Sizing Stress Corrosion Cracks using Laser Ultrasonics

Munendra S Tomar, Martin Fingerhut, Niels Portzgen
Applus RTD, Houston, TX, USA

Marvin Klein, Homayoon Ansari
Intelligent Optical systems, Torrance, CA, USA

Abstract:

Managing Stress Corrosion Cracking (SCC) damaged pipe has been a formidable challenge to the pipeline industry. Development of a practical solution for 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 an inspection technology wherein lasers are used for generation and detection of ultrasonic waves in the pipeline steel to be inspected. Unlike conventional ultrasonic testing, laser Ultrasonics has a large frequency bandwidth and a tiny (~0.5mm) footprint. These characteristics make it ideally suited for application as a depth sizing tool for closely-spaced cracks in a colony. It has been conclusively proved 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.

1. Introduction

Stress Corrosion Cracking is the phenomenon in metals where-in 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 (colony). In pipelines, 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 including USA, Canada, Russia, Saudi Arabia and South America. While the number of incidents attributed to SCC is less than those attributed to other threats to pipelines such as corrosion or mechanical damage, it constitutes a formidable challenge due to the following key reasons:

- No reliable and accurate in-line-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 evaluation of SCC, once found.
- No reliable and widely accepted tools exist that are capable of measuring the depth of these cracks accurately.

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. The work was partly funded by United States Department of Transportation (US DOT) and Pipeline Research Council International (PRCI).

2. Stress Corrosion Cracking

Stress Corrosion Cracking, as found in pipelines is classified into two major types based on the environment in which they are found to originate. They are:

1. High pH SCC
2. Near Neutral SCC

2.1 High pH SCC

Also known as ‘classical’ SCC, high pH SCC tends to occur at locations where the immediate environment of the pipe and 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. Also, it is 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 usually comprises of cracks that aligned in a direction parallel to the axis of the pipe and the colonies tend to conform to shape of the disbanded area where-in the electrolyte was trapped.

Figure 1: High pH SCC

2.2 Near Neutral SCC

This type of SCC is also known as low pH SCC because it is usually found to be associated with locations wherein the electrolyte found 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 disbondment of the coating leads to the entrapment of conducive electrolytes.

Near neutral SCC cracks are also primarily found to be oriented in a direction parallel to the axis of the pipe. But 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 2: Near Neutral SCC

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 to lead to a rupture.

2.4 Evaluation of SCC

While no generally accepted method for fitness for service evaluation of SCC exists, several models have been suggested and used for evaluating the impact of an SCC colony on the integrity of the pipeline. Most such methods have had limited validation using extensive testing.

The most commonly referred models in the industry comprise:
- API 579, section 9
- CorLas
- NG-18 In-Secant method
- Pipe axial flaw failure criterion

It is to be noted that all of these methods rely on the ability to measure the depth of the cracks within a SCC colony.

3. Detection and measurement of SCC

Currently, Magnetic Particle Inspection (MPI) is the most widely used non-destructive method used for detection of SCC. A magnetic field is applied onto the surface of the pipe by means of a yoke and powdered or liquid-suspended ferro-magnetic particles are introduced to the pipe surface. If there are any cracks present on the pipe surface, the ferro-magnetic particles tend to accumulate at the cracks.
In this way, the field-operatives can detect the presence of SCC. Furthermore, as the cracks are visible now, manual measurements of colony and crack dimensions (excluding depth) can be performed.

Figure 3: An SCC colony detected using MPI

Such measurements, as performed manually using rulers, include:
- SCC Colony location
- SCC colony dimensions

Further measurements of the individual crack length and mutual separation can be performed, but due to the sheer volume of cracks within a small area of pipe affected, these measurements are practically a best effort estimate. Recent efforts in the direction of automating the detection and measurement of these cracks and colonies have shown good success and are expected to reach commercial markets soon.

Fig 4: Sample results from SCC detection and mapping tool

3.1 Depth Measurement (sizing) of SCC
Various efforts have been made to measure SCC depth using Ultrasonics and electromagnetic methods with varying degrees of success. The physical characteristics of SCC make it exceptionally hard to measure using conventional Ultrasonic techniques. Specifically:

- **The irregular shape of the cracks**: 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.

- **Crack Colony**: SCC occurs in colonies wherein individual cracks are closely spaced in generally similar direction. This makes it hard to identify individual crack responses. Additionally, the couplant, needed for the sound to enter the material, infiltrates into the cracks, effectively making the crack invisible using ultrasound.

- **SCC within Corrosion**: SCC, sometimes, occurs within areas of general corrosion with highly irregular surface. This makes it harder for the transducers to couple with the pipe and for sound to travel through the pipe material.

Furthermore, efforts of implementing electromagnetic techniques for sizing of SCC have been generally unsuccessful in providing usable data due to the lack of resolution and quantifiably consistent accuracy. Attempts have also been made to use EMAT transducers with in-line-inspection tools with limited results. Technologies such as ACFM and ACPD have been tested on SCC with some success, but have failed to provide a comprehensive solution. Electromagnetic techniques have generally shown some promise in detection of SCC, but sizing has been a challenge due to the random geometries of cracks and their proximity within a cluster.

### 4. Laser Ultrasonics

Laser Ultrasonics is a modification of the conventional, transducer-based ultrasonic inspection. Conventional Ultrasound used peizo-electric crystals for generating sound. Electrical pulses, when introduced into these crystals, cause the crystal to expand or contract. The characteristics of these oscillations, and subsequently produced sound waves can be controlled by controlling the electric pulse and its energy.

In Laser Ultrasonics, the ultrasound is generated by using a pulse laser. When the laser beam incidents on the material to be inspected, it generates vibrations, or sound. This sound then travels through the material and gets reflected or refracted by the boundary of the material, as well as any defects or discontinuities that may be present in the material, just as in conventional ultrasound. These reflected and/or refracted vibrations are measured using another laser. In this manner, any of the conventional ultrasonic techniques can be applied using Laser Ultrasonics as well.

Figure 5: Basic Laser Ultrasonics setup
Laser Ultrasonics offers a number of unique features that conventional ultrasound does not. They are as:

- It is a non-contact technology and therefore doesn’t require the use of couplant for the introduction of sound into the material.
- It has an extremely small foot-print on the material (about 0.1 mm) and therefore, can be used to target a very small area.
- Laser Ultrasound has a much larger bandwidth than contact transducers.
- It induces a rich admixture of various types of waves into the material.
- Can operate in harsh environments such as high temperatures.

5. Development of a Laser Ultrasonic application for sizing SCC

In early 2005, Applus RTD initiated a joint industry project, ‘Parametric Study of Ultrasonic Techniques for Stress Corrosion Cracking’ with the objective of improving the understanding of how various ultrasonic inspection techniques would perform at sizing SCC.

To do so, Applus RTD utilized a finite-difference based simulation technique in-order to understand how sound interacts with the cracks as found in a stress corrosion colony, and to determine if any of the commonly used conventional ultrasonic techniques such as shear wave, time of flight diffraction (TOFD), crack tip diffraction, and phased array could be used reliably to determine the depth of the cracks as found in SCC.

The study revealed that while in some cases, one or more of the techniques may provide accurate depth measurements; the reliability of such measurements was very much a function of operator skill and experience as well as the distribution and characteristics of the cracks within a colony. The study also determined that TOFD was the most reliable and widely applicable technique for depth determination of cracks, if it could be ensured that the ultrasonic response would not be affected by the neighbouring cracks.
Figure 6: An illustration of the effect of a crack cluster on ultrasound

Laser Ultrasonics, owing to the extremely small foot-print, provided a means to effectively examine the cracks within a colony in isolation from its neighbouring cracks. A subsequent project, partly funded by PRCI and US DOT was initiated in April 2006 to develop a laser ultrasonics based application for sizing SCC. The project was performed by Applus RTD and Intelligent Optical Systems.

5.1 Identifying the most appropriate technique

At the onset of the project, the first objective was to identify the most appropriate inspection technique that would provide repeatable, reliable and accurate depth measurements. In order to do so, a model for simulating laser ultrasound generation was prepared and validated against analytical, as well as experimental results. Subsequently, various simulations and corresponding experiments were performed over a period of 12 months with an objective of identifying the best suited technique and the best suited system parameters for the purpose.

The results from the year 1 efforts conclusively proved that TOFD was the most appropriate method for sizing SCC using laser ultrasonics as well. Furthermore, we were able to verify that using laser ultrasonics could eliminate the masking or distorting effect of the neighbouring cracks by isolating it. At the end of year 1, we were able to define:

- The most appropriate technique
- Laser Ultrasonic parameters
- Coarse system requirements

5.2 Developing the tool

Year 2 of the project comprised of developing a prototype tool to implement the developed technology. For the purpose of the application, an eddy current based tool has been used to map SCC. Once a digital record of the SCC is available, the generation and detection lasers are guided along the cracks of interest that need to be sized. A demonstration of the prototype is expected soon.
5.3 Some results

One of the objectives for the project was to develop a system capable of sizing SCC with little or no variability due to operator skill. In order to do so, it was necessary to develop a sophisticated signal processing algorithm and software that could accommodate various different crack morphologies and provide accurate measurements. Furthermore, since near-neutral SCC is often found in association with some corrosion, the remaining wall thickness measurement was also required along with the crack depth profile.

It was determined that a B-scan representation of the data provided the most reliable means of identifying the desired signal. It also provided a better dataset for automated signal processing.

Figure 7: A B-scan of SCC crack as obtained by Laser UT

![B-scan representation of SCC crack](image)

As shown in the figure above, using a B-scan for data interpretation enables quick and easy identification of the crack, as well as provides an easy way to measure and validate the crack depth information.

Several such measurements were performed and data interpreted using the automated software tool. The data was then compared with the corresponding measurements as interpreted by an expert and showed very good agreement. By automating this process, the system becomes largely operator independent as well as facilitates integration of the Laser UT system into an automated tool.

Figure 8: crack profile as obtained
6. Conclusions

Managing SCC has been a challenge to the pipeline industry for decades with no widely accepted methods to locate, detect, measure or evaluate SCC. Measurement of the crack depths as found within a colony is a crucial step in developing the appropriate tools 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 limited success.

The efforts presented above have been able to successfully develop a technology capable of doing so by capitalizing on the unique features and capabilities that laser ultrasonics offers. The results prove that:

- Laser Ultrasonics can be reliably utilized to size SCC cracks
- The interpretation of such data can be automated to reduce operator variability
- Laser Ultrasonics offers a unique opportunity to develop a field-ready tool that could provide the data required for development, implementation and validation of a reliable fitness for service determination method.

In succession to this project, a follow up project to develop an integrated, field ready tool for measurement and evaluation of SCC is expected to begin shortly.