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Applications of Laser Ultrasonics in the Pipeline Industry

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Abstract
Managing pipe damaged by Stress Corrosion Cracking (SCC) has been a formidable challenge to the pipeline industry. The development of a practical solution for the measurement and evaluation of SCC has been marred by the complexity of crack shapes, their distribution within a crack colony, and the lack of non-destructive technology capable of reliably measuring the crack depths. Laser ultrasonics is a promising noncontact technique for pipeline inspection. The large frequency bandwidth and small footprint make laser ultrasonics ideally suited for application as a depth sizing tool for closely-spaced cracks in a colony. It has been conclusively proven that laser ultrasonic inspection, using the time of flight diffraction (TOFD) technique, can reliably and accurately measure the depth of naturally occurring SCC, and potentially, other cracks and seam weld anomalies.
Keywords: Pipeline, laser ultrasonics, time of flight diffraction, corrosion, cracks

1. Introduction

The in-service inspection of gas and oil pipelines is a subject of great current interest. Issues of safety, and fitness for service, have driven extensive efforts to develop effective monitoring and inspection techniques. A number of effective NDT screening techniques have been developed to identify regions of interest for more detailed evaluation. The three anomalies of greatest interest are (1) corrosion, (2) mechanical damage, and (3) stress corrosion cracking (SCC). In this paper, we will focus on the application of laser ultrasonics to the characterization of SCC.

Stress corrosion cracking is the phenomenon in metals wherein the simultaneous presence of tensile stress, a corrosive environment, and a susceptible metallurgy leads to the nucleation and propagation of highly irregular and complex cracks, usually found in closely spaced clusters or colonies. In pipelines, detecting SCC has been a particularly elusive and challenging problem.

Several pipeline failures around the world have been attributed to SCC since its discovery in pipelines in the 1960's. While the number of incidents attributed to SCC is less than those attributed to other threats to pipelines, such as corrosion or mechanical damage, the detection of SCC constitutes a formidable challenge due to the following key reasons:

- No reliable and accurate inspection tools or predictive modeling based tools exist that are capable of determining what locations along the pipeline are affected by SCC;
- No reliable and widely accepted assessment tools exist for the evaluation of SCC, once found; and
- No reliable and widely accepted tools exist that are capable of accurately measuring the depth of these cracks.

The efforts presented in this paper were concentrated primarily towards developing a non-destructive means to measure the depth (sizing) of cracks as found in SCC colonies.

2. Stress corrosion cracking

Stress corrosion cracking, as found in pipelines, is classified into two major types based on the environments in which they are found to originate. They are: (1) high pH SCC, and (2) near-neutral SCC.

2.1 High pH SCC

Also known as 'classical' SCC, high pH SCC (Figure 1, left) tends to occur at locations where the immediate environment of the pipe and the resulting electrolyte has a pH of between 8 and 9. This form of SCC is known to have relatively jagged crack shapes with extensive branching. It is also known to be more prevalent at locations along the pipeline that are subjected to higher temperatures and cyclic pressures, such as downstream of a compressor station.

This form of SCC is usually comprised of cracks that are aligned in a direction parallel to the axis of the pipe, and the colonies tend to conform to the shape of the disbonded area wherein the electrolyte was trapped.

2.2 Near-neutral SCC

This type of SCC (Figure 1, right) is also known as low pH SCC because it is usually found to be associated with locations wherein the electrolyte has a pH of between 5.5 and 7.5. The cracks formed by this mechanism are usually relatively straight, and have been found to be associated with areas of relatively minor corrosion, and at weld locations where disbonding of the coating leads to the entrapment of conductive electrolytes.

Near-neutral SCC cracks are also primarily found to be oriented in a direction parallel to the axis of the pipe. However, several locations have been discovered where such cracking was found to occur in the circumferential direction. This is believed to be caused by stresses other than the hoop stress, such as bending loads at bend locations.

Figure 1. High pH SCC (left) and near-neutral SCC (right)

2.3 Crack Characteristics

Both types of SCC share a lot of common crack characteristics. Cracks grow in both length and depth. An isolated crack would lead to a rupture if the length and depth reaches a critical length. Conversely, if a crack grows in depth at a faster pace than the length, and penetrates fully through the cross-section of the pipe before reaching a critical length, it will lead to a leak.

At times, adjacent cracks, if aligned, coalesce to form a combined or 'interlinking' crack. These interlinking cracks have a much higher length to depth ratio than the isolated cracks, and therefore have a high probability of leading to a rupture.

3. Detection and positioning of SCC

At this time, there is no generally accepted method for the fitness for service evaluation of SCC. Currently, Magnetic Particle Inspection (MPI) is the most widely used non-destructive method used for the detection of SCC. Once cracks have been detected, manual measurements of colony and crack dimensions (excluding depth) can be performed. Due to the sheer volume of cracks within a small area of affected pipe, these dimensional measurements are, practically, a best effort estimate. Recent efforts in the direction of automating the detection and positioning of these cracks and colonies have shown good success, and are expected to reach commercial markets soon.

3.1 Depth measurement (sizing) of SCC

Various efforts have been made, with varying degrees of success, to measure SCC depth using transducer-based ultrasonics. The physical characteristics of SCC make it exceptionally hard to measure using conventional ultrasonic techniques, specifically:

- Irregular crack shape: Standard ultrasonic inspection techniques are based on calibrating the system using known, idealized reflectors, and deducing results for real anomalies by comparative interpretation of the response. While this approach has been successful with simpler geometries, SCC, with its highly irregular shape and branching, has been a challenge for conventional ultrasonics;

- Appearance of cracks in colonies: SCC occurs in colonies wherein individual cracks are closely spaced in a generally similar direction. This makes it hard to identify and evaluate individual crack responses. Additionally, the couplant, needed for the ultrasound to enter the material, infiltrates into the cracks, effectively making the crack invisible; and
- SCC within corrosion: SCC sometimes occurs within areas of general corrosion with highly irregular surfaces. This makes it harder for the transducers to couple with the pipe, and for sound to travel through the pipe material.

Ultrasonic techniques have been used for many years to characterize isolated cracks. In particular, time of flight diffraction (TOFD) can be used to measure the depth of surface-breaking (or buried cracks). The beam configuration for sizing top surface cracks is shown in Figure 2. The laser generation process produces bulk and surface waves. An incident bulk longitudinal wave (Linc) is diffracted at the crack bottom to both a longitudinal wave (Ldif) and a shear wave (Tdif), with the diffracted longitudinal wave generally being stronger. By detecting these waves, and measuring their arrival time, the crack depth can be determined.

The reliability of TOFD measurements is very much a function of operator skill and experience, as well as the distribution and characteristics of the cracks within a colony. TOFD is considered to be the most reliable and widely applicable technique for depth determination of cracks, but only if it can be ensured that the ultrasonic response will not be affected by the neighboring cracks.

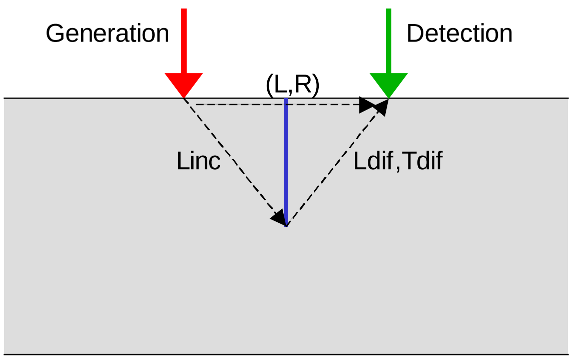

Figure 2. Beam configuration and propagating waves for TOFD.

4. Laser ultrasonics for SCC depth measurement

Laser ultrasonics offers a number of unique features for crack depth measurement using TOFD:

- It is a non-contact technology, and therefore doesn’t require the use of couplant for the introduction of ultrasound into the material;
- It has an extremely small footprint on the material, and therefore can be used to target cracks with closely spaced neighbors;

- It has a higher bandwidth than contact transducers, thereby enhancing crack diffraction, and providing higher depth resolution; and
- It can interrogate cracks even in the presence of local surface corrosion.

Laser ultrasonics has been used before to study tip diffraction from cracks originating on the opposite surface from the incident surface [1, 2]. We are not aware of any TOFD experiments on top surface cracks using laser ultrasonics.

5. Technical approach

5.1 TOFD Simulations

We have used finite difference modeling to simulate wave phenomena associated with TOFD. In Figure 3 we show a calculated separation B-scan in which the position of generation (2.5 mm) and the position of the crack (5 mm) are fixed, and the detection position is scanned. We observed the direct Rayleigh wave and surface-skimming longitudinal wave (blocked by the crack), the back wall reflections, and all three crack-diffracted arrivals. Note that the crack-diffracted arrivals all appear before any other arrivals, so no clutter is present.

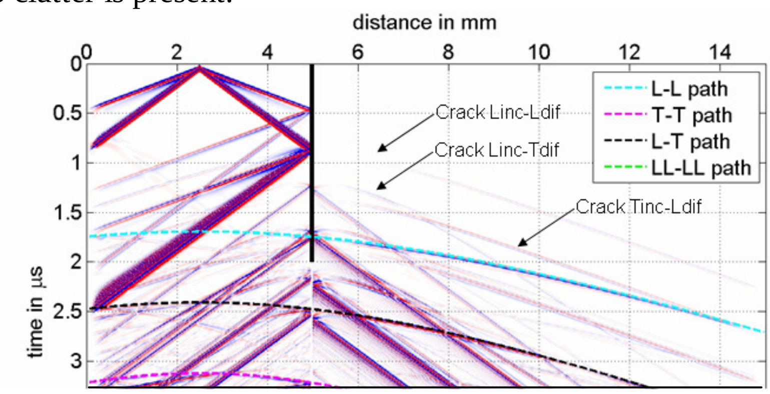

Figure 3. Separation B-scan across 2 mm crack.

5.2 Scan of SCC crack

We have scanned a crack in a typical high-pH colony, shown in Figure 4. The beams straddled the crack and were spaced by 8 mm. The scan started off the crack, and then moved over the crack in a parallel direction.

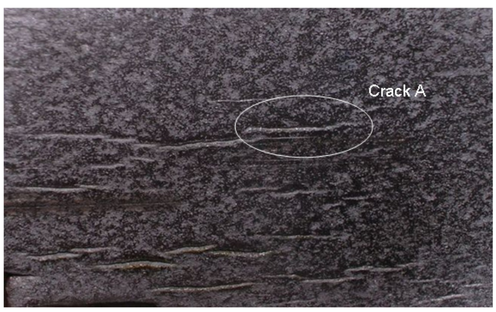

Figure 4. Photo of portion of SCC colony, showing crack that was scanned.

The resulting B-scan is shown in Figure 5. We see the Rayleigh wave disappear over the crack, at the same time as the surface-skimming longitudinal arrival begins to convert to a crack-diffracted (Linc-Ldif) arrival, and mode-converted arrivals appear. From a measurement of the crack-diffracted arrival time at each position, we have calculated the crack profile shown in Figure 6. The estimated measurement accuracy is +/-0.2 mm.

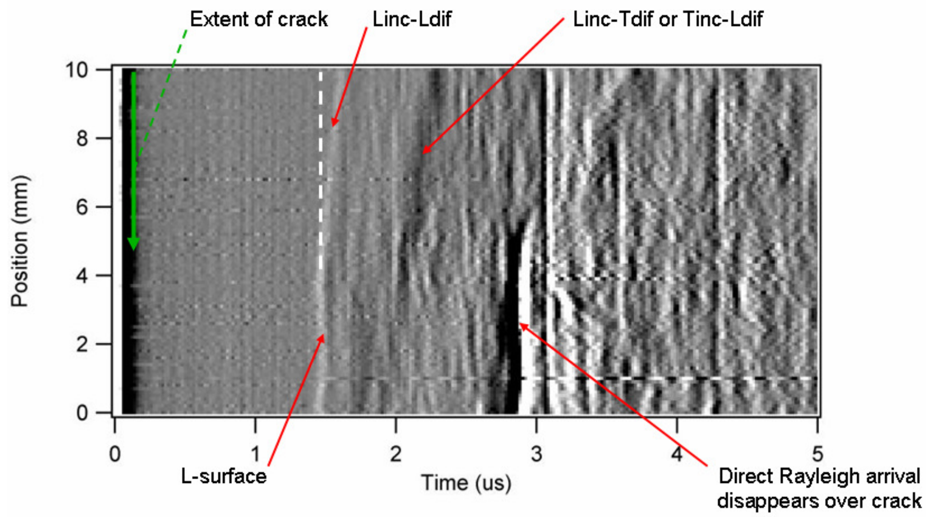

Figure 5. B-scan over crack shown in Figure 4.

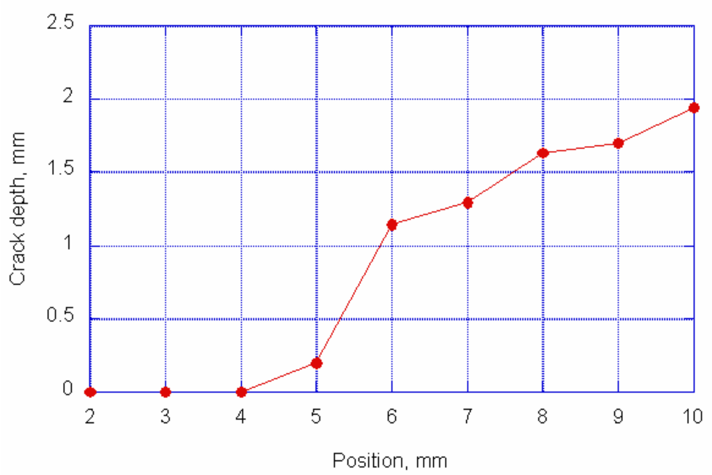

Figure 6. Crack depth profile estimated from crack-diffracted arrival time.

6. Conclusions

Managing stress corrosion cracks has been a challenge to the pipeline industry for decades, with no widely accepted methods to locate, detect, measure or evaluate these cracks. The measurement of the crack depths as found within a colony is a crucial step in developing an integrated tool to manage SCC, once found. Conventional ultrasonics, as well as various other non-destructive tools and techniques have been developed to address the issue, with only limited success.

We have shown that laser ultrasonics has the ability to measure the depth profile of stress corrosion cracks using time-of-flight diffraction. We are now developing robust signal processing software to fully automate the measurement process. Later efforts will be devoted to develop an integrated, field-ready tool that can provide the data required for the accurate determination of pipeline safety and fitness for service.

Acknowledgements

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