PIPELINE CORROSION AND PROTECTION

By

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Corrosion

Millions of dollars are lost each year because of corrosion. Much of this loss is due to the corrosion of iron and steel, although many other metals may corrode as well. The problem with iron as well as many other metals is that the oxide formed by oxidation does not firmly adhere to the surface of the metal and flakes off easily causing "pitting". Extensive pitting eventually causes structural weakness and disintegration of the metal. (It should be noted, however, that certain metals such as aluminum, form a very tough oxide coating which strongly bonds to the surface of the metal preventing the surface from further exposure to oxygen and corrosion).Corrosion occurs in the presence of moisture. For example when iron is exposed to moist air, it reacts with oxygen to form rust,

$$Fe_2O_3 - XH_2O$$

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The amount of water complexes with the iron (III) oxide (ferric oxide) varies as indicated by the letter "X". The amount of water present also determines the color of rust, which may vary from black to yellow to orange brown. The formation of rust is a very complex process which is thought to begin with the oxidation of iron to ferrous (iron "+2") ions.

$$Fe \;\text{------->}\; Fe^{+2} \;+\; 2\,e^{-}$$

Both water and oxygen are required for the next sequence of reactions. The iron (+2) ions are further oxidized to form ferric ions (iron "+3") ions.

$$Fe^{+2} \;\text{------------>}\; Fe^{+3} \;+\; 1\,e^{-}$$

The electrons provided from both oxidation steps are used to reduce oxygen as shown.

$$O_2\,(g) \;+\; 2\,H_2O \;+\; 4e^{-} \;\text{------>}\; 4\,OH^{-}$$

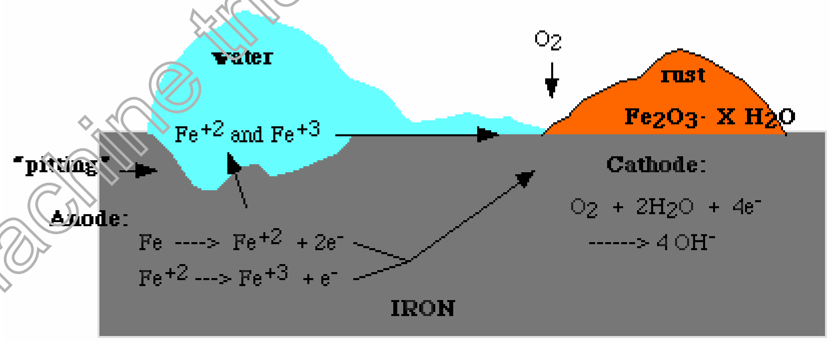
The ferric ions then combine with oxygen to form ferric oxide [iron (III) oxide] which is then hydrated with varying amounts of water. The overall equation for the rust formation may be written as:

$$4\,Fe^{+2}(aq) + O_2\,(g) + [4 \;+\; 2\,x\,H2o\,(1)\,]\text{--------->}\; 2\,Fe_2o_3.\,X\,H_2o\,(s) + \;\; 8H^{+}\,(aq)$$

"Rust"

The formation of rust can occur at some distance away from the actual pitting or erosion of iron as illustrated below. This is possible because the electrons produced via the initial oxidation of iron can be conducted through the metal and the iron ions can diffuse through the water layer to another point on the metal surface where oxygen is available.

This process results in an electrochemical cell in which iron serves as the anode, oxygen gas as the cathode, and the aqueous solution of ions serving as a "salt bridge" as shown below.



The involvement of water accounts for the fact that rusting occurs much more rapidly in moist conditions as compared to a dry environment such as a desert. Many other factors affect the rate of corrosion. For example the presence of salt greatly enhances the rusting of metals.

This is due to the fact that the dissolved salt increases the conductivity of the aqueous solution formed at the surface of the metal and enhances the rate of electrochemical corrosion. This is one reason why iron or steel tend to corrode much more quickly when exposed to salt (such as that used to melt snow or ice on roads) or moist salty air near the ocean.

Welding Inspection

Today, the use of inline inspection tools is standard procedure for the collection of pipeline data required for integrity assessment and fitness for purpose studies. In addition to the well established ultrasonic metal loss inspection methods, ultrasonic crack inspection has also proven to be a valuable technique for the inline inspection of pipelines over the last decade.

With the latter, the main task is the early detection of cracks or other crack-line defects in the pipe body and weld area. Usually, inline inspection tools for the detection and sizing of cracks are designed to find axial cracks. This is the predominant defect orientation for operationally induced cracking, due to the normal loading conditions in pressurized pipes. In some cases, however, the inspection of cracks is girth welds or spiral welds are required. The current inline inspection tool can be adapted to the specific inspection task by modifying the sensor carrier. For data analysis to be applied to all the different configurations, a comprehensive software package is available.

This article describes the inspection technique and the set-up of the inspection tool. Furthermore, some particular issues related to data recording, data processing and data analysis are addressed. The different applications are illustrated by practical examples from operational experience.

Inline inspection tools:

The major task for inline inspection tools is to provide accurate geometric information regarding the length, width, depth, orientation and location of a flaw. The major advantage of inline inspection tools is their ability to survey the entries pipe circumference whist the pipeline remains operation. They are usually pumped through the line (i.e., free-swimming tools) and do not require their own drive.

Apart from the inspection for metal loss, which was introduced at the beginning of the 1980s (skerra, 2000), the inline crack inspection of pipelines (liquid lines) by means of ultrasound has made considerable progress in the last 10 years (willems and barbican, 1999, willems et al., 2003, beller et. al., 2006). The task of an inspection is the early detection of cracks and crack-like defects. In the case of welded pipes, the inspection of the welds and adjacent heat affected zone (HAZ) is of particular importance. In the majority of the cases, longitudinal (axial) welds are of interest as the loading conditions, including hoop stresses in the pipe wall, favour the generation of axial defects (particularly in the weld area). In special cases, however, the inspection of girth welds or spiral welds is also required. Recent modifications of inspection systems developed for the inspection of axial welds also now allow for the inspection of such weld geometries.

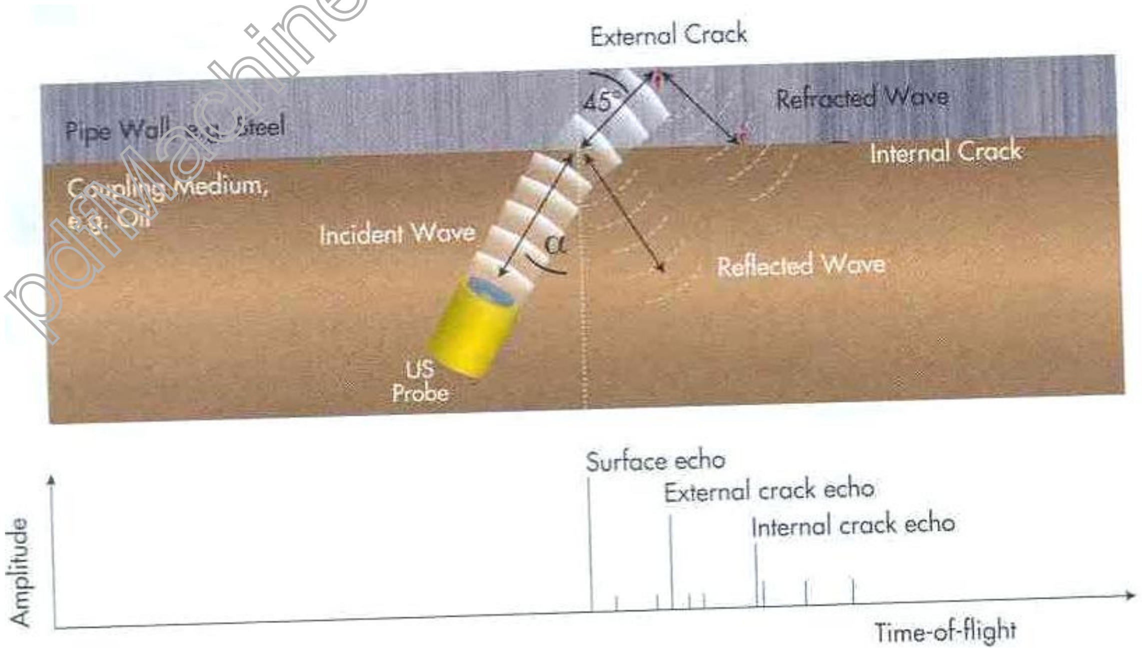
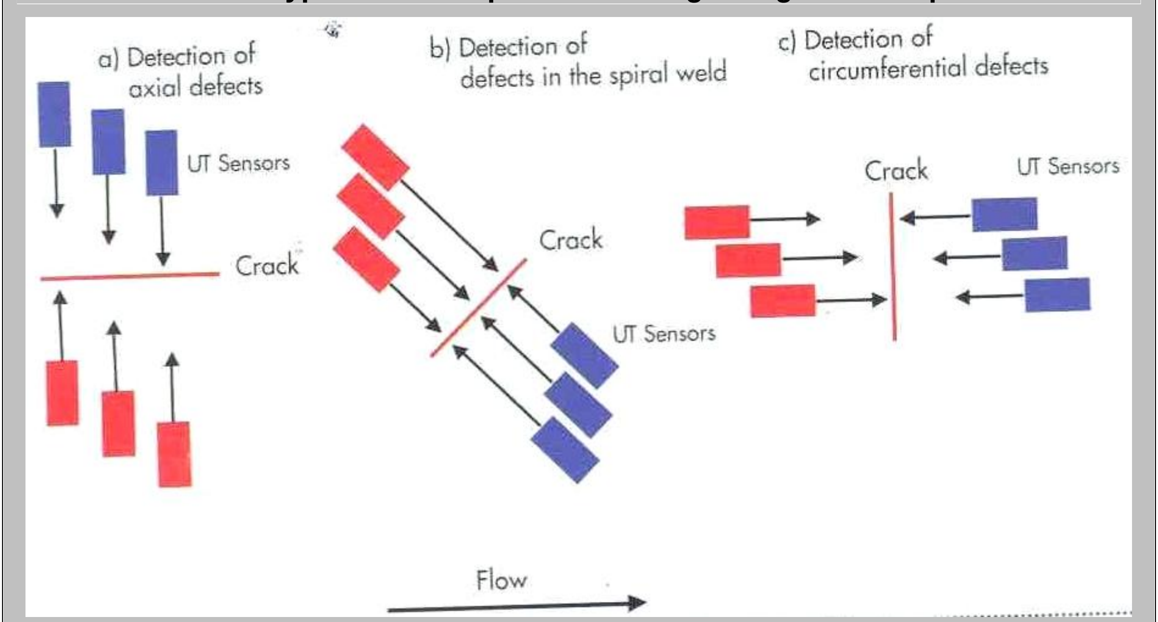


Table 1. Typical defect specification regarding crack inspection



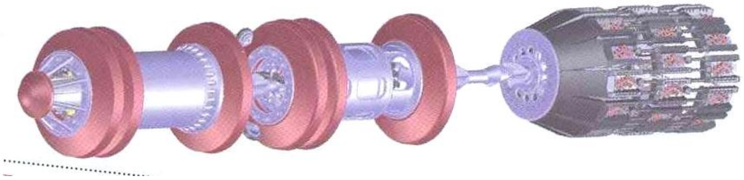
Minimum length of flaw to be detected.	**30 mm**
Minimum depth of flaw to be detected.	**1 mm**
Minimum orientation relative to the inspection. Direction.	**<± 10˚**
Probability of detection of the minimum Defect size.	**>90 %**

The inspection task:
Ability for detection of the defects and, on the other hand, by the characteristics of the inspection system. Atypical specification with regard to the detection of crack-like defects is shown in table 1.typical requirement for the inspection systems are shown in table

Ultrasonic crack inspection: the principles:
An objective of the ultrasonic crack inspection in pipelines is the early detection of crack-like defects, which allows the pipeline operator to take appropriate measures at an early stage in order to avoid pipeline failures caused by cracks. The principle of the ultrasonic crack inspection is based on the 45 ˚angle beam technique using transverse waves. Due to the so-called corner reflection, even minor cracks from approximately 1 mm onwards give quite strong reflections. The pulse echo technique is applied. For instance, the same probe serves both as transmitter and as receiver. Then the signals undergo further processing.

Figure 1 shows the measuring principle and a schematic representation of the measuring signal (A-scan). The position of the defect (external, internal) can be reliably determined from the distance between the entry echo and the defect echo.

For inline inspection, the coupling of the ultrasonic pulses into the pipe wall is achieved through the pipeline medium (usually oil). Due to the different sound velocities in the coupling medium and in steel, an appropriate angle of incidence is required in order to obtain



A refraction angle of approximately 45 ˚in the pipe wall. Crack-like indications will be recorded if their amplitude exceeds a pre-defined threshold and if the indication is present over a pre-defined minimum length (typically 30 mm).

To fully cover the circumference of the pipe, the individual transducers are arranged at a peripheral distance of 10 mm, using a flexible sensor carrier.

Perpendicular to the expected defect orientation, two inspection direction, insonification therefore done in hoop direction, both clockwise and counter-clockwise. Sensor carriers are now also available in a modified version to detect cracks along girth welds. For this purpose, insonification directions are in upstream and downstream voith turbo hydrodynamic variable speed drives are in service in the oil, gas and petrochemical industry under the toughest conditions around the world. These drives are installed at facilities from production to transportation to processing.

On offshore platforms, natural gas pipelines, crude oil and liquid pipelines, refineries, petrochemical plants and other industrial facilities, in the desert, or in arctic environments-**voith** drives are running 24 hours a day, 365 days a year.

Compared to alternative drive systems, such as frequency inverters, the system offers distinct advantages: excellent availability and reliability of the units and high efficiency proven by field testing. In addition, hydrodynamic systems often have lower investment and maintenance costs as well as a longer service life than electronic speed control systems.

Table 2. Typical requirements placed upon the inspection system

Inspection distance	> 100 Km
Inspection speed	< 2 m/s
Wall thickness range	2 -- 20 mm
Axial spatial resolution	- 3 mm
Temperature range	0 -50 ℃
Maximum pressure	< 10 MPa

Directions. In the case of spiral welds, the spiral angle (relative to the axial direction) has to be taken into account. An overview of the different sensor arrangements in given in figure 2. In most cases, the medium transported in the pipeline is used as a coupling medium (crude oil, diesel, kerosene, etc.).

Inline Inspection system (ILI)

An example of an ILI system for inline crack inspection of pipelines is depicted in figure 3. Depending on the diameter of the pipeline to be inspected, the system consists of two or more bodies which are connected by universal joints. Such system usually has the following components:

◆**Battery module**: As the system (after launching in the pipeline) operates autonomously, the required electric energy has to be supplied by batteries. For longer inspection distances, additional battery units can be used if necessary.

◆**Electronic module**: this part contains the electronic devices necessary to generate and receive ultrasound (transmitter/ receiver boards), as well as the data processing which is performed by microprocessors and high- speed electronic circuits. In this module, the data storage devices are also integrated. Nowadays, solid-state memories are commonly used, allowing storage capacities of up to 100 GB at low space requirements.

◆**Odometer wheels**: depending on the pipe diameter, two or these odometer wheels are applied to record the distance information. The odometer information is also used to produce a distance dependent trigger signal to trigger the ultrasonic transmitters. In the standard system, scan pitches of 3 mm (axial weld inspection) and 1.5 mm (girth weld inspection) are typically used.

◆**Sensor carrier**: The sensor carrier is located at the end of the system. It consists of several skids made of polyurethane and connected by flexible spring. For the crack inspection of a 28 in. diameter pipe, for example, 420 crack detection sensors together with 28 wall thickness sensors are integrated in the sensor carrier.

Data evaluation and interpretation.

Online processing.

During inline inspection, the inspection data are preprocessed in the following steps:

♦Digital filtering (band pass filtering).
♦Data reduction according to the ALOK-algorithm (Barbian et al., 2003).

♦Identification of crack- like indications by pattern recognition.

♦Project and sorting of the inspection data according to distance and circumferential position.

♦Based on the pre-processing procedure, a visualization of the inspection data is possible, already shortly after the inspection.

■ **Offline Processing.**

Before starting the data analysis, an automatic evaluation is performed with the following steps:

Girth weld search to compile a pipe tally. The completed pipe book lists all pipe book lists all pipes of the inspected line, together with identification number, pipe length and wall thickness.

②Long seam search. In the case of longitudinally welded pipes, the circumferential position of the weld seam is determined. Otherwise, the type of pipe is indicated (seamless, spirally welded).

Search for anomalies. As a result, a list with defect candidates (position, length, width etc.)Is compiled.

The automatically generated information is stored in a database. A separate database is used in order to handle all relevant information on the inspection runs.

Data Analysis.

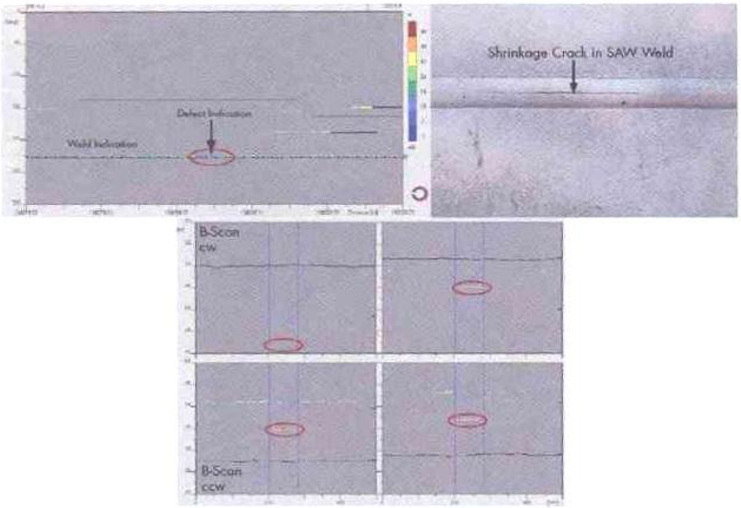
The actual data analysis is still preformed by human experts using special PC-based software for visualization, classification and sizing of the data. The data are displayed using standard representations such as, for example, A, B and C-scans. The automatically compiled feature list is processed in compliance with customer-specific requirements. The major steps are:

❖Visualization of the regions with indications (C-scan, B-scan).

❖Classification of the indication (type, position in the pipe wall, position relative to the weld.

❖Adjustment of indication length and width, if necessary.

❖Estimation of defect depth in the case of crack-like indications.



After completion of the data analysis the result are documented in an inspection report.

❍ **Determination of defect length:**
In contrast to the length determination, the flaw depth cannot be directly measured. Even in the case of well-defined artificial EDM notches as reflectors, the reflected amplitude is not a very reliable measure of the depth. Moreover, in the depth range > 4mm, a saturation effect is observed for the given conditions. This means that the defect depth can only be estimated to a certain degree. Several characteristics are used for the estimation. These are:

Maximum reflection amplitudes obtained from the defect.

✓Indication overlap.

✓Indication shape.

✓Crack tip signals, if recognisable.

✓Occurrence of special signal patterns.

Experimentally determined result can be interpreted very well by using a ray-tracking model. Different crack depths values can (besides the variation in the amplitude) result in distinguished signal patterns which can be used for depth estimation.

Basic on these findings, a depth grading according to the following ranges is applied:

- < 1mm
- 1-2 mm
- 2-4 mm
- >4 mm

In practice this approach has proven quite successful. The confidence level as based on more than 100 verification is approximately 80 %. If crack tip indications can be identified in the inspection data, the crack depth can be determined even more precisely by using the difference in time- of fight between the crack tip echo and the corner reflection echo.

Shrinkage crack in an axial weld (DSAW weld).
In longitudinally welded SAW (submerged arc welding) pipe, crack-like indications are mainly found in the HAZ (Heat affected zone) of the long seam. They are often caused by undercuts (the depth of which is usually below 1mm).another defect type that can be found in the long seam is LOF (lack of fusion).such defects are easily detected by sensors insonifying the weld

from the same side where the defect is located. The detection form the opposite side is restricted to some extent due to the disturbing influence of the weld bead. Generally, in V-Shaped welds, geometrical indications resulting from the weld geometry are more or less continuously present in the inspection data. However, as the weld region is completely recorded by three geometry indications and defect indications is usually not a problem?

Figure shows a shrinkage crack in the centre of the long seam, as detected in a 40 in. crude oil line. In the C-Scan, a continuous indication is visible resulting from the geometry of the long seam.

In order to classify and to size the indication, the corresponding B-Scan has to be evaluated. Defects located in the centre of the weld provide similar patterns form both sides of the weld. In the example the defect is detected by two sensors from either inspection side. Length and location are easily obtained. The depth was grades as 1 -2 mm. On the right hand side of figure the verification result demonstrates that by excavating a surface breaking shrinkage-crack with a depth of 2 mm was found in the centre of the weld.

Fatigue crack at external Attachment.

The following example refers to the detection of circumferential defects in an offshore pipeline. The aim of the inspection was to inspect externally welded-on anode pads. Experience had shown that circumferential fatigue cracking may occur along the welds of the anodes which then can grow into the pipe wall.

In order to solve the inspection task a special sensor carrier was developed. To validate the new inspection system, several test runs were performed in a special test loop. Furthermore the data analysis software had to be modified to include this type of inspection geometry. After validation and offshore pipeline was successfully inspected with the modified inspection tool. In the data analysis process all the anode pads were initially identified in the data and then analyzed in order to detect additional crack indications.

One result of this inspection is documented in figure. In the C-scan a girth weld and two nearby anode pads can be identified due to the clearly visible weld indications. By additionally analyzing the B-scans a crack- like indication at the upper anode pad was found. Beside the corner reflection here the existence of an intermediate echo can be observed. This phenomenon is also demonstrated by modelling using a ray tracing algorithm. The intermediate indication is clearly reproduced if the crack depth is larger than approximately half the wall thickness. Based on these findings, a depth >6mm (here >50 % wt) was estimated. A verification test using the TOFD technique for depth sizing yielded a depth of 8.1 mm.

Conclusion and Outlook.

After being in use for longer than a decade ultrasonic crack inspection by means of inline inspection tools is a well proven technology in the pipeline inspection business particularly with regard to weld inspection. In the meantime technically mature systems are available for the reliable and early detection of crack- like defects in axial circumferential and spiral weld. However the use of inspection tools based on conventional ultrasound is normally limited to liquid lines because of the required liquid coupling. Inline crack inspection of gas pipelines is still a great challenge. Here the EMAT technology seems to offer encouraging potential for suitable solution. First tools are already available on the market

Another direction for further development lays in the combination of two or more test methods in single tools for example simultaneous inspection of axial and circumferential cracks in one inspection run. Apart form advantages for the data analysis the use of combined systems will provide considerable cost savings to the pipeline operator. Such development will be encouraged by the ongoing miniaturisation of electronic components and their increasingly cost-effective production.