Abstract

In recent years there have been a number of pipeline failures attributed to circumferential cracking. Although these failures remain rare, they do pose a major hazard and often the threat has not been previously identified or included in any risk assessment. Of course these failures also result in significant disruption to pipeline operations. Failure investigations involving circumferential cracking have identified tensile axial strain and a corrosive environment as contributing to the development of stress corrosion cracking (SCC). Most cases of SCC result in axial cracking, often linked to stress raisers such as dents, areas of corrosion, and weld toes. The industry has developed tools capable of detecting these axial cracks. In addition, inline inspection tools for the detection of circumferential cracks are now available; in particular tools utilizing liquid coupled piezo electric ultrasonic sensors. Sensor technology for ILI of gas pipelines is being developed.

In this paper we present a process for (i) identifying pipelines potentially susceptible to circumferential SCC, (ii) selecting specific high-risk sites, and (iii) developing appropriate inspection and mitigation plans. The process is based on readily available information on pipeline design, construction, cathodic protection performance, and routing, as well as publicly available spatial information including terrain models, soil data and rainfall records, combined with proven inline inspection technologies for corrosion detection, coating disbondment detection, and bending strain estimation. We argue that following this process will result in a justifiable basis for decisions on managing the threat of circumferential SCC, such as running specially configured circumferential crack detection tools and completing site investigations.

1. Introduction

Failure investigations have identified tensile axial strain and a corrosive environment as contributing to the development of stress corrosion cracking (SCC). While these failures remain rare, they are often unexpected (a hazard not previously identified or included in any risk assessment), and of course they can result in a major hazard and cause significant disruption to pipeline operations.

In recent years, there have been a number of pipeline failures attributed to circumferential stress corrosion cracking [Pope et al., Chauhan et al.], or where the nature of the failure is not confirmed but is indicative of circumferential stress corrosion cracking (CSCC) [Carroll et al. 2015]. The industry has taken steps to develop protocols for managing CSCC, for example a recent report from the Pipeline Research Council International (PRCI), which reviewed 55 cases of CSCC [Fessler and Batte 2013].

Most cases of SCC result in axial cracking, sometimes linked to stress raisers such as dents, areas of corrosion, and weld toes [CEPA 2015]. Hence the industry has developed tools capable of detecting these axial cracks, and now inline inspection tools for the detection of circumferential cracks are available using liquid coupled piezo electric ultrasonic (UT) sensors. More recently, magnetic flux leakage (MFL), and electro-magnetic acoustic transmission (EMAT) sensor technology have been developed to the extent that they are capable of detecting circumferentially-

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orientated cracking. These UT, MFL and EMAT-based tools for the detection of circumferential cracking are not widely available, since the incidence of circumferential cracking is rare and hence the market demand is limited. This results in the requirement for the tools to be set up on a one-off basis, which is, of course, costly. Therefore it is unlikely that these tools will be available as a standard service, similar to the tools used for metal loss detection. Accordingly, a rigorous methodology is needed for identifying where and when to run a tool to detect circumferential cracking.

In this paper we present a process for (i) identifying pipelines potentially susceptible to circumferential SCC, (ii) selecting specific high-risk sites, and (iii) developing appropriate inspection and mitigation plans. The process is based on readily available information on pipeline design, construction, cathodic protection performance, and routing, as well as publicly available spatial information including terrain models, soil data and rainfall records, combined with proven inline inspection technologies for corrosion detection, coating disbondment detection, and bending strain estimation.

2. Circumferential Cracking

Circumferential cracking is rare in pipelines, and is not a common cause of failures; however, failures have occurred [Hopkins 1993, Amend 2010], and any comprehensive integrity management program should consider the possibility of this type of cracking. The causes of circumferential cracking can include girth weld flaws and vortex induced vibration; however, in this paper we will focus on stress corrosion cracking.

2.1. Stress Corrosion Cracking

The combination of a susceptible steel microstructure, corrosive environment and sufficiently high tensile stress can result in stress corrosion cracking (SCC) of pipeline steels. There is now an extensive list of publications suggesting that there are two forms of SCC known to cause external cracking in pipelines [NEB 1996]: high pH SCC and near-neutral pH SCC, where these refer to the pH of the corrosive environment (electrolyte) at the crack tip (generally under disbonded coating). The first documented incident [Bureau of Natural Gas 1965] and many of the occurrences involved intergranular high pH SCC. However, more recently, cases of near-neutral pH SCC have been reported, with characteristic transgranular cracking morphology. Apart from cracking morphology, there are several factors which differentiate these two mechanisms. There is an increased risk of high pH SCC occurrence in pipeline sections within 16 km downstream from compressor stations, believed to be related to temperature-accelerated coating degradation and higher stresses. Whilst no temperature dependence is found for near-neutral pH SCC, both forms of cracking seems to be associated with poorly drained soils; there is also an ongoing argument about the importance of CO₂ in the soil environment. Other contributing factors include pipeline age, cathodic protection performance, coating type (polyethylene tape, asphalt), topography, dents, etc. For most cases of SCC the corrosive environment is a result of coating disbondment and ineffective or shielded cathodic protection, with the stress generally caused by internal pressure. Hence the cracks are axially orientated, perpendicular to the direction of stress.

High pH SCC is now relatively well understood [Parkins 2000], with a repetitive (periodic) process of film rupture and slip dissolution generally accepted as the cracking mechanism; here the crack walls are passive, whilst the crack tip is subject to film rupture and subsequent dissolution. By contrast, the situation for near-neutral pH SCC is more complicated [Smith et al. 2016]. In general, it may be argued that whilst cracks may appear dormant (shallow, blunt and containing corrosion products), it is the extent of anodic activity and absorption of atomic hydrogen into to the metal ahead of the crack tip (hydrogen embrittlement) which controls crack propagation. The mechanism of hydrogen embrittlement is not fully understood at present.

In the case of circumferential SCC, this can occur when there is a significant axial stress, usually attributed to some form of ground movement [Ward 2012]. Other sources of locally high axial stress can be dents caused by rocks in the trench, residual stresses from pipe bending, and thermal contraction [Fessler and Batte 2013].

3. CSCC Susceptibility – Industry Guidance

A number of publications have addressed the issue of CSCC [e.g. Leis and Eiber 2007]. The Canadian Energy Pipeline Association (CEPA) has published detailed guidance on the management of stress corrosion cracking [CEPA 2015]. This includes a section on first-level susceptibility assessment for CSCC, based primarily on the 2013 Fessler and Batte report to PRCI.
Factors identified in the CEPA 2015 guidance document as relevant are:

- Coating type
- Proximity to previously discovered CSCC or axial SCC
- Year of pipeline construction
- Construction season
- Age of the pipe
- Terrain
- Grade of pipe
- Pipe diameter
- Wall thickness

Further guidance is given in the CEPA 2015 publication on how to investigate for CSCC, with the following additional factors:

- Coating condition
- Deformations
- Bends
- Angle of terrain
- Location on slope
- Soil type for tape-coated pipe
- Soil type for asphalt-coated pipe
- Soil moisture for tape-coated pipe
- Soil moisture for asphalt-coated pipe
- Pitting corrosion in the pipe joint

Where CSCC is identified as credible the CEPA 2015 guidance document references the use of circumferential crack-detection ILI technology as an option.

This CEPA guidance document provides a very useful starting point; however, for practical application some thought is needed on how to gather all the relevant data, and how to make use of other data sources not explicitly referred to that may be of benefit.

For example ‘terrain’ is listed as a factor linked to the potential for pipe movement or unstable slopes, and — by association — high axial stresses that may wrinkle the coating, allowing water in and creating the tensile loads that are required for SCC. In most places, terrain can be relatively easily identified from topographical maps of a pipeline route. However, high-localized bending can occur in relatively flat terrain where there are areas of differential ground settlement.

4. CSCC Susceptibility and Investigation — Proposed Process

From the very broad basic susceptibility criteria given in the CEPA guidance document, it is clear that many onshore pipelines will have some susceptibility to CSCC. Therefore, most operators will require a rational method for improving their understanding of the likelihood of CSCC. The following process is proposed based on the CEPA/PRCI guidance documents and the authors’ experience. Key parameters are selected and technologies available for collecting and aligning relevant data are proposed. An overview of the process is presented in Figure 1. Additional details are given in the following sections of the paper.
4.1. Coating Type and Condition

Coating types are generally known and their condition can be qualitatively evaluated based on factors such as age, operating temperature and CP performance. Information from past excavations can also provide a good indication of coating condition and the state of the pipeline in general. An indication of coating type, and for some coatings (e.g. bitumen) areas of coating disbondment, can be performed through EMAT inline inspection. In addition, the detailed review of metal loss internal inspection data, particularly where all metal loss features are reported, can give a very good indication of both coating type and condition from representative patterns or distributions of features. For example, the pattern of metal loss in Figure 2, where there are multiple features close to the girth weld, is indicative of a systematic breakdown of the field joint coatings. This is perhaps due to poor initial application, or inappropriate specification and higher temperatures near the start of the line.

![External Corrosion 2007](image)

Figure 2. External metal loss pattern typical of field joint coating failure

Other patterns of corrosion features may be associated with tape coatings, bitumen coatings subject to soil stress, rock damage to the coating, etc..

Review of CP data and its historical performance can provide valuable information on both the possible coating disbondment and the level of pipeline protection, i.e. indicating possible risks of external corrosion associated with under-protected areas that may be subject to coating damage. In the case of SCC susceptibility analysis, the focus is on identifying locations with CP overprotection, such as areas with CPOFF potential more negative than \(-1.2\) V (vs. Cu/CuSO₄); although, pipeline sections subject to a long-term polarization close to \(-1.1\) V (vs. Cu/CuSO₄) may be at risk of coating disbondment as well. It is important to realize that with cathodic polarization of buried pipelines and
when the supply of electrons (level of CP polarization) exceeds the diffusion-controlled oxygen flux to the interface between pipe wall and external environment (e.g. controlled by disbonded coating), it is the decomposition of water and hydrogen evolution which dominate the cathodic process, as opposed to the oxygen reduction that is the rate-controlling reaction under moderate polarization and sufficient concentrations of oxygen. Although both reactions result in localized alkalization, and thus promote coating disbondment, it is the nascent atomic hydrogen (process preceding hydrogen evolution during decomposition of water) that poses the risk for pipeline cracking.

4.2. Axial Tensile Stress Level

The occurrence of SCC requires a tensile stress to be present in the pipe wall that exceeds a threshold value. For the axial direction, operational loads in buried pipe are typically less than the threshold value with the exception of longitudinal bending caused by significant thermal expansion.

UKOPA [2016] states that for circumferential SCC, the principal stress acting on the crack is a bending stress due to:

• construction settlement,
• slope movement, or
• alignment stresses at tie-ins or at field bends.

This can also include elastic bends due to changes in topography. For example, an undulating slope profile with associated elastic bending strain is illustrated in Figure 3.

![Figure 3. Slope profile showing vertical out-of-straightness and associated elastic bending strain](image)

In terms of susceptibility of these factors, hilly undulating terrain will exhibit an increased likelihood of elastic bending strains, and this terrain with rugged mountainous areas are more exposed to ground-movement geohazards.

XYZ mapping during inline inspection is widely used to provide a curvature and bending strain profile along the pipeline centerline, as illustrated in Figure 3. Correctly designed and fabricated field bends are normally assumed to be installed without additional alignment stresses. Distinguishing between the design curvature of a field bend and additional elastic bending due to alignment is a challenge because of the masking effect of the bend geometry. However, it is possible to observe elastic bending where it extends beyond the formed bend section, as shown in Figure 4.
Figure 4. Example of elastic bending adjacent to field bends.

An example showing the occurrence and location of colonies of circumferential SCC in a pipeline section containing horizontal field bends is presented in Figure 5. The locations of CSCC are shown on the horizontal bending strain profile. It is clear that there is a strong correlation between the location of the field bend and the development of CSCC. Furthermore, there is no CSCC found at locations other than the formed bends. There is also little evidence of additional bending through this section; the increased horizontal strain from chainage 29 m and 37 m is a vertical field bend that is rolled slightly into the horizontal plane.

It can be concluded that the cause of the SCC development at this location is not linked to elastic bending stresses due to alignment differences between the formed and required bend curvature.

Figure 5. Slope profile showing vertical out-of-straightness and associated elastic bending strain

The explanation for the circumferential SCC appears to be linked to the radial deformation of the pipe wall during fabrication of the bend.

By definition, the forming process involves development of permanent strains in the pipe wall from localized deformation around the forming die. A plot of wall deformation based on the variation measured in pipe radius is shown in Figure 6 for the pipe spool from chainage 14 m to 26 m using a high-resolution geometry tool. The location of the field bend is clearly shown by the deformation associated with the location and spacing of the forming die, illustrated by the regular banding through the section of field bend.

Although coating damage in the field bend section may preferentially allow CSCC to develop, an axial tensile stress is also necessary.
In the absence of an elastic bending stress, two sources of residual stress may develop during the field bend forming process;  
1. The elastic springback of the pipe upon removal of the forming load.  
2. The change in fiber length within elastic sections of pipe adjacent to regions that have undergone plastic deformation.

The final distribution of residual stress is likely to be complex due to the non-linear stress-strain behavior as loads approach and exceed the nominal yield point of the pipeline steel. In addition, residual stresses may exist in the pipe following fabrication in the pipe mill.

The bending process causes the pipe to ovalize. This is controlled, but rarely completely eliminated, through the use of an internal mandrel that supports the pipe wall during the forming process. Ovalization of the pipe cross-section results in the development of circumferential bending stresses. This stress acts in addition to the hoop stress from internal pressure, although its effects tend to diminish at higher pressures due to re-rounding effects.

### 4.3. Local Deformation such as Dents or Pipe Wall Wrinkles/Buckles

High-resolution geometry tools, shown in Figure 7, are now well established and able to provide accurate measurements of deformation, including ovality, dents, and pipe wall buckles or wrinkles.

![Figure 7. Example of geometry tool](image)
4.4. Soil Type, Location on Slope, Rainfall Levels

Factors such as soil types, location on slope, and rainfall levels contribute to the potential for coating damage and soil movement-induced stresses. This data is often available in the public domain in digital map form, or may be included in original pipeline design information. Modern geographic information systems allow these types of data to be overlaid with data from the pipeline design, construction and inspection, as illustrated in Figure 8.

![Slope Model and Aerial Imagery](image)

Figure 8. Illustration of data layers

This data overlay enables operators to develop and visualize a detailed picture of the changing conditions along the line, which in turn can feed a suitable susceptibility model.

5. CSCC Inspection and Identification

There are a number of inspection options where CSCC is considered credible. Sometimes the number of locations that display the full combination of factors is relatively small, so that excavations and direct assessment may be cost-effective. In all cases, some direct assessment is prudent to gain information on the coating condition, soil properties, construction practices, etc. However, inline inspection may be preferable in cases where there are several possible locations. Generally speaking, the use of a sensor technology such as shear wave UT or EMAT is the preferred choice for cracks. These crack-detection ILI tools can be reconfigured to inspect for circumferential cracking. The accuracy and reliability of these re-configured systems is not yet well understood due to infrequent use. In theory, the capabilities should be similar to the performance with axial cracks. Prototype testing has demonstrated the feasibility of using both tool types. Data obtained using an axial EMAT (EMAT-A) prototype in a pull-through test for a set of electric discharge machined (EDM) circumferentially orientated crack-like anomalies is shown in Figure 9.
Figure 9. EMAT-A data for a set of manufactured circumferential crack like anomalies.

Data from EMAT-A on girth welds in the same pull-through tests indicate that the detection of crack-like features in or close to the weld depends on the weld quality. Identification is very difficult for a typical hand-welded girth weld with an uneven profile, while detection of a crack-like feature is entirely feasible for a high-quality machine-welded girth weld.

Data obtained with a commercial UT-A ILI tool is shown in Figure 9.

Figure 10. UT-A data for a circumferential linear girth weld anomaly.

The two data sets are taken from two sensors scanning in opposite directions. An angled signal pattern can be observed. This is caused by the fact that one sensor is moving towards and the other away from the girth weld. The reflections with a short time of flight are related to the ID of the pipe, while reflections with a longer travel time are related to the OD of the pipe. The raw data displayed here reveal reflections from the girth weld at ID and OD position, but also three distinct circumferentially-oriented crack-like indications on or in close vicinity of the girth weld.

An example of the development of a UT tool for the inspection of deep-water steel catenary risers for potential circumferential girth weld cracking caused by VIV is presented by Baumeister et. al. 2010. The performance of that tool in a test sample is illustrated in Figure 11.
Figure 11. C-Scan of two cracks close to a girth weld. Crack depths are 2.5 mm (upper crack signal, length 15 mm) and 4 mm (lower crack signal, length 14 mm).

Where the axial stresses are sufficiently high, circumferential cracks may open to such an extent that they become detectable by very careful review of typical MFL data collected to identify external metal loss. This is illustrated by MFL pull test data for the same EDM notches used in the EMAT-A testing and shown in Figure 12. These signals might be below typical metal loss reporting thresholds, or be seen as low significance, unless the combination with high bending stress is identified and additional data evaluation effort is put in, emphasizing the need for careful threat identification in advance of any inspection.

Figure 12. C-scan of EDM pipe body notches detected by MFL-A tool.

6. Discussion

There are three certainties in life:
1. Death,
2. Taxes, and
3. SCC is always perpendicular to the maximum stress

CSCC therefore requires an axial stress in the pipeline, and understanding the level of and source of axial stress are key in any susceptibility assessment. These stresses may be imposed or residual. In addition, CSCC is a form of corrosion and is therefore time dependent. If the potential for this threat can be identified, the process presented here illustrates how existing industry guidance can be used in a practical way to better understand the threat and justify activities designed to collect more information and manage the threat. Examples of such activities include excavation.
and direct assessment, material testing, cathodic protection modifications, monitoring of bending strain and pipe movement, corrosion diagnosis, coating inspections, and the deployment of specialist crack detection inspection tools.

Any CSCC identified should be repaired. Where the cracking is shallow, this can be accomplished by grinding or buffing, taking care to measure the profile of the cracks and hence understand the severity of the problem. For deeper cracks, the repair options are less clear. Systems such as the pre-stressed steel sleeve designed for axial SCC may not be suitable, and the bending that may be associated can make fitting a type-b steel repair sleeve difficult. Composite wraps with a suitable axial strength design may be suitable but would require testing. A loose-fitting steel sleeve with a high-performance epoxy grout to fill the annulus between pipe and sleeve is likely to be the most reliable option. While hydro-testing is suggested as an option by CEPA, it should be noted that hydro-testing does not generate high axial stresses, and it is known that circumferential cracks require high axial stresses to cause failure [Knauf and Hopkins].

7. Conclusions

Circumferential cracking and specifically circumferential SCC has caused a number of pipeline failures, but it is not a common hazard and may be neglected in integrity management planning.

Good industry guidance, for example from CEPA, is available that gives advice on the management of CSCC. However, it provides limited guidance on the collection and integration of the information required; more specifically when considering identification of areas with damaged or disbonded coatings and estimation of axial stress levels.

The process described here, which integrates inertial monitoring ILI data to calculate bending strain with modelling to estimate total axial stress, corrosion diagnosis to understand coating condition, EMAT coating inspection to identify areas of disbonding and transitions in coating type, and GIS-based data alignment to correlate other risk factors, fills some key gaps and aids in identifying pipelines (and specific locations on those pipelines) where there may be a real threat of CSCC, and where there is a genuine benefit in running tools designed to detect circumferential cracking, or carrying out additional evaluation of metal loss detection data, before the combination of cracking and loading reaches a critical level and results in a failure.

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