Abstract
Train axles undergo high stress during service that calls for periodical verification of their integrity and checking for possible formation of cracks. The knowledge of the stress concentration on the axles allows operators to predict the location of occurrence of the cracks and to perform scheduled inspection in these specific areas. This paper presents results obtained from the detection and imaging of both machined notches and real cracks in train axle shafts using an encoded phased array rotating scanner head. The scanner was designed to perform inspections from the axle ends, eliminating the labour intensive work of disassembling the axles. This solution also makes use of a linear array to inspect the inner structure of the axle by firing at multiple refracted angles through focusing, as well as C-Scan imaging to visualize the amplitude of the echoes from the axle’s critical areas and allow for an easier flaw sizing. Results show the advantage of using a combination of A-Scan, Sectorial and C-Scan data presentation. Various axle samples were studied and good defect detection was obtained.

Keywords: Ultrasound, phased array, train axle, axle scanner, flaw detection

1. Introduction
Train axles undergo high stress during service which calls for periodical verification of their integrity and for possible crack formation and growth. The knowledge of the stress concentration on the axles allows predicting the location of occurrence of the cracks and to perform scheduled inspection in these specific areas and ultrasonic inspection proves to be an efficient detection method considering the axles material, dimensions, shape, and well as the expected defects type. It has been established that the most vulnerable areas for fracture are the inner wheel seat, journal and transitions zones [1].

Ultrasonic testing of railway axles have been achieved by both angled beam inspection from the axle circumference and from the axle ends [2, 3]. It has been estimated that a POD of 90% could be attained for crack depths of 3 mm for a near end inspection and 12 mm for a far end scan [3].

The ultrasonic inspection of axles from the ends has inherent difficulties. One of the first difficulties in detecting flaws is to distinguish real indications from geometrical echoes. This is accentuated when a component such as the journal bearing is present on the axle. Because of the presence of lubricant between the axle and the journal bearing components, ultrasonic waves can penetrate the bearing structures, leading to hardly predictable sound reflections. The bearing sometimes needs to be pulled out prior to the inspection in order to minimize the probability of false calls. The presence of threaded holes and centering hole at the axle end can also be challenging since it reduces the possible scanning positions on the shaft, as well as possibly interfering with the propagating waves.

This paper focuses on the inspection of in-service train axles from the axles ends. A rotating scanner equipped with positional encoder is used to perform a scan around the axle
longitudinal axis of three different axle dimensions. Ultrasonic phased array technology is used to perform the inspection of specific areas within the journal and wheel seat of an axle through beam steering. The benefits of combining phased array technology with an encoded scanner are highlighted by the conclusions of a one year utilisation period at the Industrial Site and Railway plant of ArcelorMittal in Port-Cartier (Quebec, Canada). This data is compared with that of the scanning head previously used by that same company, which was based on conventional transducers and A-Scan analysis. Results obtained on multiple axes are presented for both the calibration and, when accessible, real defect detection. Difficulties inherent to the presence of a journal bearing and threaded holes on the axle ends are also covered.

2. Ultrasonic Inspection from Axle Ends

The inspection of railway axles from their ends is well established (see [3] for example). It consists on sending ultrasonic waves from the end of the axle at specific angles to aim at the areas of interest inside the axle. A 360° scan is then performed to cover the full axle volume in the area of interest. Among the inspections performed on axles at ArcelorMittal, two areas are of interest and are identified on the generic axle schematics of figure. 1.

Figure 1. (a) Representation of a train axle and the areas of interest during the inspection. The brighter sections labeled Area #1 and Area #2 shows where cracking needs to be monitored. Dashed lines represent the travelling path of the ultrasonic waves. (b) Same axle represented with the journal bearing.

The ultrasonic probes must be carefully selected to induce ultrasonic waves at the proper angles inside the axle. When using conventional mono-element or dual crystal probes, a different wedge must therefore be used for the different angles at which waves need to be sent inside the axle. Due to transducers beam profile, the scanned area can include sections of the axle that are not of interest (figure 2) and from which geometrical reflections that are not related to problematic axles can occur.
The first difficulty that can arise from such an inspection is the presence of centering and threaded holes of various dimensions on the shaft end, which complicates the task of sending waves at the desired angle inside the axles. As illustrated in figure 3, the ultrasonic waves need to be sent in the small volume between the centering cone hole and the threaded holes. Since there is a possibility of interaction between the ultrasonic waves and the threaded holes, the radial position of the probe is critical in order to properly cover the desired areas.

Ultrasonic echoes resulting from the geometry of the axles can also mask defect indications or be interpreted as defects (false calls). These undesired echoes can be the result of incident waves or mode converted waves reflecting on corners within the axle. They can also be the result of internal reflections within the wedge used to generate angled waves in the axle. The presence on the axle of the journal bearing, which links the axle to the train wagon, can also be the cause of geometrical echoes, especially if they are filled with a lubricant. In that case, sound is transmitted from the axle to the bearing components through the lubricant and additional geometrical echoes can appear in the A-Scans. As an example, figure 4 shows the axle with a journal bearing which components are covering Area #1.
Figure 4. Representation of a train axle with the journal bearing installed: internal view with ultrasound path (pale blue) and probable locations where reflections from the bearing can arise (red circles).

Since an A-Scan will include all the echoes within the beam profile, aiming at Area #1 is more likely to result in a superimposition of corner echoes and bearing echoes with those returning from real flaws. Trying to discriminate between all these echoes proves to be often difficult. When echoes are observed in that area, the journal bearing has to be pulled out until it no longer interferes with the sound path (figure 5).

Figure 5. Internal view of the axle with the bearing pulled out to avoid sound transmission in the bearing components.

Once the journal bearing has been pulled out, the inspection can be performed an additional time to confirm the nature of the echoes. If the echoes observed prior to pulling out the bearing are not present in this second inspection, they can be identified as originating from the bearing, otherwise they correspond to a real reflection within the axle (flaw). As an example, the apparatuses used to pull the bearing in and out of the axle are presented in figure 6.

3. Problematic: Inspection Requirements

Three different axle models need to be inspected at ArcelorMittal, and are identified as the diameter and length of the journal of the axle. These axles are displayed in figure 7 and are respectively labeled 6x11, 6.5x9 and 6.5x12. These drawings illustrate the difference in the refraction angle of the waves that is required to aim at the area of interest in the journal. This angle is evaluated to be approximately 21° for the 6x11 and 6.5x12 axes, and 28° for the 6.5x9. As for Area #2, a refraction angle of 15° allows to inspect all three axes.

It is preferable to use a scanning head that is auto-centered with the axle and that can maintain the probes at the proper radial position. If mono-element (or twin crystal) angled beam transducers are used to perform these inspections, different probe combinations and positioning need to be used in order to properly cover the required areas in all axles. Since the positioning is critical, trying to use a single scanning head for all axle types rapidly becomes difficult since each axle would require changing the probes and their radial position.
Until 2009, axle inspection was performed using sets of pulse-echo and/or pitch-and-catch angled transducers with various wedge angles at ArcelorMittal as described above. Different scanning heads were used for the axles, each scanning head comprising two to three probes located at predetermined radial positions. A 360° manual scan was performed for each probe and A-Scans were monitored live using calibrated alarms.

Figure 6. Picture of (a) the apparatus used to pull the journal bearing out; (b) a bearing being pulled from the axle for re-inspection; (c) the axle after the bearing has been pulled out to a position where it does not interfere with the sound path; (d) the tool to push the journal bearing back.

Figure 7. Scaled representation of the three axles that need to be inspected: (a) 6x11; (b) 6.5x9; (c) 6.5x12. Red arrows indicate the ultrasonic waves path required to aim at the area of interest within the journal.
4. Solution: Phased Array Scanner Head

Phased array technology allows to focus ultrasonic waves at specific locations inside a material, as well as to steer an ultrasonic beam to a specific direction. This is achieved by applying delays at the emission and/or reception of the ultrasonic waves by an array of transducers in order to create constructive interference (focusing) or plane waves at a desired angle (beam steering). Angled beam inspection can therefore be achieved by steering the ultrasonic beam electronically with a phased array unit.

A common display mode of phased array units is the sectorial scan, which is a color coded image displaying echo amplitude as a function of distance from the probe and steering angle. A sectorial scan can therefore display a wide enough range of angles allowing to scan Areas #1 and 2 simultaneously. Figure 8 shows an example of sectorial scan displaying reference notches detected on a 6.5x12 axle in both areas of interest at the same time. A drawing of the 6.5x12 axle is superimposed with the sectorial scan for clarity. It is interesting to note that both notches are detected at the calculated angles.

As it was previously mentioned, the radial position of the probe depends on the relative dimension and position of the threaded and centering holes. Using a long enough linear array probe, the point of entry of the ultrasonic waves can be changed without physically moving the probe. It is rather done by selecting the appropriate group of elements on the array that allow to generate the ultrasonic beam at the right location on the axle surface. Therefore, the phased array probe does not need to be moved radially when inspecting different axle models. Since all required refraction angles can be obtained with a single array, without having to change its radial position, a single scanner can be used to inspect all three axle types. By gating at the right time window in the A-Scans recorded at each circumferential position, C-Scan images can be generated for Areas 1 and 2 independently.

![Figure 8. Example of sectorial scan recorded on a 6.5x12 axle and superimposed with the axle’s drawing. Reference notches that are detected are displayed in red on the sectorial scan.](image-url)

A scanner was designed to perform phased array inspections on a full 360° around the axis of all three axle types. It has a self-centering device and is designed with a positional encoder to record data at selected angular positions. It encloses a phased array probe with an
adjustable radial position. Since journal bearings sometimes need to be partially pulled out, the external dimensions of the scanner were adjusted to fit within the bearing. This scanner is presented in figure 9.

![Figure 9](image)

(a) Picture of the Phased Array Scanner Head. (b) Picture of the scanner during an inspection at ArcelorMittal.

5. Reference Axles: Results

A set of reference axles was prepared for all three types of axles. Notches with depths of 6.35 mm (0.25") were machined in Areas #1 and 2 of axles that were shorten to be manipulated more easily (figure 10). Since threaded holes represent an obstacle in the ultrasonic path, the notches were prepared at a circumferential location corresponding to one of these holes.

![Figure 10](image)

Figure 10. Picture of the reference axles with machined notches (Left to right: 6x11, 6.5x9, 6.5x12) with an enlarged view of the notches of the axle 6.5x12 on the right. Notches are encircled while the dashed line shows the alignment between a threaded hole and the notches.

These axles serve to establish a detection level reference in both areas #1 and 2. C-Scans representing echo amplitude as a function of beam steering angle and circumferential location is displayed using a detection gate covering the depths of interest for each area. C-Scans obtained on the reference axles are presented in figure 11.
Figure 11. Results of the inspection of the reference axles. (a) 6x11; (b) 6.5x12; (c) 6.5x9 with the A-Scan showing the wheel seat echo at 18°; (d) 6.5x9 with the A-Scan showing the journal echo at 26°.

6. Results from in-service axles

Inspection of in-service axles is done based on the calibration performed on the reference axles. The beam angles and C-Scan color scales used in these inspections are based on the optimal setups defined with the reference axles. The entry surface is first cleaned and polished in order to ensure proper sound transmission. Typical scan results are presented in figure 12 for three 6.5x12 axles that did not present any defects.

Figure 12. Examples of scans recorded on in-service 6.5x12 axles that do not have rejectable indications. (a) Without indications; (b) Visible bearing echoes in Area #1; (c) Echoes below the rejection threshold.
As it was presented before, the presence of the journal bearings can result in non-rejectable echoes above the detection threshold. This phenomenon is illustrated in figure 13 where indications were found in both the journal and wheel seat of a 6.5x12 before the bearing was pulled out (figure 13a), but only in the wheel seat afterwards (13b).

![Figure 13](image1.png)  
**Figure 13.** Inspection of a 6.5x12 axle presenting rejectable indications in (a) both the journal and wheel seat with the bearing in place and (b) only in the wheel seat once the bearing has been pulled out.

A total of 3771 axles have been inspected at an interval of 200 000 miles (~322 000 km) since the introduction of the new phased array scanning head at ArcelorMittal at the end of 2010. Thirty (30) axles have been rejected over this period of time (0.8%), which is comparable to the rejection level observed with the previous scanning heads, which was 0.7% in 2009 (7 rejections out of 971 inspections). Examples of defect detection in the wheel seat of 6.5x12 axles are presented in figure 14.

![Figure 14](image2.png)  
**Figure 14.** Examples of scans for in-service 6.5x12 axles presenting rejectable indications in the wheel seat.

Notable improvements have been noted since the introduction of this new scanner. While journal bearings still need to be pulled out periodically (~40% of 6.5x12 axles and a negligible number of times for the 6.5x9 and 6x11 axles), the overall inspection time of a complete axle went from 10-12 minutes with the previous system down to at most 4 minutes with the new scanner if no indication is found under the journal bearing. Furthermore, a record of the inspection is now kept in files in the form of C-Scan images. This allows to follow the evolution and/or apparition of flaws in the axles over time. This was not possible using the previous scanning heads since calls were made based on the alarms of the flaw detectors only and no A-Scans were recorded. The C-Scan images also provide the operators with a representation that is easier to interpret and compare with the reference axles.

### 7. Conclusion

A new scanner was introduced to perform the inspection of the journal and wheel seat of in-service and new train axles from the axle ends. The use of phased array technology allows
replacing the set of angled beam transducers that would otherwise be used to inspect both areas of interest in the axle. Results obtained on calibrated samples were used to establish a reference detection level and in-service axles have been inspected since the end of 2010. With a rejection level of 0.8%, this scanner presents similar performances to the scanning heads previously used with the additional advantages of requiring a single scanning head to cover the three axle types. In addition, scanning time has been reduced by 65-70% and inspection data can be inspected for traceability and to follow the evolution of flaws over time.

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References