INTRODUCTION TO ULTRASONIC IN-LINE INSPECTION OF CRA PIPELINES

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ABSTRACT
Pipelines manufactured from corrosion-resistant alloys (CRA) are becoming more common in special applications, in particular with offshore pipelines which are in many cases exposed to a harsh and highly corrosive environment. For many years the inspection of CRA pipelines (solid CRA, clad and lined pipe) was not a high priority. Due to the special composition of these types of line pipe it also posed specific challenges to in-line inspection methods as compared to the inspection of common line pipe.

In this article, the different types of CRA line pipe and the relevant characteristics regarding in-line inspection (metal loss inspection, crack inspection) are described. Typical damage mechanisms (e.g. pitting corrosion) that may develop during operation are illustrated and the specific capabilities that are available for ultrasonic in-line inspection as well as the limitations are explained. Several examples from inspection runs in CRA pipelines are presented demonstrating that reliable in-line inspections with good data quality are feasible to a wide extent.

1 INTRODUCTION

The number of pipelines operated in corrosive environments is more and more increasing as, for example, many oil fields have passed their peak production resulting in an increase of the water fraction in the crude oil coming from the well. Other reasons are related to the development of deep-water offshore fields with high pressure and high temperature conditions promoting corrosion processes. Furthermore, the increasing production of corrosive sour gas and sour crude oil result in high CO_2 or H_2S concentrations with highly corrosive potential. Conventional means of corrosion protection such as cathodic protection or chemical inhibitors typically used in standard pipelines may neither be effective nor economic for these new challenges. As an alternative, corrosion resistant alloys are more and more applied in the construction of pipelines operated under difficult corrosive conditions. Compared to carbon steel (CS) CRA materials provide much better corrosion protection by their chemical composition using chromium or nickel as main alloying elements. However, these materials usually have lower strength and toughness, and they are considerably more expensive.

As experience with CRA pipelines has already shown, there is no 100 % protection against corrosion damage. This directly leads to the question whether conventional in-line inspection (ILI) can be adequately used for CRA pipelines or what kind of limitations have to be faced. After a description of the different types of CRA pipe and their manufacturing methods we will try to answer these questions in the following as based on theoretical considerations and as backed-up by practical inspection results. This article focuses on ultrasonic ILI of CRA pipelines; information on other ILI methods (e.g. MFL) for CRA pipelines may be found in [1].

2 TYPES OF CRA PIPE

Basically, there are several options for using CRA in pipeline construction which can be categorized as follows:

- Solid CRA pipe
- Combined solutions
    - Clad pipe
    - Lined pipe

While solid CRA consists of one homogeneous material (like carbon steel), the combined solutions consist of two layers. Here, the outer layer is made from CS providing the necessary mechanical strength; the inner layer is made from CRA providing the corrosion protection. Based on the way the layers are joint together one differentiates between clad pipe and lined pipe (see below).

2.1 Solid CRA pipe

Solid CRA pipe is available in many versions. Some of the most common iron-based materials are listed in Table 1. The main corrosion protective effect is achieved by the chromium content. Further alloying elements are nickel and molybdenum. The strength of the ferritic/martensitic/Duplex steels is comparable to standard carbon steels or even higher (martensitic steel) while the austenitic steels have much lower strength. Other materials used for CRA pipe are nickel-based alloys such as Inconel 625 with a nickel content of approx. 60 %.

Table 1: Typical steel types used for solid CRA pipes

STEEL TYPE	EXAMPLES	COMPOSITION	COMMENT
Ferritic	AISI 444 *(1.4521)*	18 Cr - 2 Mo	
Martensitic	SMSS	13 Cr	Super-Martensitic Stainless Steel; High Strength (~ X80)
Austenitic	AISI 304L *(1.4306)* AISI 316L *(1.4404)*	18 Cr - 8 Ni 18 Cr - 10 Ni	L – Low Carbon
Duplex	2205 *(1.4462)*	22 Cr - 5 Ni	50 % Ferrite / 50% Austenite

Compared to carbon steel, the costs for CRA solid pipe is considerably higher. Some examples are given in Table 2 where the costs are indicated with regard to carbon steel as reference.

Table 2: Relative costs of solid CRA pipes

TYPE OF STEEL	RELATIVE COSTS
Carbon Steel (reference)	1
13% Cr	3
Super 13% Cr	5
Duplex SS	8-10
Austenitic SS	12-15
Nickel based Alloys	20

Source: GeKEngineering 2009

2.2 Combined CRA pipe

Combined CRA pipes provide a more cost-effective solution as the carrier pipe is made from standard carbon steel which also provides the necessary structural strength. Only the inner cladding, which has typical thicknesses from 3 mm to 4 mm, is made from the more expensive CRA material. Typical steels used for combined CRA pipe are indicated in Table 3. Due to its austenitic microstructure, the cladding is non-magnetic. This means in particular, that it cannot be inspected by magnetic methods such as MFL.

Table 3: Steel types used for combined CRA pipes

CARRIER	CLADDING
X52, X60, X65, X70	AISI 316L, 317L, 904L, ...
(ferritic)	(austenitic)

Based on the manufacturing of combined CRA there are two variants (Fig. 1):

1. Clad pipe

   The cladding and the substrate are bonded metallurgically. The bonding is similar to a fusion line between a weld and the base material. In particular, there is no gap between the two layers.
2. Lined pipe

   The two layers are bonded mechanically. Looking from a microstructural scale there is a tiny gap between the layers.

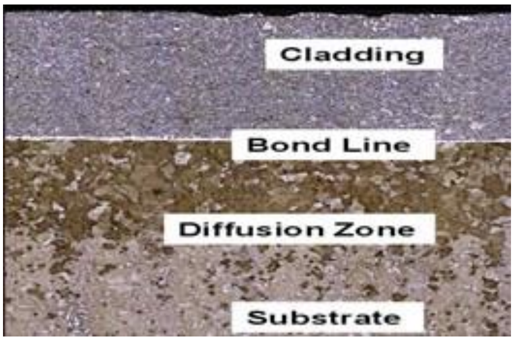
TYPE OF PIPE	CHARACTERITICS	EXAMPLE
Clad pipe	**Metallurgical bond**	
Lined pipe	**Mechanical bond**	

Figure 1: Types of combined CRA pipe

2.2.1 Manufacturing of clad pipe

The main manufacturing processes for clad pipe are based on roll bonding and weld overlaying (Fig. 2).

- Roll bonding

  The CRA pipes are produced from roll bonded plates with subsequent pipe-forming and longitudinal welding. The plates are manufactured either by hot rolling or by cold rolling followed by thermal treatment to achieve metallurgical bonding.

- Weld overlaying
  The cladding is produced by welding the CRA material on the inner surface of the CS pipe. Either axial welding or orbital welding can be applied. Fig. 2 shows an example of orbital weld overlay.

Weld Overlay	Roll Bonding
	

Figure 2: Common manufacturing methods for clad pipe

2.2.2 Lined pipe

Lined pipe is produced by fitting a CRA pipe into a CS pipe (Fig. 2). Both pipes are expanded by hydraulic pressure until the desired diameter is reached. After releasing the hydraulic pressure, the inner pipe is placed under residual compressive stress which results in a tight mechanical bonding between the two pipes.

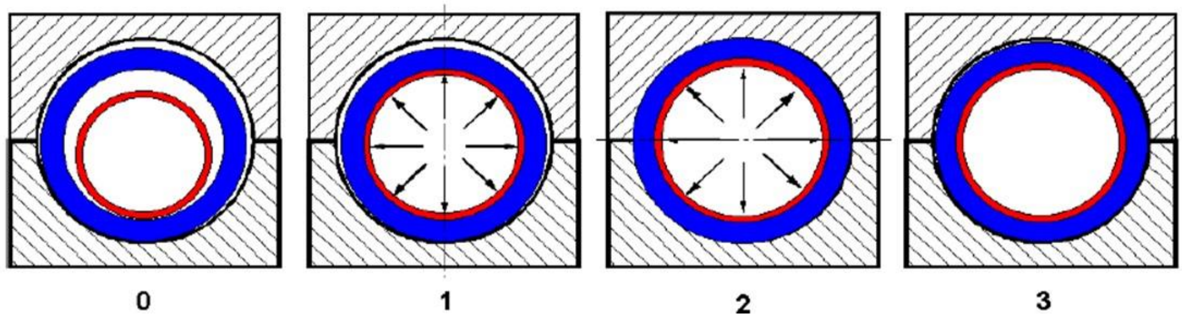


Figure 2: Manufacturing of lined CRA pipe by hydraulic expansion [2]

3 CORROSION IN CRA PIPELINES

Generally, CRA pipes provide excellent corrosion protection. The question arises, however, why do CRA pipelines sometimes show corrosion damage, after all. There are several answers that can be found in the literature:

- Manufacturing related anomalies may promote corrosion.
- Wrong handling during storage, transportation and installation may initiate corrosion damage even before the pipeline goes into operation.
- The selected CRA material may not be suitable for the actual operational conditions [3].

The types of corrosion that are found in CRA pipelines are in particular:

- Crevice corrosion: Intensive localized electro-chemical corrosion occurs within crevices when in contact with a corrosive medium.
- Pitting corrosion: Highly localized attack that eventually results in holes in the cladding.
- Galvanic corrosion: Potential difference between dissimilar metals causes corrosion of the anodic metal in presence of an electrolyte.
- Stress Corrosion: A disadvantageous combination of stress, corrosive environment and

susceptible steel type can lead to hydrogen induced stress corrosion cracking (HISSC).

4 ULTRASONIC IN-LINE INSPECTION OF CRA PIPELINES

In this section some basic considerations on the ultrasonic inspection of the different types of CRA pipes are presented. As the majority of defects found in CRA pipelines is related to corrosion damage, the main focus is here on ultrasonic metal loss inspection.

4.1 Ultrasonic metal loss inspection

Ultrasonic metal loss inspection is a well-proven ILI application for reliable detection and precise sizing of corrosion damage. With the latest tool generation excellent resolution (axial & circumferential) is available ideally suited for the inspection of small pits and pinholes down to a diameter of 5 mm [4]. The inspection method is based on ultrasonic wall thickness (WT) measurement. The principal of the WT measurement as applied in ultrasonic ILI is explained in Fig. 3.

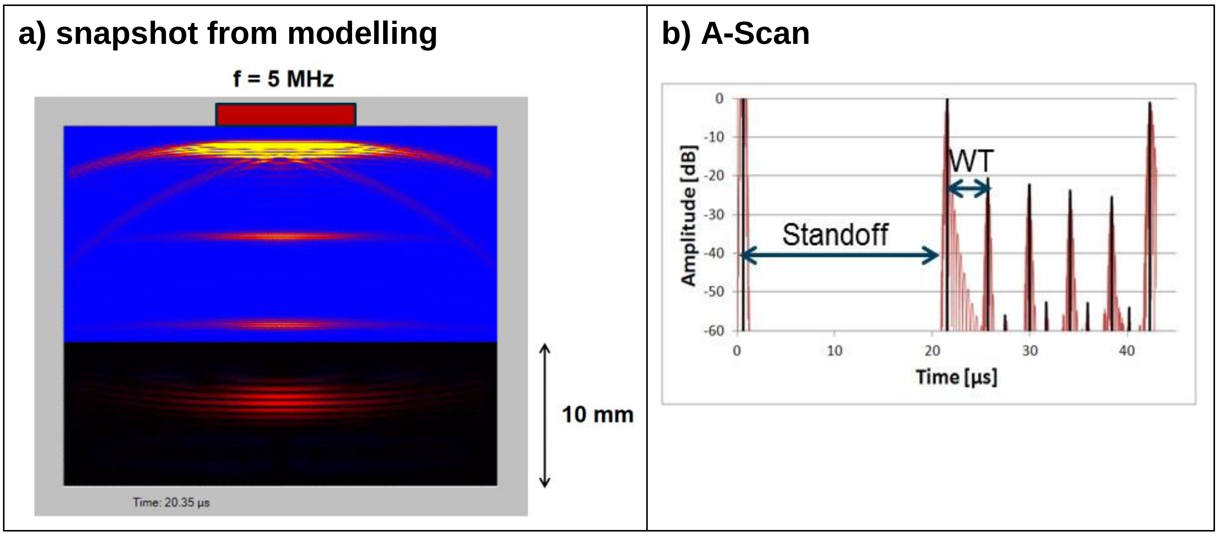


Figure 3: Principle of ultrasonic wall thickness measurement using longitudinal waves with straight incidence (a: modelling example; b: resulting A-scan)

An ultrasonic pulse (center frequency: 5 MHz) is transmitted from the ultrasonic transducer through the liquid medium into the pipe wall using straight incidence (Fig. 3a). The reflections from the interface and from the backwall are received by the same transducer (pulse-echo technique). The received signals are represented as A-scan (Fig. 3b) showing the signal amplitude as a function of time-of-flight (TOF). The distance to the inner surface (standoff SO) is calculated from the TOF of the interface echo and the ultrasonic velocity of the medium. The wall thickness WT is determined from the time difference between the interface echo and the first backwall echo using the ultrasonic velocity of the pipe material. Using this method, a direct measurement of the (remaining) WT is obtained with a tolerance of ± 0.4mm.

In order to reliably detect and size the corrosion damages typical for CRA pipes inspection tools providing highest resolution are required. High resolution ultrasonic inspection is ensured by applying appropriate ultrasonic transducers in connection with a dense measuring grid with 4 mm circumferential sensor spacing and 1.5 mm axial sampling distance (UMp inspection). An ultrasonic sensor carrier developed for this type of high resolution inspection is shown in Fig. 4.

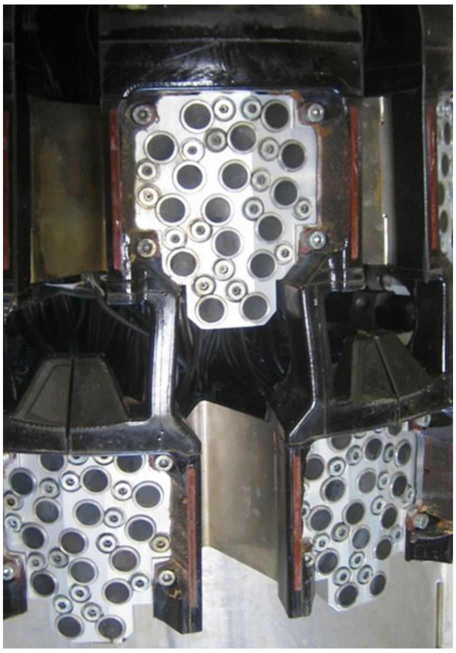


Figure 4: Example of sensor carrier for high resolution ultrasonic metal loss inspection (UMp for pitting resolution) with 4 mm circumferential sensor spacing

4.2 Inspection of solid CRA pipe

From an ultrasonic point of view, the inspection procedure for solid CRA pipe is basically the same as for CS pipe. This is due to the fact that the ultrasonic properties (speed of sound, density) of typical iron-based CRA materials are very similar to those of carbon steels (see Table 4). Also the transmission angle for crack inspection (calculated for water as coupling medium) is hardly affected meaning that the same sensor carriers as designed for crack inspection in carbon steel can be used without modification for the CRA steels indicated in Table 4.

Table 4: Ultrasonic velocities and density of some steels used for solid CRA pipes (data partly taken from literature).

Material	v_{Long} (mm/µs)	v_{Trans} (mm/µs)	Density (gr/cm^3)	Transmission Angle* for 45° Shear Wave (°)*
Carbon Steel	***5.96***	***3.23***	***7.85***	***18.5***
13% Cr (SMSS)	5.90	3.20	7.72	18.7
AISI 316L	5.75	3.27	8.00	18.3
Duplex	5.80	3.30	7.80	18.1
Super-Duplex	5.85	3.20	7.80	18.7
Deviations (%)	***± 1.4***	***± 1.4***	***± 1.3***	***± 1.4***

*for crack inspection using water as medium

4.3 Inspection of combined CRA pipe

The different type of bonding for lined pipe vs. clad pipe plays an important role for the ultrasonic inspection of these combined structures. As the mechanical bond present in lined pipe constitutes a mechanical separation between the CRA layer and the carrier pipe, ultrasonic pulses are fully reflected at the inner side of the cladding (Fig. 5a). Thus, only the cladding can be inspected by ultrasound. For clad pipe having a metallurgical bonding the situation is completely different as the ultrasound can now propagate through the bond (Fig. 5b). There occurs some marginal reflection at the interface that results from the acoustic impedance mismatch between the CRA material and the CS. Based on the data from Table 4, a maximum reflection coefficient of approx. 3 % at the transition from the CRA to the CS is calculated for the indicated materials.

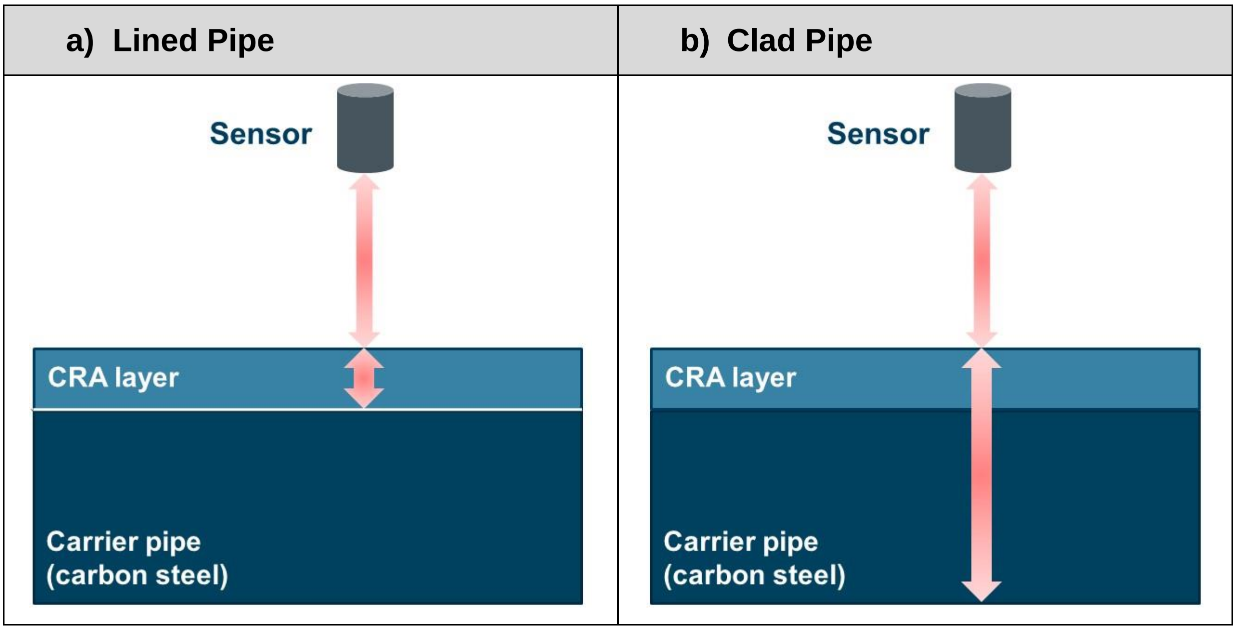


Figure 5: Ultrasonic propagation in lined pipe (a) and clad pipe (b)

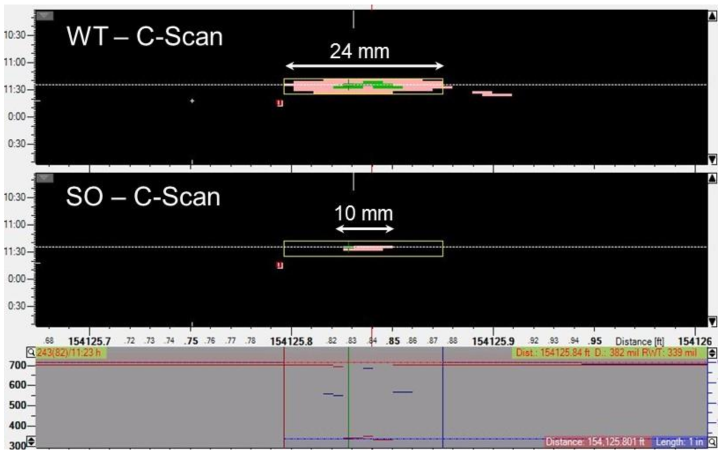
5 INSPECTION EXAMPLES

In the following section some selected inspection results are presented to demonstrate the potential & limitations of ultrasonic inspection regarding different defect types in CRA pipe.

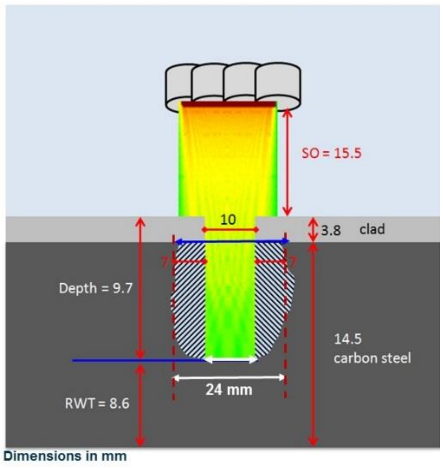
5.1 Metal loss inspection

5.1.1 Pitting corrosion

Pitting corrosion is the dominant type of defects found in CRA pipelines. Fig. 6 shows an example obtained from longitudinally welded clad pipe. The wall consists of 14.5 mm carbon steel plus a 3.8 mm CRA layer made from Incoloy 825. The data quality is comparable to inspection data from plain CS. The standoff inspection data (Fig. 6a) show a pitting with 10 mm diameter and a 9.7 mm increase of standoff while the WT data indicate a defect size of approx. 24 mm with echo loss in the center area. In Fig. 7b, the defect geometry is explained. The SO data indicate a through-clad pinhole that extends 9.7 mm into the CS. Within the pinhole area the WT data show echo loss. The WT data around the pinhole result from reflections at the backside of the clad indicating that the CS has disintegrated by corrosion over a total range of 24 mm diameter. Based on the WT data, it can thus be concluded that the corrosion is spreading underneath the cladding laterally into the CS as depicted in Fig. 6b by the shaded sections.



a) Ultrasonic inspection data



b) Defect geometry (schematic)

Figure 6: Through-clad pinhole extending into the CS carrier in roll-bonded clad pipe

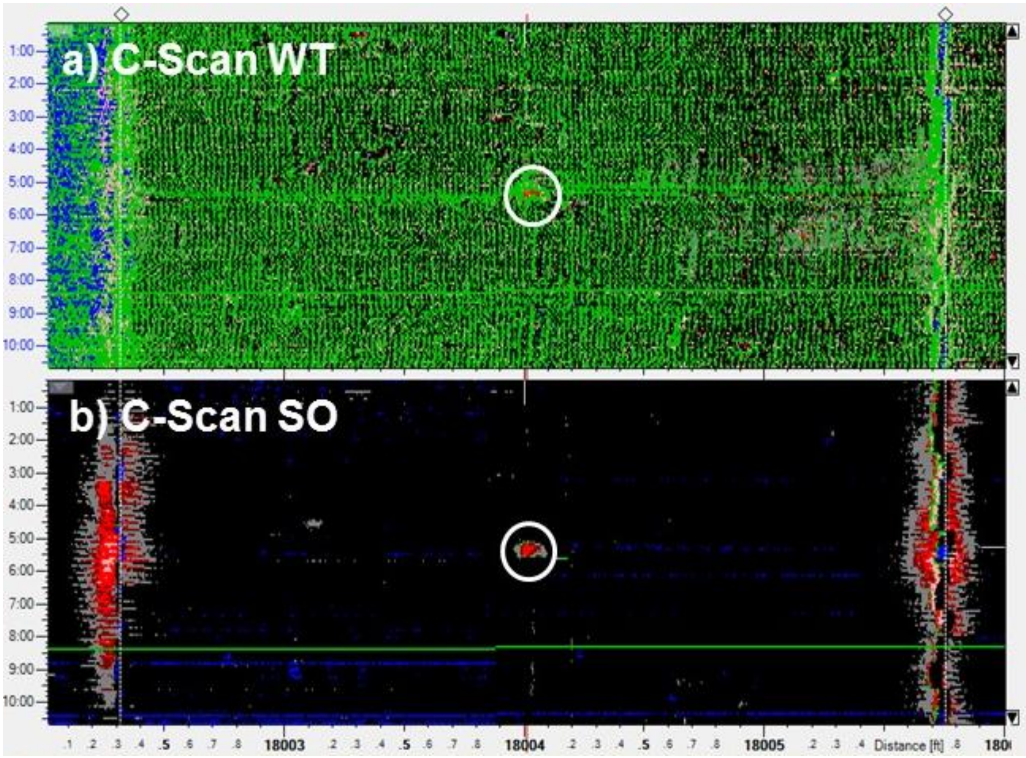


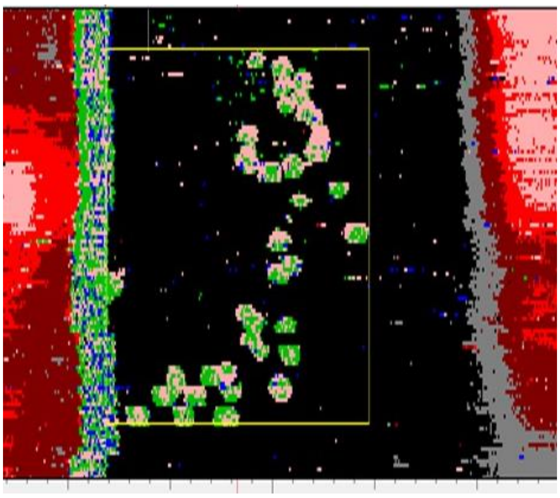
Figure 7: Ultrasonic C-scans as recorded in CRA pipe (clad pipe, weld overlay) showing an internal pit: a) wall thickness data   b) standoff data

The next example (Fig. 7) shows a pitting defect in a CRA pipe made by orbital weld overlaying. Although the defect can be recognized in the WT data (Fig. 7a) the wavy structure of the surface leads to reduced data quality as indicated by the green color representing echo loss. The SO data resulting from the direct reflection at the internal surface, however, provide very good data quality that still allow for precise sizing of internal corrosion defects.

5.1.2 Disbonding

Another type of defect in metallurgically bonded CRA pipe is disbonding between the CS and the CRA layer. The ultrasonic wall thickness inspection is ideally suited to detect and size disbonding as the ultrasonic pulses will be fully reflected at the disbonded areas. Fig. 8 shows a comparison between ultrasonic ILI results and results from high-resolution external UT as obtained from a section of clad pipe containing a larger number of small disbonded areas. Here, the match between the two data sets is quite demonstrative.

a) wt data from ILI



b) wt data from external UT

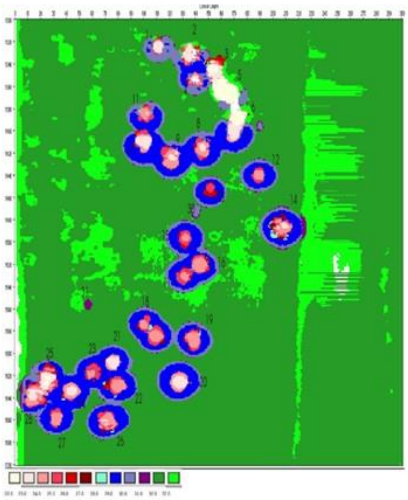


Figure 8: Ultrasonic C-scans (WT data) showing disbonded spots in clad pipe.
a) in-line inspection b) high-resolution scan using external UT

5.1.3 Wrinkling/Buckling

The inner CRA layer of lined pipe is vulnerable to wrinkling/buckling due to excessive bending especially occurring during laying of off-shore pipelines. An example is shown in Fig. 9a. Apart from a negative impact on the medium flow the plastic deformations cause changes of the material properties which may increase the risk of corrosion damage. These deformations are easily detected by the ultrasonic standoff measurement which allows reliable detection of smallest changes of the pipe geometry as caused by wrinkling or buckling (Fig. 9b).

a) Damaged liner

b) ILI data

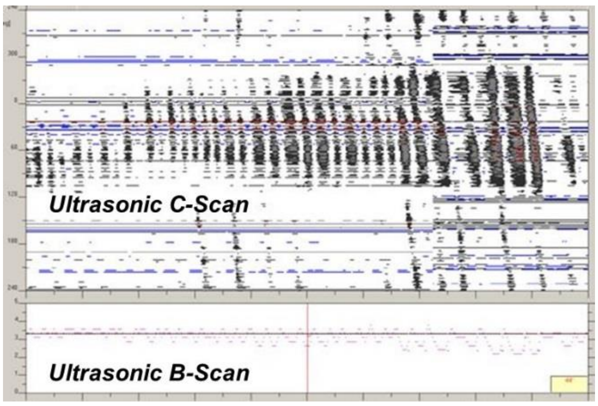


Figure 9: Damaged liner in lined pipe (a) and corresponding ultrasonic ILI data (b)

5.2 Crack inspection

The inspection principle used for ultrasonic crack detection in pipelines is based on the well-established 45° shear wave method as illustrated in Fig. 10.

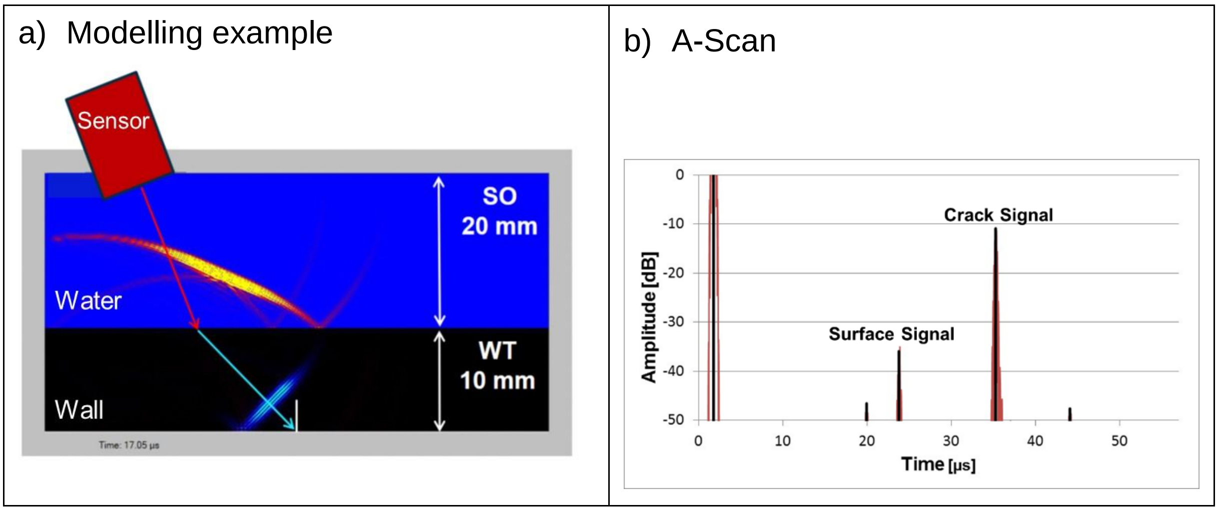


Figure 10: Ultrasonic crack inspection using 45°- shear waves in the pipe wall
a) modelling example   b) resulting A-scan

An ultrasonic pulse (center frequency ≈ 4 MHz) is transmitted from the sensor through the liquid coupling medium into the pipe wall. The angle of incidence is selected such that a refracted shear wave is obtained propagating through the wall at an angle of approx. 45°. Using water as a couplant, the angle of incidence is then approx. 18°. If the pulse hits a radial crack a strong reflection is obtained (corner reflection) that is received by the same sensor (pulse-echo method). Depending on the time-of-flight of the crack signal relative to the surface signal one can readily determine whether the crack is internal or external. Fig. 1a shows the situation where the transmitted pulse is already reflected at the internal pipe surface while the refracted shear wave is about to hit the external crack. The received signal is displayed as an A-scan showing the measured reflection amplitudes as a function of time-of-flight (Fig. 10b).

Fig. 11 describes an example of crack inspection of clad pipe. The CS (X60) has a thickness of 10 mm, and the cladding (316L) has a thickness of 4mm. The expected area for cracks initiation is in particular the edge of the girth weld (Fig. 11a). Artificial crack-like features were introduced at the girth weld by spark erosion (EDM notches) for a demonstration test. Fig. 11b shows an example of three adjacent external crack-like defects. The corresponding ultrasonic C-scan of the defect section is shown in Fig. 11c. Here, the defects can be clearly identified at the left side of the girth weld with a similar signal-to-ratio as for plain CS pipe.

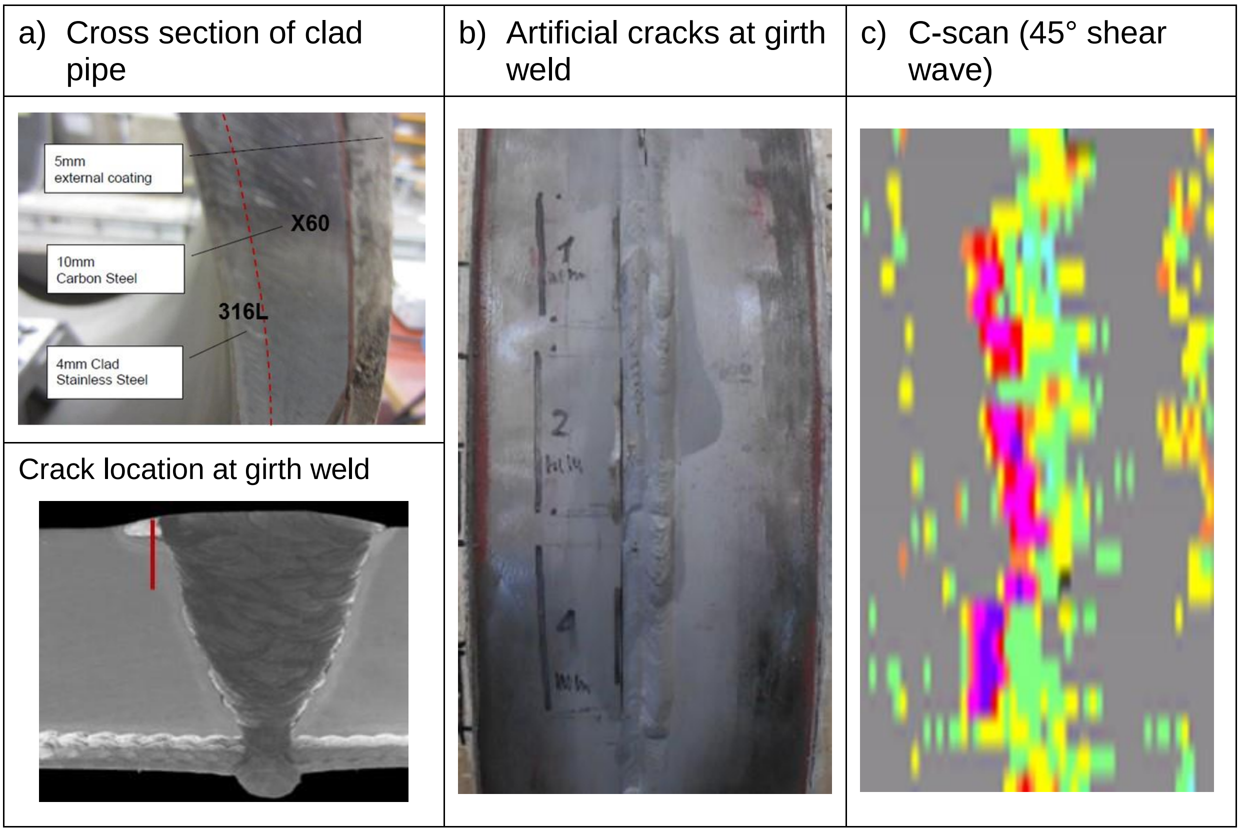


Figure 11: UT results from in-line crack inspection of a girth weld in clad pipe

6 Summary

All the different types of CRA pipes (solid, clad and lined) can be inspected using ultrasonic ILI tools. While the inspection of solid CRA pipe & seam welded clad pipe is similar to CS pipe some restrictions have to be considered for weld-overlay clad pipe and for lined pipe. Due to the wavy surface pattern of weld-overlay cladding the quality of the WT data is affected which results in reduced performance for external metal loss defects. The more important inspection of internal corrosion is however fully ensured when using the less affected standoff data. As far as lined CRA pipe is concerned only the CRA liner can be inspected as the mechanical bonding represents a barrier that cannot be crossed by the ultrasound.

The corrosion damage mainly encountered in CRA pipelines (pitting corrosion) is often below the specified dimensions for detection & sizing of standard ILI tools. Therefore, high-resolution tools (e.g. UMp-tools) are required for adequate inspection results. From the experience gained so far it can be concluded that many of the corrosion issues present in CRA pipelines can be addressed by using high-resolution ultrasonic ILI. MFL inspection of CRA pipes is restricted to magnetic materials meaning that only the CS carrier pipe of lined or clad pipe can be inspected while inspection of the austenitic CRA layer is not possible

7 REFERENCES

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