Omni-directional Ultrasonic Inspection for Enhanced Defect Detection in Mill Rolls

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ABSTRACT

Rolls used for hot and cold rolling of steel strips are subject to wear and severe mechanical and thermal stresses that lead to surface cracks and surface annealing or "bruises", and sometimes internal defects. Traditionally, roll inspection systems have used Eddy Current sensors for both crack and bruise detection due to the simplicity and low cost of the instrumentation and sensors. Increased requirements from mills and final customers has pushed manufacturers to add Ultrasonic Testing (UT) sensors for detection of internal defects, and more recently for detection of surface defects.

This paper covers our experience of three years benchmarking Eddy Current and Ultrasonic Testing techniques on rolls of different chemistries with natural and artificial defects.

One finding of this work is that Ultrasonic Testing provides far superior results for detection of cracks and discontinuities, while Eddy Current is best used for detection of "bruises" on the surface of the roll. Another important finding is that while most defects have an axial component and are best detected when sending sound around the circumference, some of them are more visible when inspecting across the circumference of the roll. Arguably the most interesting finding is that many surface defects are completely undetectable ultrasonically when inspecting from one side while they reflect ultrasound strongly when approached from the other side.

The paper explains the final configuration that proved to be ideal for inspection of mill rolls to guarantee detection of all defects relevant to rolling mills and roll manufacturers.

INTRODUCTION

In the fall of 2002, Innerspec introduced and patented an Ultrasonic Testing (UT) inspection system for surface inspection of mill rolls. This novel approach was designed to overcome known limitations of Eddy Current (EC) systems such as:

- False readings due to residual magnetism in the roll.
- Variability due to roll material chemistry.
- Bad readings due to lift-off variations.
- Very limited sensitivity to fire cracks and other shallow surface defects.
- No sensitivity to sub-surface defects.

This first full UT system from Innerspec (Rollmate G1) had only three ultrasonic channels and limited inspection capabilities, but the UT technique was proven very effective, and several mills adopted it with great success. Following Innerspec's lead, other manufacturers started offering some UT inspection for internal and surface inspection on their high-end systems, but the industry as a whole still relies heavily on EC systems for flaw detection in mill rolls. An important unintended consequence of this reliance is that many users will not try new rolls -or even change suppliers- for fear of destabilizing a fragile inspection process that is known to be finicky, and requires careful calibration for different materials and inspection conditions.

Fig.1. Rollmate G1

In 2014, Whemco Steel Castings Inc., a leader in mill roll manufacturing and service, approached Innerspec Technologies to expand the original Rollmate design with more capabilities. The objectives stated by Whemco for this new design were:

- It should consistently detect all defects that could be present in a roll, surface and internal, whether they happen during manufacture or during operation.
- It should be able to inspect rolls of any chemistry, forged and cast, and provide consistent and reliable results in a mill environment.
- It should be designed to be used by mill personnel without special knowledge and training in non-destructive testing.

TECHNIQUE AND EQUIPMENT

After discussions with Whemco and several rolling mill operators, the defects of interest were divided in five categories:

1) Surface defects on the first 2mm of the surface of the roll that appeared during hot and cold rolling. As the roll hardens, these cracks can be generated in any orientation and be as shallow as 0.1mm in depth and 2mm in length.
2) Near-surface defects from 2-60mm that could include cracking and internal porosity created during the manufacturing process.
3) Core-shell disbond and laminations on cast rolls. In addition to detection of these defects, there was also an interest in measuring the thickness of the shell to estimate its remaining life.
4) Internal defects from 60mm to the centre of the roll that have been created during the manufacturing process and can eventually propagate to the surface and cause spalls.
5) Soft-spots or "bruises" caused by annealing of the surface during cold mill rolling. On EC systems these defects are detected at the same time as the surface cracks. Only relevant for cold mills.

During these meetings we benchmarked all commercial systems and conducted multiple tests on natural and artificial defects using with Eddy Current, Eddy Current Arrays, and Ultrasonic Instruments. The results from these tests was that in order to detect all the defects of interest, the system should include the following:

- Ultrasonic Surface Inspection in all four directions. Ultrasonic testing proved to be far more sensitive and reliable than Eddy Current on small defects and rolls of different alloys, but it was also very susceptible to defect orientation. A key finding of our tests is that in order to have complete detection assurance, the final system should include four ultrasonic sensors inspecting axially (clockwise and counterclockwise) and circumferentially (left and right).
- Ultrasonic near-surface Inspection in all four directions. As with surface inspections, the response of a natural defect varied greatly with the orientation, and the best solution included inspection with four sensors in all orientations. Near-surface inspection not only detected non-visible defects, but it was especially useful to determine the depth of surface breaking defects. This capability was very useful to determine the estimated amount of time required to remove a crack, and whether it would be better to scrap the roll or remove a thicker layer using a lathe.
- Normal inspection (0º) with near and deep focus. This technique is very useful for detecting internal roll defects created during manufacturing, and to measure remaining shell thickness and find core-shell disbond.
- EC/electromagnetic sensors for bruise detection. While Eddy Current performed much worse than ultrasonic sensors for detection of cracks, it is still a good tool for detection of soft-spots by measuring the magnetic permeability of the material. However, instead of using EC sensors for both crack and bruise detection, the electromagnetic sensors on Rollmate G3 would be designed, sized, and tuned specifically for detection of bruises. The instrumentation and custom sensors designed to measure magnetic permeability are easier to calibrate, and tolerate much greater variability in chemistry and magnetism without triggering false positives.

On the final system all the channels mentioned above were duplicated to provide an inspection swath of approximately 20mm per pass, which coupled with an inspection speed of 2m/s it permits inspecting a 1000mm D x 1900mm L roll in 2.5 minutes. The complete system includes 18 UT channels for detection of cracks and discontinuities, and 2 EC channels for detection of bruises. All UT channels are standard in Rollmate G3 since they are required for crack detection, while the EC channels are optional for hot mill rolls were bruises are not typically present.

For the user interface, we conducted interviews with operators and adopted all views that they liked from existing systems, and added others. The final system includes the following:

- Four different views.:
  - Oscilloscope (A-Scan in UT). The X axis shows time and Y amplitude. It permits looking at individual defects or features and analyze the defect response. Mainly used to troubleshoot the equipment and for advanced defect analysis.
  - “Spread out roll” map (C-Scan in UT) in which the X axis shows the axial dimension of the roll, Y the circumference, and the severity of the defects are represented with color (user configurable).
  - Bar graph. The X axis shows the axial dimension of the roll and Y the maximum amplitude of any defect around the circumference at a particular axial point.
  - 3D view. Full representation of the roll that permits turning, rotating, and selecting cross sections to visualize the defects within the roll.
- Ability to turn on and off different tests. All the tests (surface, sub-surface, deep, bruise) are color coded and can be visualized individually or together.

	Direction of Ultrasound	Detection	Color Code
Surface Axial	Perpendicular to roll axis	0-2mm	Yellow
Surface Circumferential	Perpendicular to roll circumference	0-2mm	Yellow
Sub-surface Axial	Perpendicular to roll axis	2-60mm	Orange
Sub-surface Circumferential	Perpendicular to roll circumference	2-60mm	Orange
Core-Shell Disbond	Normal to roll surface	1-100mm (variable)	Pink
Deep Inspection	Normal to roll surface	1-900mm	Red
Bruises	NA	Surface	Purple
Core-Shell Thickness	Normal to roll surface	1-100mm	Green

- Reporting.
    - Full reports exportable to PDF for every inspection.
    - Roll history to track previous test results for each roll as it returns to the roll shop for service.
- Web-browser interface. For this application, Innerspec introduced NDT-Web™, the first user interface in the Non-destructive Testing industry that provides full access to the equipment in real time through a web browser. This technology includes some unique capabilities:
    - The system broadcasts its own wireless signal for simple access from any device (tablet, phone) using a regular browser and IP address (no client software needed). Alternatively, users can connect to the equipment using an external video monitor or Ethernet port.
    - Permits easy customization of user controls and display without affecting the operation of the equipment.
    - Includes built-in features to connect to NDT-Link™, Innerspec's web portal for support, spares purchasing, and automated/remote operation and process control tools.

For the inspection head, the main challenge was to integrate all 20 inspection channels in a compact package that could fit on different grinder models. After several iterations and tests, the final configuration includes:

- Modular design with four different components; instrumentation, inspection head, actuator, and PLC and couplant management. These modules can be re-arranged to fit the customer's requirements and the grinder model.

Fig. 2. Free-Standing on Grinder Platform

Fig. 3. Overhead Mounting

- Maintenance-free sensor head. Innerspec used a proprietary water column design that keeps the sensors protected and clean, and reduces couplant consumption by 90% when compared to conventional models. The head also includes six proximity sensors that keep the inspection head assembly in the proper position throughout the scan, and protect against potential crashes with adjacent equipment. When the automated scan sequence begins, the system deploys the sensor assembly and will rapidly retract it if anything comes near its path.

CALIBRATION

A calibration procedure was developed to automatically verify the correct functionality of all UT and EC channels. This procedure is fully automated and design to facilitate troubleshooting if needed. Figures 4 and 5 show the calibration blocks specific to each technique.

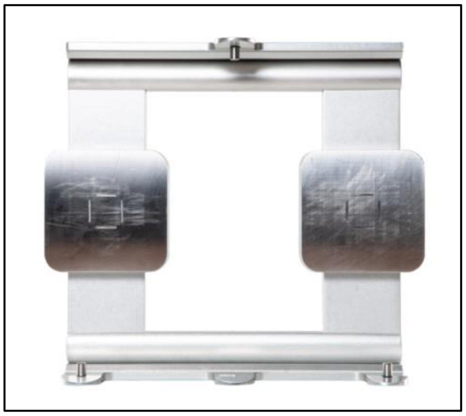

Fig. 4. Calibration block UT

Fig. 5. Calibration block EC

Once a calibration block is attached to the sensor head, all the channels are tested following an automated sequence. Results out of specification will be shown as “Failed” so the operator can troubleshoot accordingly. Figure 6 shows a successful calibration test for the UT channels.

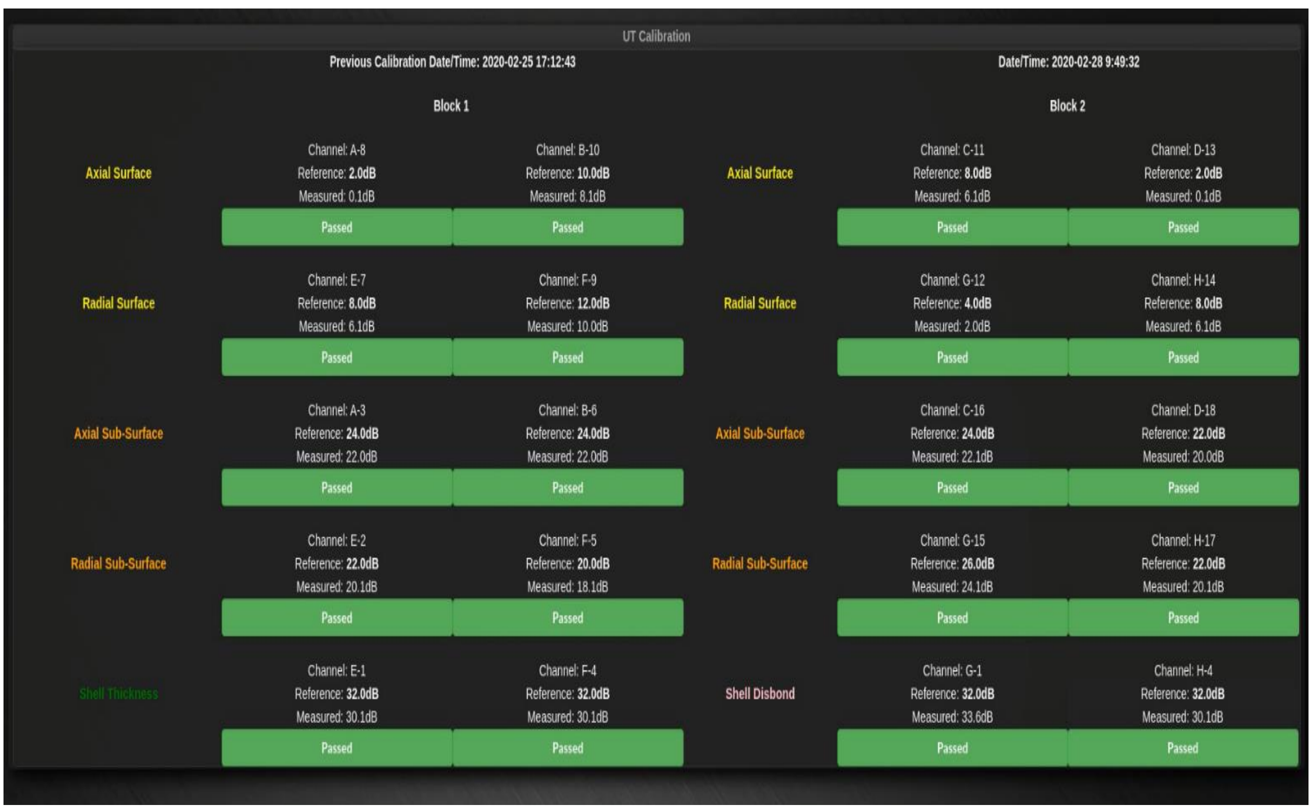

Fig. 6. Calibration window UT

RESULTS

Lab Tests

Preliminary tests for this new NDT design were completed on a partial roll sample provided to Innerspec by Whemco and other calibration specimens. This roll sample had a number of natural and machined defects.

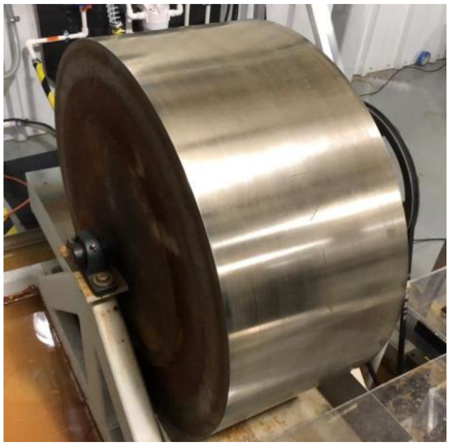

Fig. 7. Whemco Roll Sample

Defect	Type	Location	Size
Fire cracks	Natural	Surface & Subsurface	Various patches
Side Drilled hole	Machined	Below surface - 60mm	1.5mm DIA
Core-Shell Disbond	Natural	Roll core	Various patches
Notch – Longitudinal	Machined (EDM)	Surface	0.3mm deep x 25mm long
Notch – Circumferential	Machined (EDM)	Surface	0.3mm deep x 25mm long
Notch – Oblique	Machined (EDM)	Surface	0.3mm deep x 25mm long
Bruises	Natural	Surface	Various patches

Fig 8. Roll Sample Defect Table

During the scan, the different defects are categorized by color.

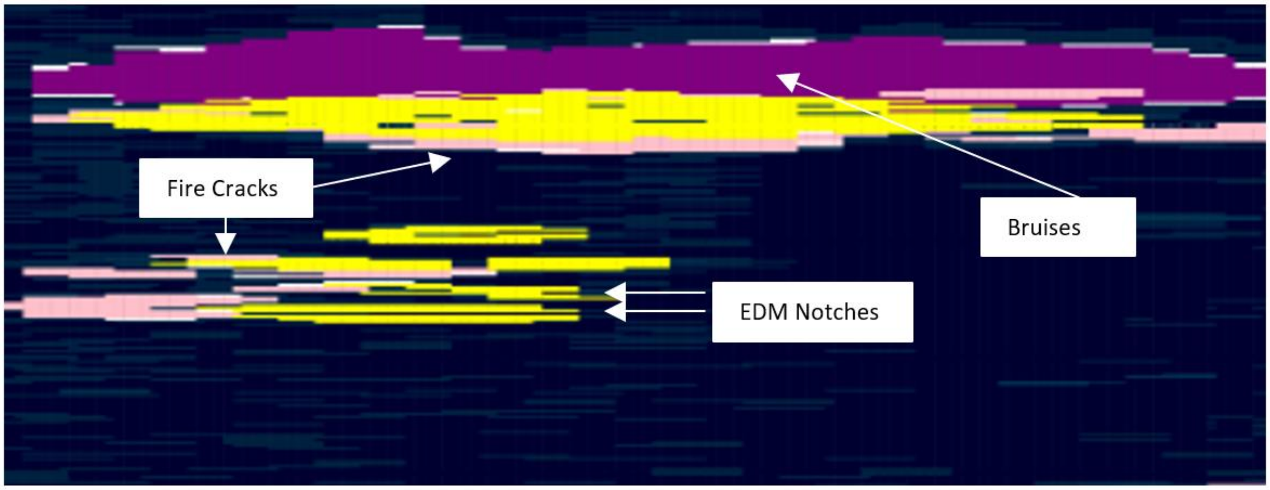

Fig. 9. Roll Sample Scan with surface defects

Sub-surface defects are shown in orange while core-shell disbond is shown in pink. The core-shell disbond channel can be focusing at different depths as needed..

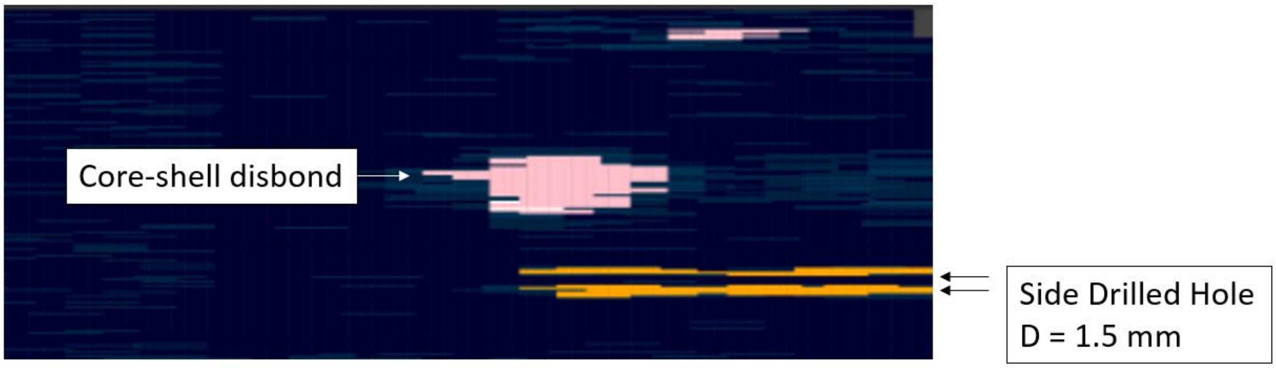

Fig. 10. Roll Sample Scan with subsurface defects

A typical view for the operator includes a traditional C-scan view on top which can be complemented with bar charts for different defects or a 3D representation of the roll. The 3D representation permits selecting different cross-sections to help in locating different defects. Figure 11 shows a view with a C-scan on top and a 3D cross-section at the bottom.

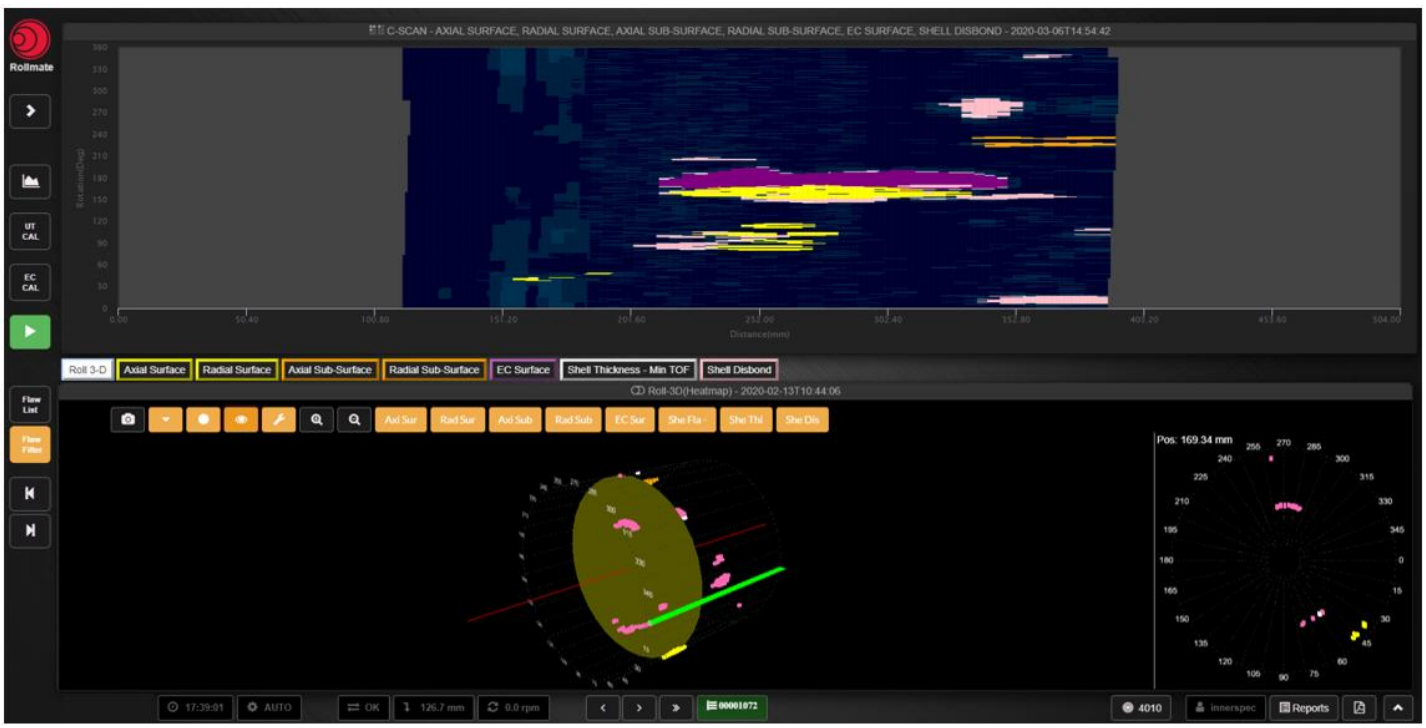

Fig. 11. 3D vies of all the surface and subsurface defects

On-Site Tests

Over the course of several months, Innerspec and Whemco engineers tested and optimized the technique and equipment inspecting rolls that had been used in different mills. Some of these rolls included defects that could not be detected using conventional EC inspection systems and other unusual problems.

As an example, the following results were obtained on an Indefinite Chilled Double Poured (ICDP) work roll with a hardened shell of 45mm nominal thickness which had been particularly hard to test with EC systems. On the left side there is a small area with fire cracks which also exhibited the traits of a bruise because of the surface hardness change. On the bottom right, there is a small crack which resulted in a fatigue band at approximately 20mm depth.

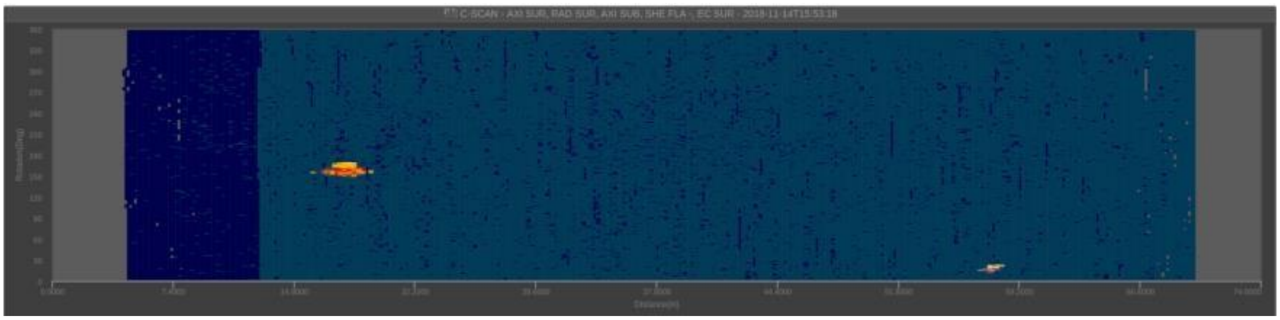

Fig. 12. Whemco Test – Surface & Sub-Surface

The image below shows both defects in the 3D view.

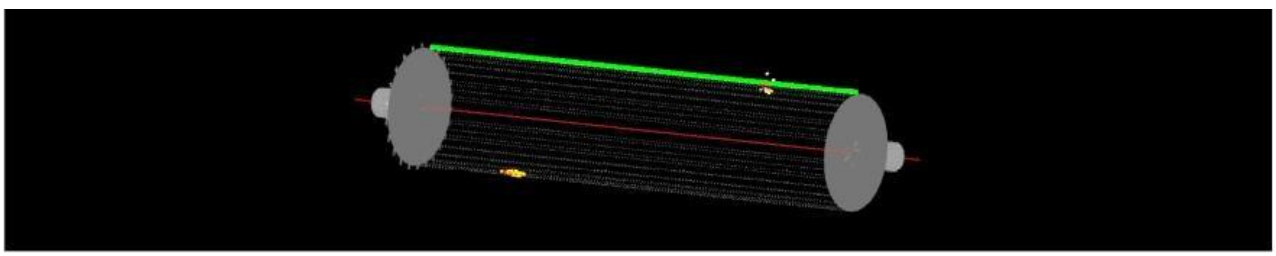

Fig. 13 Whemco Test – 3D View

The image below from the same roll represent the defects in a bar chart. The maximum amplitude is shown for each scan rotation, and an alarm threshold is represented by the dashed line. The first image shows the fire cracks on the left, and the small fatigue band crack on the right. This image displays data from the channel for axial oriented defects.

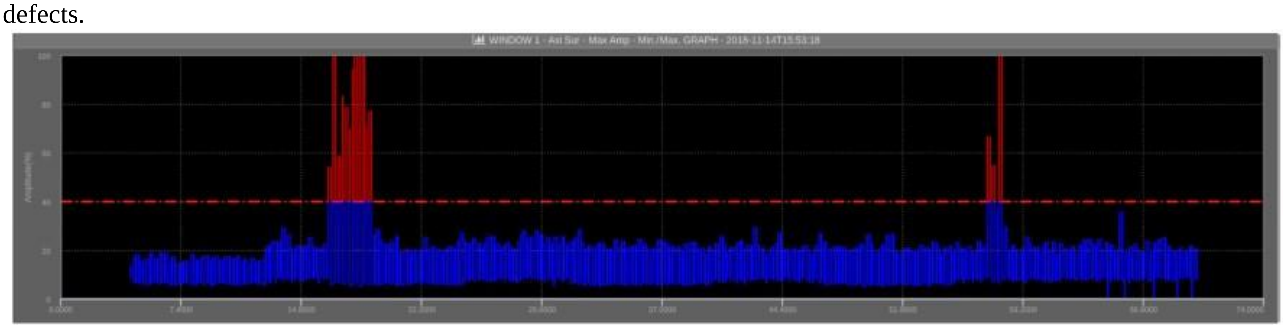

Fig. 14. Whemco Test – Maximum Amplitude Chart, Axial Defects

This second image from the same scan displays the data from the channels used for circumferential defects. While the cracks on the left are detectable, the small crack on the right is completely undetectable by this channel due to the orientation of the defect. This crack was missed by a new Eddy Current system installed at the customer.

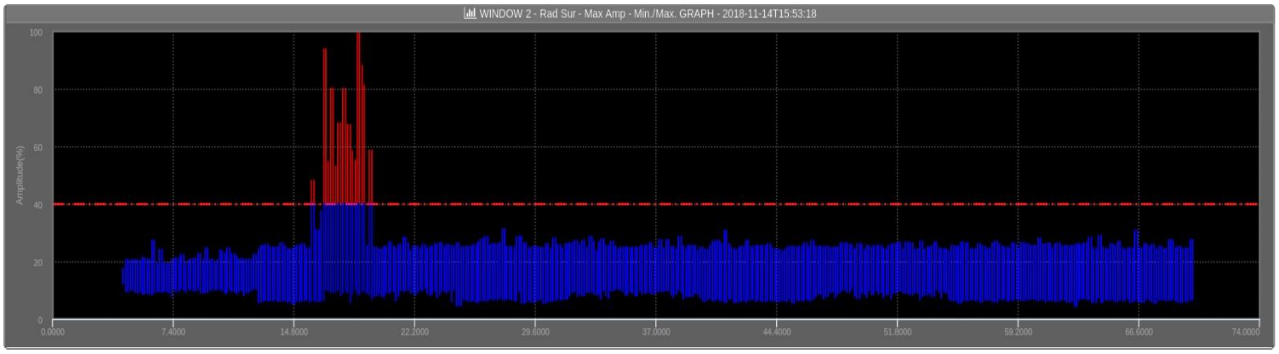

Fig. 15. Whemco Test – Maximum Amplitude Chart, Radial Defects

The importance of having sensors scanning in all four directions for detection of surface and near-surface defects became more obvious over time since the amplitude of the reflections from natural defects will vary greatly depending on the orientation of the sensor and the geometry of the defect. An example of this phenomenon is shown on the two scans below. A fairly large defect is clearly visible on the axial channel inspecting counterclockwise (bottom left), and it is completely invisible on the clockwise inspection.

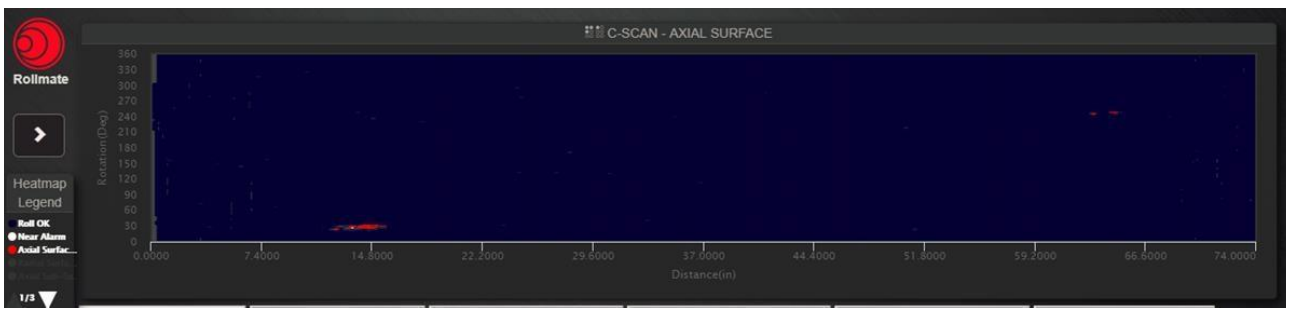

Fig. 16. Axial Inspection Result - Counterclockwise

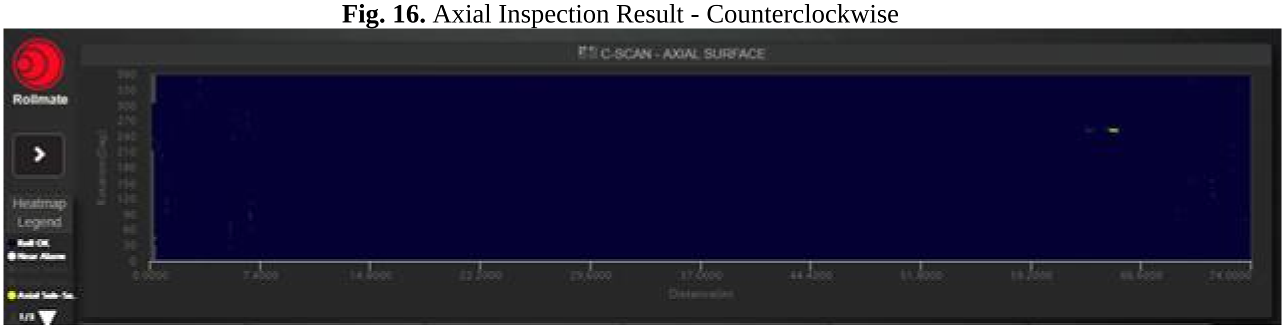

Fig. 17. Axial Inspection Result - Clockwise

After further analysis with a handheld UT instrument, it was observed that the angle of the crack allowed the sound to be reflected in one direction but not the other. As per the drawing below, the sensor A pointing counterclockwise detects the slanted defect whereas sensor B (located in the same head but pointing in the opposite direction) does not detect the defect.

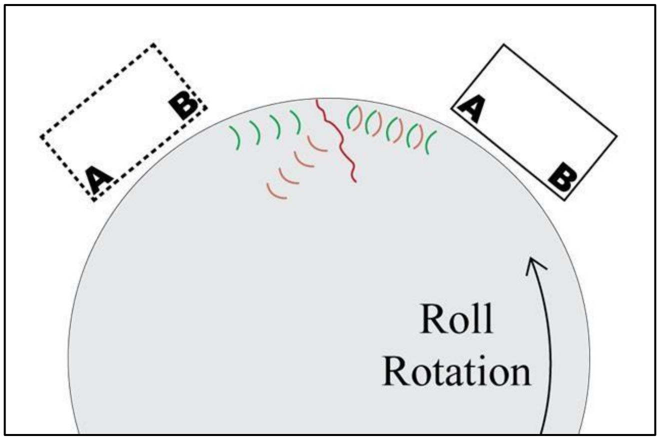

Fig. 18. Effect of Crack Orientation on Defect Detection

CONCLUSIONS

When challenged to develop a new generation of mill roll inspection systems, Innerspec embraced the task and sought to design a comprehensive solution using the best NDT techniques available for the task.

After several years of analysis, and thorough testing in the laboratory and an independent roll shop, Innerspec designed a system with no compromises on detection capability or quality; the new Rollmate G3 detects all the defects that could cause problems in a mill, regardless of geometry, location in the roll, or whether they were created during the manufacturing process or during rolling in the mill. It is also designed to inspect any type of roll, forged or cast, with any metallurgical composition and from any manufacturer, with minimum calibration requirements and user involvement.

The omnidirectional inspection capabilities of Rollmate have now been proven in the real-world, and all Rollmate systems come fitted with sensors in all four orientations by default.

The system is fully designed and manufactured in the United States, and serviced and supported by Innerspec offices in the US, Mexico, Europe and China.

REFERENCES & ACKNOWLEDGMENTS

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