmission signal amplitude, time of flight and frequency allows for identification of different types of coating repair material and detection of areas of coating disbondment. Identification of coating types ensure correlation to the pipe book or areas being previously excavated and is helpful in feature prioritization as some coating are more prone to SCC susceptibility [5]. Additionally the evaluation of coating disbondment provides useful information about the general as well as very local condition of the pipeline. For correlation purposes it supports the comparison to external corrosion at locations detected by CMFL, which in turn is unaffected by the coating or its condition. The two independent datasets provide valuable information on the same location and mechanism. Correlation of both datasets requires careful evaluation and parameter selection by experienced analysts since adjustment and accuracy influences prioritization and assessment.
For the 20” pipeline segment SCC history and operating experience, combined with pipeline construction and EMAT data provided invaluable for the project. Geospatial data such as latitude, longitude and elevation of the pipeline also supported identification of local variations of the pipeline environment.

The main outcome of the criteria described above is a prioritization of crack-like indications based on EMAT ILI, soil, CMFL ILI, coating and pipeline construction data. Confidence in the call as a measure of coincidence of criteria was very beneficial for the evaluation of ROSEN EMAT data and selection of verification sites. Site selection for validation of the classification and crack sizing was also carried out by the pipeline operator using a secondary analysis of all available signal data together with the data analysts at the ILI vendor office. Timely feedback of results from the in-field correlation and assessment process was also critical in further improvement of feature identification and sizing during the project.

A successful 24” EMAT performance test with regards to identification of Polyken tape coated girth welds of factory applied FBE pipe joints allowed for qualification of the ROSEN EMAT tool and the ILI coating assessment project to go ahead. The 24” ROSEN EMAT tool was launched for identification of tape coated girth-welds. Data analysis results were requested within 10 days after the run to allow two verification crews working in parallel and to finish the project on time. Out of 271 girth welds analyzed, 26 tape coated girth-welds and additional areas of tape coating in the pipe body have been reported. 30 welds have been verified. 6 out of 30 welds were reported at low confidence due to low signal to noise ratios caused by increased sensor lift off at the weld area. All 6 low confidence callouts were confirmed as being in-field liquid epoxy coated. 20 out of 20 reported welds have been verified as being actually tape coated. 4 additional verification digs confirmed the epoxy coating as reported.

4 EMAT ILI Sensitivity and Sizing

The minimum crack and crack colony dimensions in the pipe body specified for the EMAT technology are 40mm (1.58”) in length and 2mm (0.079”) in depth with a Probability of Detection (POD) of 90% [6]. The minimum crack dimensions in the longitudinal weld area are 40mm (1.58”) in length and 3mm (0.118”) in depth at 90% confidence interval. The depth and length sizing accuracy in the pipe body and the longitudinal weld area at 80% confidence and for the 20” pipelines are 0.95mm (0.037”) for depth and 10mm (0.394”) for length respectively.

Sensitivity of the EMAT technology is influenced by the signal-to-noise-ratio of the time-integral of the EMAT echo amplitude. A sub-critical flaw can be detected if its effective cross section is above the detection threshold of the applied EMAT ILI sensor system. The specification has been derived from artificial and natural crack-like indications. Since the first commercial EMAT ILI runs in 2006 the amount of natural defects used to derive the specification increases continuously. The total length of pipe containing crack and crack-like flaws available for testing and verification nowadays exceeds 1000m (3280ft). Furthermore over 2,500 historic excavation results and corresponding ILI data have been gathered in a database to continuously improve and test latest sizing improvements. The collection of different pipes and field results enabled the development and improvement of sizing models for commercial applications.

5 Results of the Validation

In total 66,694 anomalies have been initially detected by the ROSEN EMAT anomaly search algorithm in the pipe body (29,839 anomalies in the longitudinal weld area). By applying all criteria described above 755 (500) crack-like indications have been reported. The initial result of the automatic search emphasizes the sensitivity of the EMAT technology to a variety of superficial and sub-critical pipeline anomalies. However, application of distinct procedures is required for semi-automated classification of anomalies to meet industry accepted reporting times.

The pipeline operator selected 26 joints for verification of anomaly classification and sizing. Verification of 16 joints and 51 reported crack-like anomalies in the pipe body and 5 in the longitudinal weld area has been conducted. Multiple pipe joints have been removed from the pipeline to allow for NDT analysis to improve detection and sizing of flaws as well as EMAT ILI pull through testing.

Fig. 3 shows an in-field photography of a verified SCC colony after magnetic particle inspection (MPI) and corresponding EMAT data. In-field NDT depth sizing has been carried out using a phased-array ultrasonic device. The crack length and interlinked length have been determined in-field by the MPI length and application of pipeline operator interlinking rule respectively.
The colony shown in Fig. 3 (a) has been reported as a crack-like anomaly associated with corrosion at a depth of 40% and 50mm (1.968”) length. Coating disbondment and metal-loss corrosion has been reported for this indications. The area and pipe steel were both determined as being highly susceptibility to SCC. Field verification confirmed the classification and sizing at 42% wall thickness depth, an MPI length of 140mm (5.512”) and an interlinked crack length of 85mm (3.346”). The EMAT time signal is shown in Fig. 3 (b). During semi-automated sizing of the indication, the analysts capture time and frequency of the EMAT signal which are used to determine the crack depth and length. Comparison of the EMAT and NDT phased-array ultrasonic (PA UT) depth shows only slight variation of the depth by 2% of the local wall thickness. The difference in length originates from the fact that the EMAT signal corresponds to the effective cross section of the corresponding anomaly at the EMAT detection threshold inside the pipe wall. As a consequence, the length determined from the EMAT signal corresponds to the maximum length of the anomaly at a depth equal to the detection threshold. MPI and interlinking length are determined at the outer surface of the pipe wall. Consequently underestimation of the EMAT ILI length when compared to the MPI or interlinked length is be observed.

The overall result of the verification findings achieved is presented in Fig. 4. The overall POD being equal to the number of detected anomalies divided by the total number of anomalies multiplied by 100 is 56/56 and equal to 100%. In other words all anomalies meeting the published specification have been detected. The overall POI is calculated as the number of correctly identified anomalies divided by the total number of anomalies multiplied by 100 is 48/56 and equal to 86%. There have been 6 anomalies verified to be as being metal loss corrosion and 2 mid wall pipe manufacturing related anomalies.
Fig. 4 shows the unity plot of the reported ILI EMAT depth vs. the PA UT maximum depth. The boundary of specified accuracy of 15% at 80% confidence is indicated by two dashed lines. 96% of the crack-like indications are within that tolerance. This result clearly demonstrates the successful application of the sizing approach and implementation of the algorithms based on experience with real crack-like features.

Fig. 5 shows an in-field photograph of a reported and positively verified tape coated girth weld. The actual length of the tape coating has been determined as 0.4m. The photograph shows a minimum overlap of tape and mainline FBE coating. The tape is densely packed at the weld area with an overlap of about 2/3 of the tape coating width. Fig. 6 shows the corresponding EMAT transmission C-Scan. The spiral weld can be clearly identified up- and downstream of the weld located at the center of the C-Scan. The EMAT transmission signal for the pipe body FBE coating is higher than at the tape coated weld area. This is in accordance with the results of the performance test as shown by Fig. 5 Type A.
Figure 5: In-field photograph of a verified tape coated girth-weld. Position of the weld is indicated by a dashed line on the tape. Actual length of the tape: 0.4m.

Figure 6: Color coded EMAT Transmission C-Scan of the same weld as shown in Fig. 5. The tape can be identified by the lower transmission up- and downstream of the weld. Increased sensor lift-off can be identified by a low transmission signal (blue) at the weld itself.

Fig. 7 shows the corresponding EMAT transmission B-Scan of an individual EMAT sensor channel with increasing frequencies from bottom to top. Where the color coded B- and C-Scan allow for a quick assessment of the weld area a line plot of the frequency amplitude can be used for quantitative assessment. Fig. 8 shows the normalized absolute transmission amplitude of ultrasonic modes of the same EMAT channel as shown by Fig. 7. For the tape coated weld area the lower amplitude (left) decreases to about 60% where the higher mode (right) decreases to about 40% of its pipe body value. The actual length of the tape coated area was determined as 0.38m from the EMAT frequency data and confirmed by 0.4m in-field.
Figure 7: Color coded EMAT transmission frequency B-Scan of the same weld as shown in Fig. 6.

Figure 8: Normalized absolute transmission amplitude of SH0 (left) and SH1 (right) of the same EMAT channel as shown by Fig. 7. For the tape coated weld area the SH0 amplitude decreases to about 60% where the SH1 decreases to about 40% with respect to the pipe body (FBE) transmission. The actual length of the tape coated area was determined as 0.38m and confirmed by 0.4m after excavation.

The close collaboration between the pipeline operator and ROSEN, resulted in a very successful implementation of the EMAT ILI technology to replace direct examination of girth-welds suspected to be coated with tape. This technology application substantially reduced the maintenance requirements of the project. As summarized by Fig. 9, pipe replacement or direct examination of 271 weld locations was reduced to 30 investigation and repair locations and 100% success in field validation of the tool performance.
6. Conclusion

This paper has summarized the process and results of data integration and analysis of various data sets in order to further promote the POD and POI of EMAT ILI data, based on the case studies of two 20” natural gas pipelines inspection and verification excavations. It showed that the EMAT technology has become a reliable and accurate method for detection, identification and sizing of SCC cracks and crack fields, to support the management of SCC threat in natural gas pipelines.

The 24” coating identification project considered ILI tool performance tests before the tool run. Short reporting times by the data analysts and subsequent verification of the ILI results by individual digs were a success that allowed finishing the project in a short amount of time. The developed procedure based on the high resolution EMAT ILI data allowed for a precise identification of the coating material of all welds. Detailed analysis of acquired EMAT frequencies and amplitudes proved to be crucial to successfully evaluate the captured data. ILI results and construction details were included in the regulatory response, were validated and approved allowing the project to meet the regulatory requirements. No pipeline replacement or major excavation activities were required.

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8. References


[6] ROSEN EMAT crack detection and coating disbondment performance specification; August 2010