Microwave Inspection Development and Evaluation for Spoolable Reinforced Thermoplastic Pipe

Chantz Denowh[1], Robert Stakenborghs[2], Liang Yu[3]
[1]ADV Integrity, Inc.,[2] Advanced Microwave Imaging, [3]Baker Hughes

Pipeline Pigging and Integrity Management Conference

February 12-16, 2024

Organized by
Clarion Technical Conferences

https://doi.org/10.52202/072781-0086

https://doi.org/10.52202/072781-0086

Abstract

The use of spoolable composite pipe technologies in the onshore oil and gas industry has expanded significantly over the past decade. It is anticipated that interest will only continue to grow as oil and gas operators transition to transporting alternative fuels such as hydrogen and carbon dioxide. Currently, these technologies have been limited to non-regulated lines such as gathering lines or produced water transport, but the need is growing to expand into the high-pressure transmission pipelines. These lines will typically be in the 4-inch to 8-inch size range and rated up to 3,000 psig. There are several gaps in knowledge to address though before making this step. One gap is the need for viable inspection technologies that pipeline operators can for long-term integrity management.

This study works to address this gap by progressing the multifrequency microwave technology and evaluating its accuracy against simulated defects that commonly occur to spoolable composite pipes in the field. The phases of the study described in this paper include an initial calibration of the microwave technology to the pipe design, material types, and layer depths. Following calibration, an open inspection was completed on pipes with known defect location, size, and depth. This information was shared with the microwave vendor to improve sizing and location accuracy of equipment and software. Additional pipes with similar defects were then used for a closed inspection to evaluate the technology's ability to accurately locate and size unknown defects. The pipe used in this study was nominal 4-inch with a nominal pressure rating of 1,500 psig.

The last phase of the study included inspection of pipe samples with simulated damage that commonly occurs in the field. Examples of recreated damage include pipe ovalization, overbending (kinking), and over-tensioning. This damage was recreated in a laboratory setting. The damaged pipes were subjected to destructive testing following the inspection (test results not included in this paper). Results and findings from each of the above phases are described in this paper including an evaluation of the location and sizing accuracy. Inspection of the simulated damage is discussed and compared to results of the destructive testing where damage indicated the presence of damage in the pipe reinforcement.

Introduction

The use of spoolable reinforced thermoplastic pipe (RTP) in the onshore oil and gas industry has many advantages over conventional carbon steel pipelines including enhanced corrosion resistance, ease of installation, and a lower carbon footprint to manufacture. Spoolable RTP use has expanded significantly over the past decade and will play an important role in the transition to transporting alternative fuels such as hydrogen and carbon dioxide in Carbon Capture Storage (CCS) where carbon steel pipelines suffer from hydrogen cracking and corrosion. To date, most RTP installations have been in non-regulated spaces such as enhanced oil recovery, produced water transport and gathering lines, but pipeline operators and regulators are working towards their use in regulated transmission pipelines.

https://doi.org/10.52202/072781-0086

One of the main barriers to using RTP technologies in regulated applications is the ability to continually evaluate the pipe's integrity and remaining life, also known as an integrity management program. There are several gaps in knowledge to address in RTP integrity management including the need for viable inspection technologies. Inspection of RTP pipes for onshore use is challenging because most RTPs are unbonded multi-layer pipes constructed with different materials and with air gaps between adjacent layers. The unbonded layers are a challenge for commonly used acoustic technologies such as ultrasonic and acoustic emissions which cannot penetrate the air gaps between layers. A potential alternative to ultrasonic inspection though is multifrequency microwave technology.

Microwave technology is based on microwave signal reflecting on the material's complex permittivity. In other words, the reflected signal will be different for the RTP layers that have different dielectric properties. It is not affected by air gaps between the unbonded RTP layers. This makes it an appealing candidate for inspection of RTPs. The remainder of this paper describes a study completed to evaluate and advance the use of microwave inspection on unbonded fiberglass tape RTPs. This included four phases of work: baseline inspection, open inspection, blind inspection, and inspection/characterization of recreated field defects. The rationale and results for each phase are described in the sections that follow. This paper also includes a description of the microwave inspection and RTP technologies and overall observations from the inspection program.

Microwave Inspection Technology

Microwave inspection of composites operates on the principle that when a non-magnetic material is exposed to electro-magnetic radiation in the microwave frequency range, it will reflect a microwave signal back based on the material's complex permittivity. That is, the reflected signal will be different for materials that have different dielectric properties, such as dielectric constant or loss tangent. This simply means that the Material Under Test (MUT) interacts uniquely with microwave energy, and quite often that interaction changes with the microwave frequency.

This principle has been used for testing material to determine its electromagnetic properties or complex permittivity for many years. The reflected signal is typically plotted versus frequency and the MUT's complex permittivity is derived from these results. Typically, a microwave Vector Network Analyzer, or VNA, is used in the laboratory for this type of investigation. Inspection of complex composite structures and systems, such as RTP and other composites with more than one layer of non-metallic material, can be completed with this technology.

Figure 1 provides an example output from the microwave inspections performed in this study. In this figure, we are looking at 4 individual images. The upper left hand image is the A scan, the bottom left image is the B horizontal image, the lower right hand image is the C scan and the upper left and far right images are data lines associated with the C scan image. The C scan image is the top-down image at the depth (TOF) in the A

https://doi.org/10.52202/072781-0086

Scan. The B Horizontal shows the cross section from the OD of the pipe (Left side) to the ID of the pipe (Right side) in the X axis and across the entire width of the C scan image in the Y axis. In this case, we have located three small delaminations in the cross section at two depths within the thickness of the pipe, shown in the circled areas.

RTP Technology Description

Spoolable RTPs for onshore are typically 4-inch to 8-inch nominal diameter and rated up to 3,000 psig and 180°F. Higher pressure and temperature variations exist. These pipes are manufactured at a plant and spooled onto reels for transportation by truck, rail car or tractor trailer (spoolable RTP). RTPs consist of three layers.

- A thermoplastic liner that acts as a corrosion resistant internal fluid barrier. These can be either single wall or multi-layer coextruded for additional chemical resistance. Common materials included high density polyethene (HDPE), high density polyethene raised temperature (PERT), nylon, polyphenylene sulfide (PPS) and polyvinylidene fluoride (PVDF).

- Reinforcement layers that provide the structural integrity of the pipe. The layers are either steel (wire or strip) or nonmetallic (aramid, fiberglass, carbon fiber etc.). The reinforcement materials can be dry (no matrix) fibers, yarns, or braids, or embedded in a thermoplastic matrix such as fiberglass tapes and aramid fiber tapes. These layers are wound helically around the thermoplastic liner typically at 55° angle.

- An outer cover that protects the reinforcement layers from abrasion, impact, UV exposure, and prevents water ingress.

The RTP technology used in this study was a 4-inch nominal diameter pipe rated to 1,500 psi and 180°F. It had an HDPE liner and multiple layers of fiberglass tape as reinforcement. The pipe layers and reinforcement tapes were not bonded.

Approach and Methodology

The methodology for the microwave inspections included four (4) phases listed below.

- Baseline inspection
- Open inspection
- Closed (blind) inspection
- Inspection of recreated damage

 https://doi.org/10.52202/072781-0086

The purpose of the baseline inspection was to determine if the microwave technology was viable for unbonded RTP. In other words, was the technology capable of distinguishing the different layers of unbonded RTPs. This phase included pristine pipe. A secondary purpose was also to "calibrate" the microwave technology to the pipe construction. Calibrate is used in a general sense as in a preliminary scan to determine the microwave response and pipe composition (layer dimensions). This baseline pristine pipe scan also provides a reference for assessment of future indications.

Following this baseline, the next step was an "open inspection" of artificially created defects. In this context, "open" indicates that the defects' location and size were provided to the microwave vendor. The purpose of the open inspection was to determine the limitations of the microwave technology in terms of detection and measuring defect size. All defects were artificially created in either the reinforcement layer or inner liner.

A "closed" inspection followed successful completion of the "open" inspection which had similar defects (size and location), but details on the defects were not provided to the microwave vendor prior to the inspection. This was the first test of the technology to determine if it could accurately detect and measure the defects with no prior information on the defects. Defect details (size/location) were provided to the microwave vendor following the initial closed inspection to improve future results.

The last phase of the microwave evaluation was inspection of real-world defects recreated in a lab setting. These defects included damage that commonly occurs during construction and installation of the pipe (pipe accessible for inspection). Defects for this phase were created in a laboratory using test fixtures to damage full-scale pipe samples. The defects from the open/closed inspections were created with hand tools and were not realistic.

Defects must be successfully characterized before its effect on the pipe's integrity can be assessed. Characterization requires a signal response from actual defects for comparison. Currently, these actual defects do not exist. It was not expected that this initial work would advance microwave technology to field-ready, but it does provide a starting point to guide future work and investment in the technology to reach the next step in the technology readiness ladder.

Baseline Inspections

A baseline microwave scan was performed on a "pristine" pipe sample, which for this study was an unbonded glass tape reinforced RTP technology. A pipe section 36-inch in length was scanned, and the data processed into three (3) increasing levels of penetration into the pipe wall. Scan results are presented as the power of the reflected signal, with different layers indicated as different levels of reflected power due to the dielectric differences in the layer materials.

Figure 2 illustrates these results at three different depths into the pipe. The horizontal bands that are present in the first two images correspond to the fiberglass reinforcement. Their lack of complete coverage of the

https://doi.org/10.52202/072781-0086

scanned area can be attributed to the fiberglass tapes being helically wrapped around the pipe, which would create an uneven distribution when compared to a homogenous material. This is further illustrated by the inner liner showing a relatively homogeneous reflection. This reading is in line with what would be expected from previous HDPE polymer inspections.

These results indicate that microwave technology can distinguish between different layers of the fiberglass tape reinforced pipe and identify potential features within the pipe's wall. This inspection also provided a baseline for the pristine pipe.

Open Inspections

After completing the baseline inspection, the next step was to determine whether this the microwave technology could detect defects of known size and depth. Simple circular wall loss defects were machined into two test samples. The first sample had ½-inch and 1-inch diameter circular wall loss defects machined into the inner liner. The second sample had the same diameter defects machined into the reinforcement layer.

The inner liner defects were created by drilling a through-hole through the exterior of the spool and drilling a defect into the inner diameter of the pipe wall (through-hole and liner wall loss 180° apart). To fabricate the defects for the reinforcement layer spool, the outer cover of the pipe was removed with two longitudinal cuts 180° apart to expose the fiberglass reinforcement. Holes of varying depth and size were then drilled into the reinforcement layer. The outer cover was replaced on the pipe and fixed with tape.

Figure 3 illustrates the microwave scans of the ½-inch inner liner defects. As shown in the figure, the inner liner defects were consistently identified in the scans. An interesting result from liner scans was the through-hole 180° from the wall loss defect was also visible. This is the halo that appears around each wall loss defect in Figure 3. Figure 4 provides similar results for the reinforcement layer defects (includes both ½-inch and 1-inch diameter defects). Several of these defects were also sized by the microwave vendor. The results of the open inspection clearly indicated the microwave technology was capable of detecting defects in different layers of an RTP. Note though that the location of the defects was provided to the microwave vendor. In the next phase, the defect location and geometry were hidden from the vendor.

Blind Inspections

Two test spools were fabricated for the blind inspection. The two spools included a total of nine (9) features in the reinforcement layer and one "false-positive" feature. Table 1 summarizes the closed spool features (identified as CS-1 through CS-9).

 https://doi.org/10.52202/072781-0086

Defects CS-1 through CS-4 were distributed randomly along the pipe length (approximately 4-feet in length). This required removing the entire outer cover which caused some disarrangement of the reinforcement tapes. To prevent this disarrangement in the second spool, five (5) 4-inch x 4-inch windows were removed from the outer cover. These windows identified the location of the defect, but not the shape/size. One of the five windows did not include any defect in the reinforcement layer (false positive defect). The outer cover was then replaced and fixed in place with clamps. For defects CS-5 through CS-9, the microwave vendor was now aware of the defect locations so there was more emphasis on classifying and sizing the defects.

Since the vendor had approximately 4-feet to inspect for the spool containing defects CS-1 through CS-4, the vendor segmented the sample into four (4) sections. Due to sectioning the pipe, parts of several defects were identified in more than one scan. Figure 5 illustrates one section of the pipe scan that includes defects CS-1 and CS-2. Both defects are visible in the microwave scan output. Interesting is that the hole cluster has a similar indication as the wall loss feature even though the volume removal of the wall loss is much higher than the hole cluster. In other words, the hole cluster and rectangle are both shown as general indications when they are very different defects. Figure 6 includes defects CS-3 and CS-4. Only the corner of the trapezoidal cut was visible in Figure 6. The scan also identified another indication that was not artificially created. This indication could be due to the tape arrangement resulting from removal of the outer cover. The vertical cut (defect CS-4) can be seen in Figure 6.

Like the first spool, the second closed spool was divided into two (2) sections. The first section, seen in Figure 7, contained defects CS-6 and CS-9, while the second section, seen in Figure 8, contained defects CS-5, CS-7, and CS-8. The axial indications visible in all the scans are clamps that were used to keep the removed sections of the outer layer secure. All the defects were detected by the inspection vendor, except for CS-5, which is to be expected as the reinforcement layer at CS-5 was undamaged (no defect). Defect CS-6 and CS-7 showed up in the scan as general indications of damage but are not clearly defined. The scans for CS-8 and CS-9 not only indicate that there is a defect, but also clearly define the shape of the defect.

Recreated Damage Inspections

The defects up to this point of the study have been wall-loss machined into the inner liner or reinforcement layer. This is not representative of actual defects and damage that will occur to RTP pipes during installation or operation. Several defects were simulated in a laboratory environment on full-scale samples to represent damage that can occur in the field. These include defects such as exceeding the pipe minimum bend radius (kinking), ovalization/crushing of the pipe, 3rd party damage, liner collapse, and excessive tension loads. The inspection results of the kink defect are highlighted in Figure 9 and Figure 10. To recreate the kink defect, the minimum bend radius was exceeded by 50% while the pipe was unpressurized.

https://doi.org/10.52202/072781-0086

Figure 9 was post processed to show the intrados of the kink defect overlaid with the microwave inspection results. The circle drawn on the pipe sample indicates the location where the pipe kinked. As shown by the inspection results, there is a clear indication in the reinforcement layers where the kink occurred. This is further demonstrated in Figure 10 which provides another method of viewing the microwave inspection results. In Figure 10, the three layers of the pipe are clearly visible including the outer/inner HDPE layers and the reinforcement layers. There is clearly an indication at the blue dashed line indicative of the reinforcement layers pulling away from the outer cover (disbondment). The shape of this defect also aligns with expected behavior of the reinforcement layers at the intrados of a kink as the layers would be pushed toward the inner HDPE liner.

Observations and Closing Comments

The following observations can be made after completion of the four microwave inspection phases of this study:

- Microwave technology was successfully used to detect defects and damages in unbonded fiberglass tape reinforced thermoplastic pipes. Note that there are many other reinforcement types that may or may not be suitable for microwave inspection. For example, conductive materials (steel / carbon fiber) block microwaves and would not be inspectable.

- The microwave inspection distinguished between the different composite pipe layers including defects present in the reinforcement and inner liner layers.

- In the closed inspections, the technology was able to identify defects when the locations were unknown. There are limitations though in the detection resolution. Results were favorable for large types of wall loss, but the scans could not distinguish small, clustered defects vs large wall loss.

- The microwave technology was also able to detect a kink damage that was representative of damage from the field. The authors expect similar results for the other damage mechanisms simulated as part of this study for defects that cause layer deformation.

- The microwave technology successfully determined the shape/size of fabricated wall-loss defects and detected representative field damages created in lab, but it was not capable of detecting subtle changes in the material properties of the layers due to long-term use and aging (only suitable for deformation of layers).

https://doi.org/10.52202/072781-0086

In closing, this study has demonstrated that microwave inspection technology is capable of detecting and sizing defects in unbonded glass tape reinforced thermoplastic pipes. This includes the capability to detect wall loss features through multiple layers of material and air gaps between the layers. It was also demonstrated that it can detect defects in RTPs caused by representative field damage. Additional work is needed though in several areas before the technology is field deployable for RTPs. This includes additional work on detecting and sizing different defects that occur in the field. Detection is only the first step though. Additional research is required to characterize and assess the effect defects have on long and short-term pressure integrity. Only then can that information be incorporated into future integrity management programs and enable RTPs to be used in regulated pipelines.

https://doi.org/10.52202/072781-0086

Annex A

Tables and Figures

Table 1: Closed spool defect descriptions

Defect	Descri tion	ial ocation

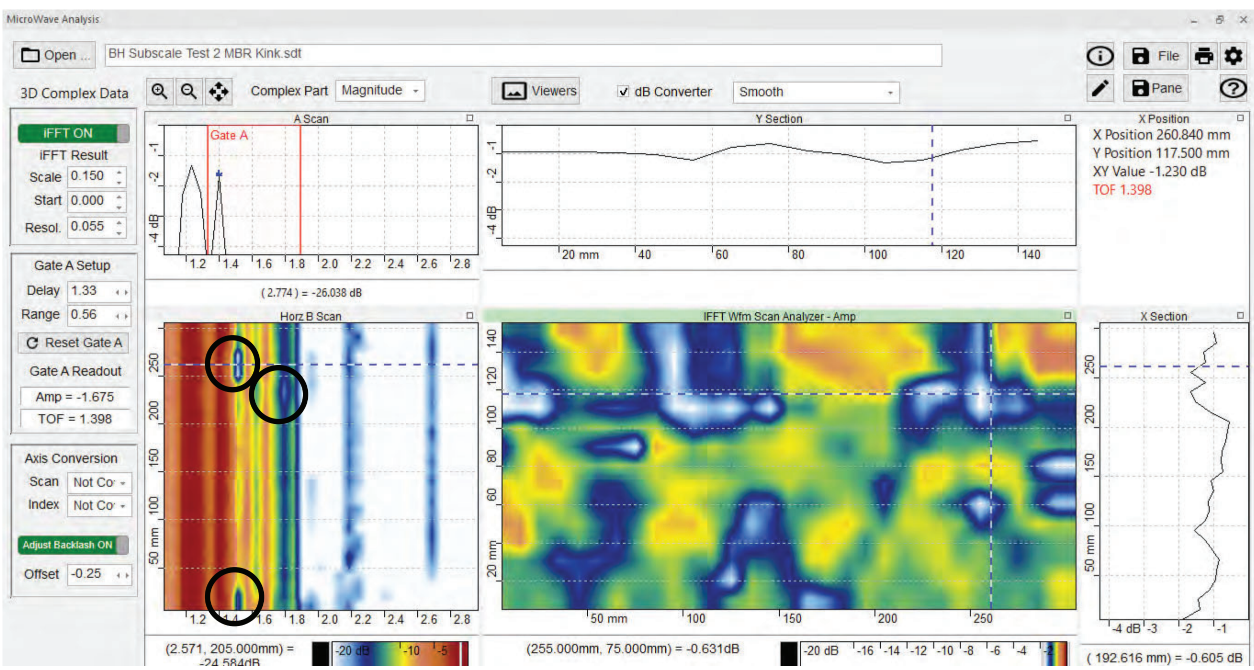

Figure 1: Typical microwave data analysis software screen

https://doi.org/10.52202/072781-0086

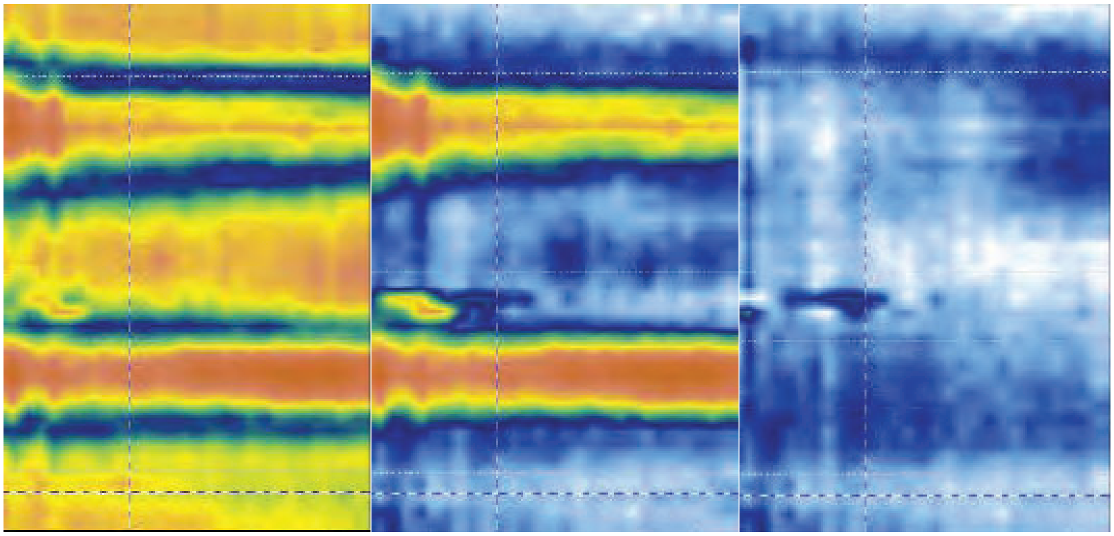

Figure 2: Baseline microwave imaging results (left: top of reinforcement layers, middle: lower reinforcement layers, right: inner liner)

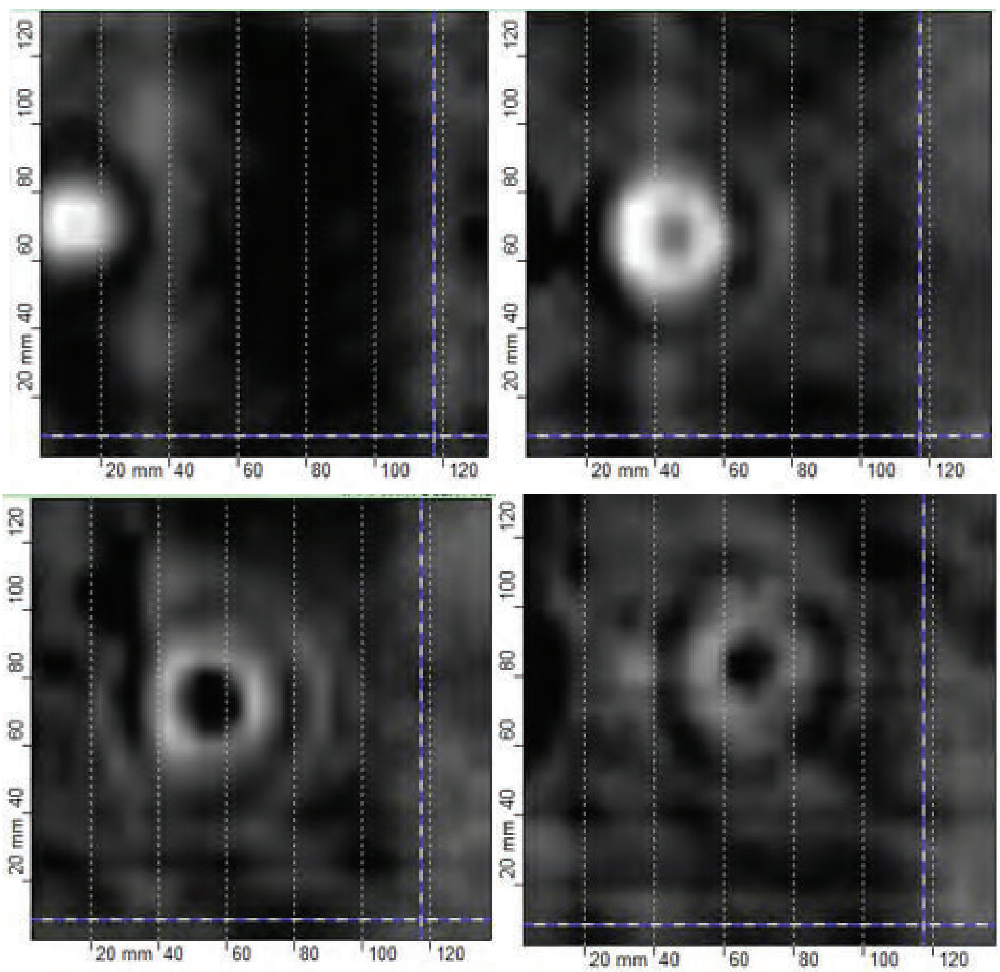

Figure 3: Inner liner open spool ½-in defect microwave scans of varying depth

https://doi.org/10.52202/072781-0086

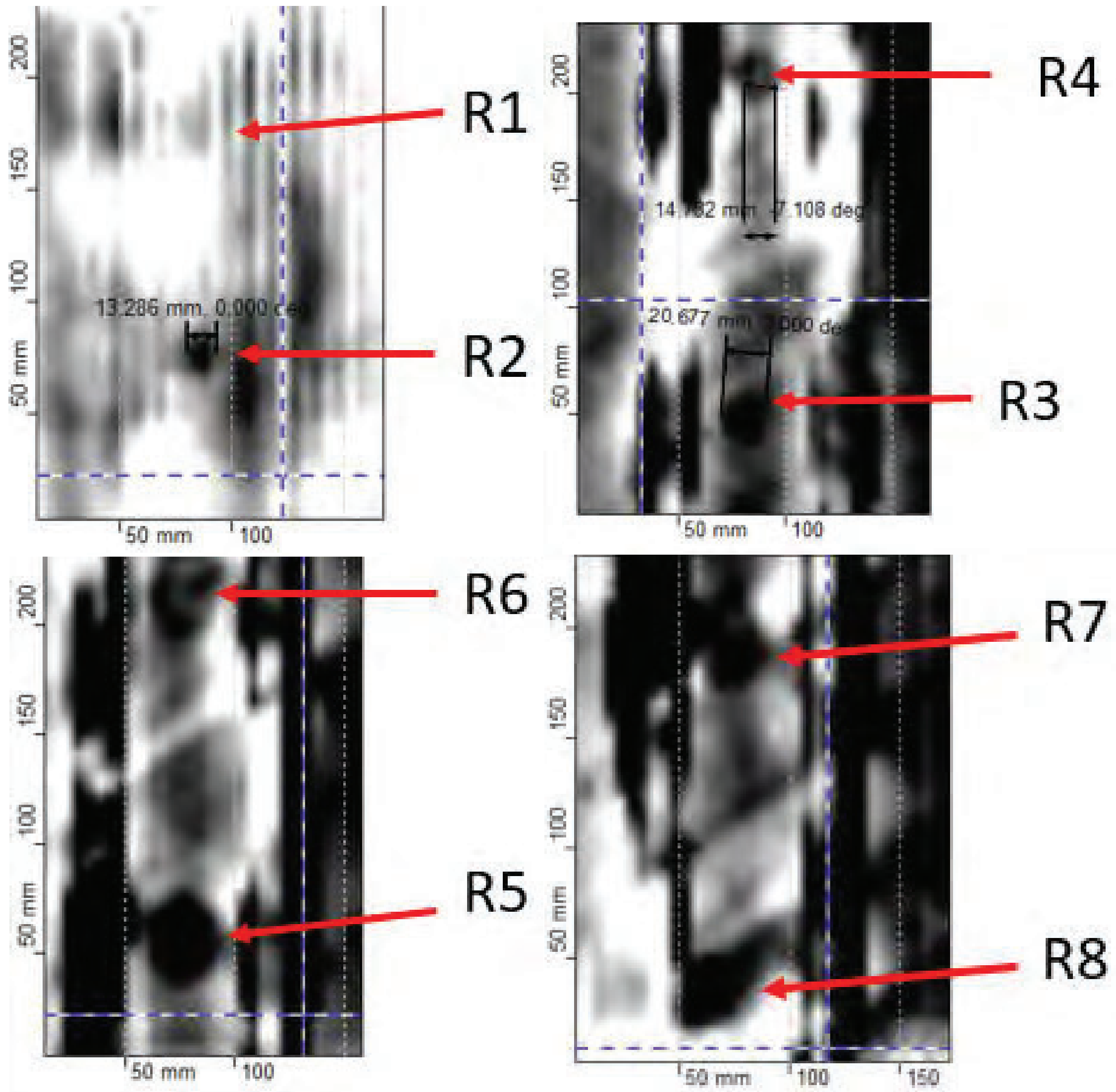

Figure 4: Reinforcement layer open spool defect microwave scans of varying depth

 https://doi.org/10.52202/072781-0086

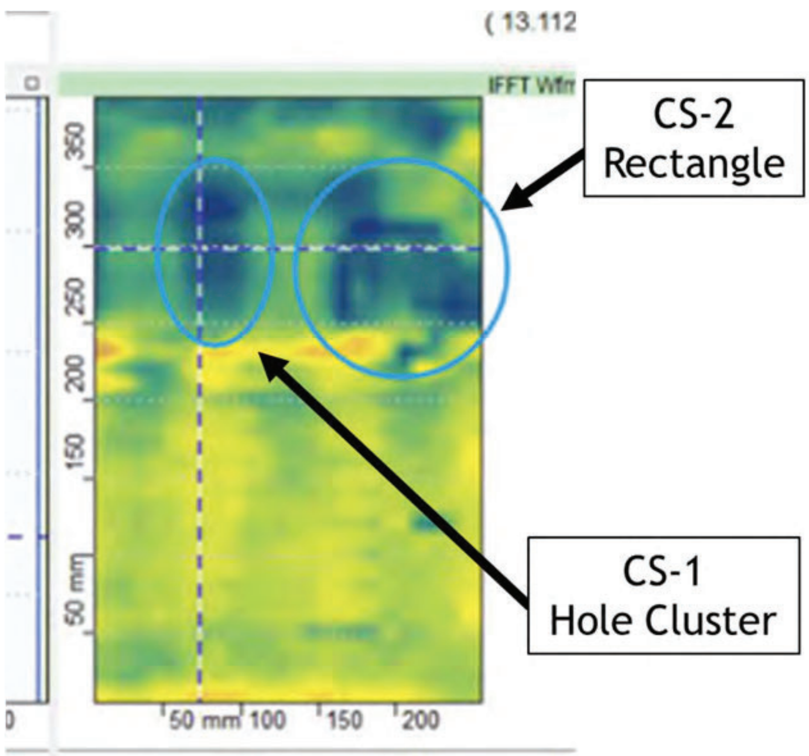

Figure 5: Microwave scan output of defects CS-1 and CS-2

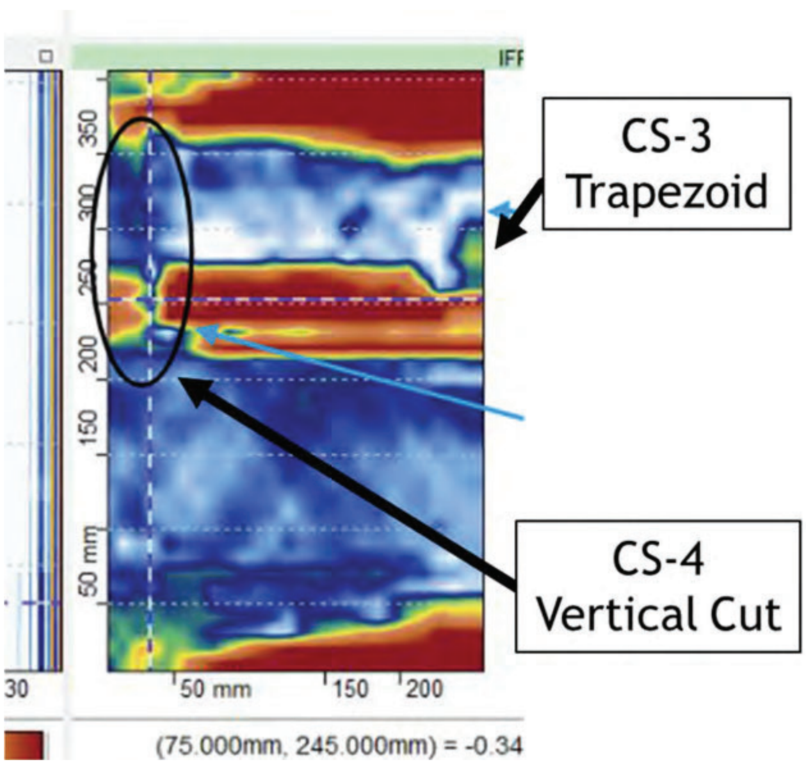

Figure 6: Microwave scan output of defects CS-3 (only part of the defect was indicated in this scan)

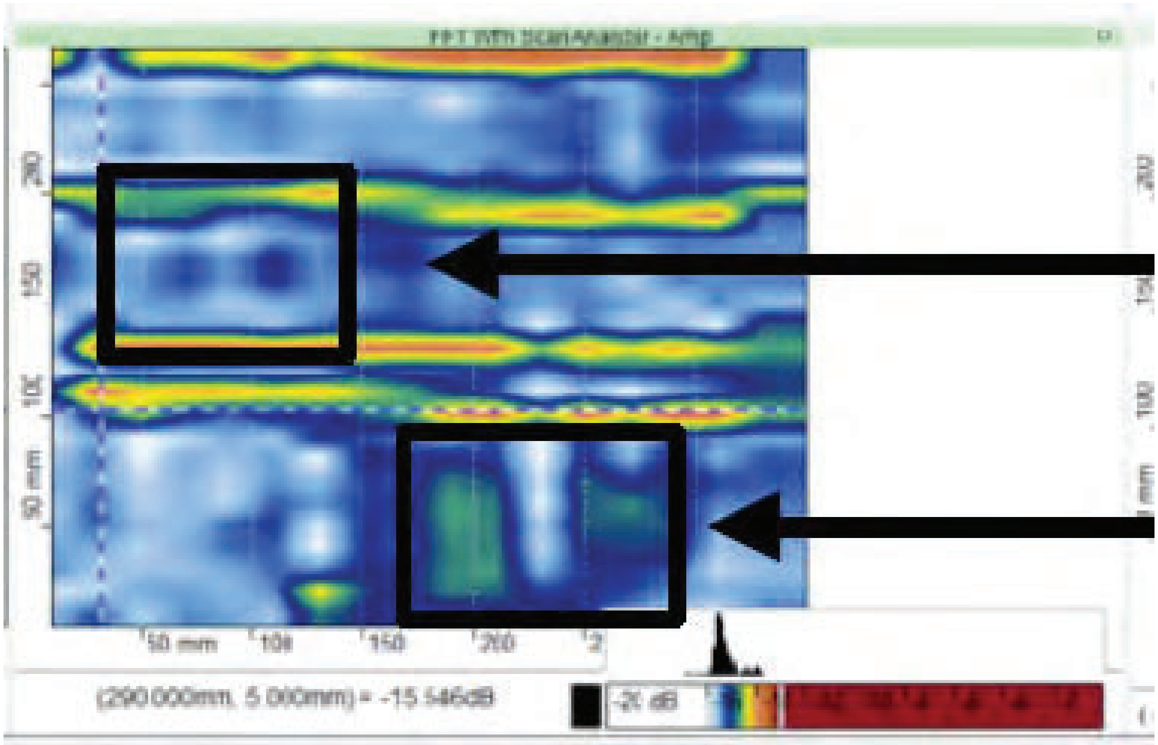

Figure 7: Microwave scan output of defects CS-6 (bottom right) and CS-9 (top left)

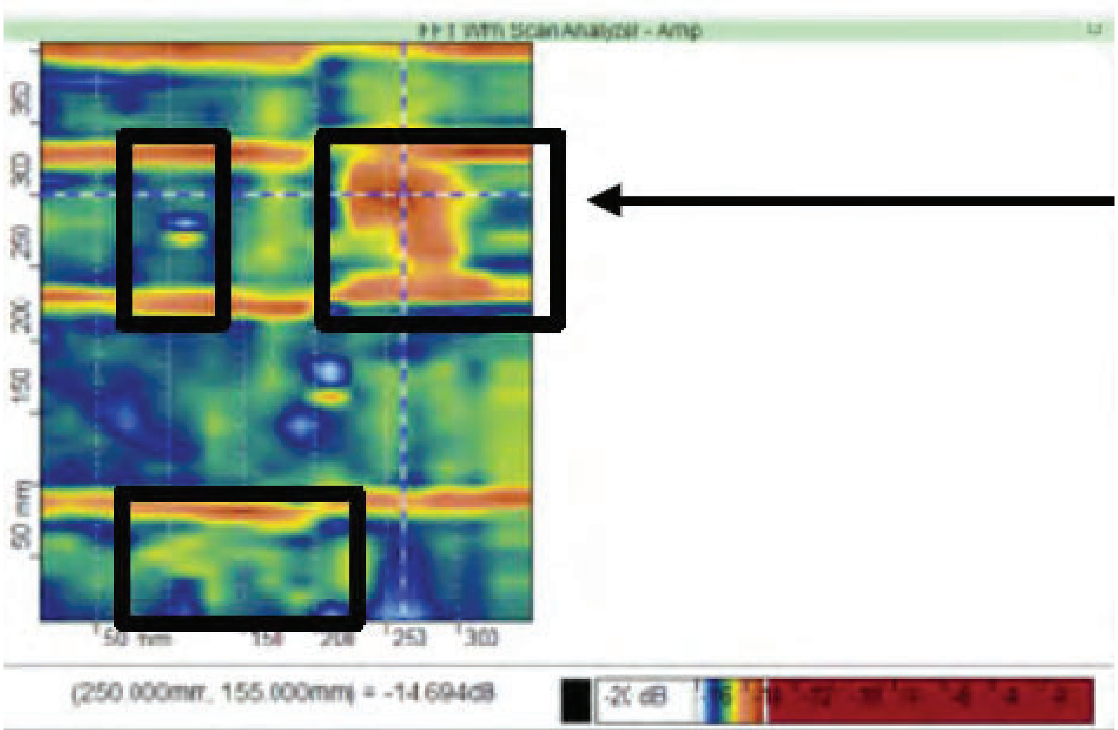

Figure 8: Microwave scan output of defects CS-5 (top left), CS-7 (bottom left) and CS-8 (top right)

 https://doi.org/10.52202/072781-0086

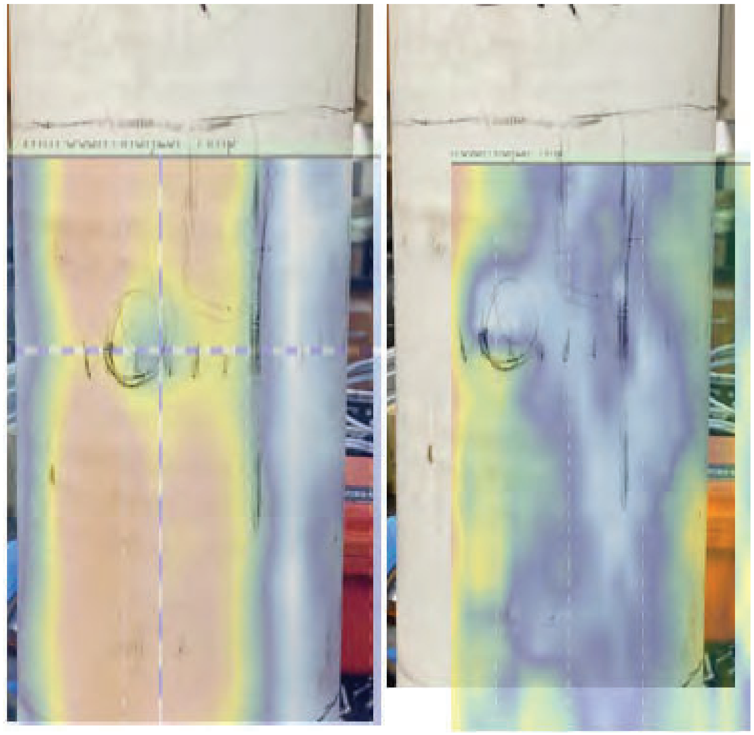

Figure 9: Intrados of kink defect pipe sample overlaid with microwave inspection results

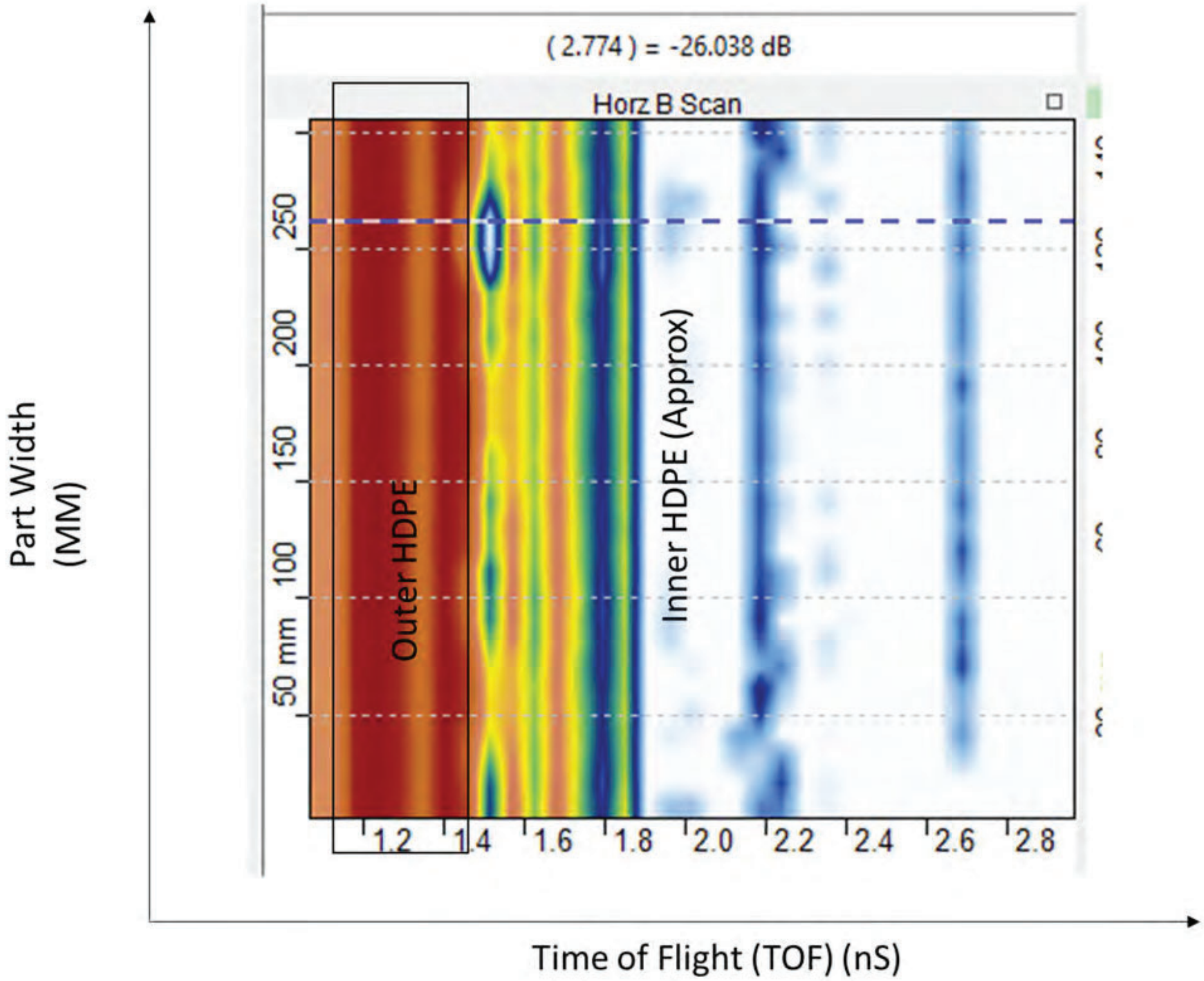

Figure 10: Kink defect microwave inspection output showing the different layers of the RTP and an area with disbondment between the outer cover and reinforcement layers

https://doi.org/10.52202/072781-0086