Implementation of a Phased array Rail Weld Inspection program for London Underground

Joseph M. Buckley¹, Peter Willats², and Daniel Harrison²
1 Level X NDT, Milton Keynes UK, joe@levelxndt.com
2 London Underground, London, UK, DanielHarrison@tfl.gov.uk
Peter.willats@tube.tfl.gov.uk

Abstract

The London Underground (LUL) network is the oldest public transit system in the world and has over 400 km of track. New and replacement sections of rails are predominantly joined using aluminothermic welds, of which there are estimated to be 50,000 on the network.

With the recent introduction of Night Tube, a 24 hour running service on the busiest lines on Fridays and Saturdays, available ‘engineering hours’, and thus the time available for inspection and maintenance, have been reduced. Furthermore, issues with previous thermic welding processes, along with increases in annual tonnages due to new, heavier trains and more ambitious timetables, have led to an increase in rail breaks and defects, a significant number of which have been located at aluminothermic welds.

While modern welding techniques are extremely reliable, there still exists the possibility of entrapped porosity, particularly on older aluminothermic welds. This can lead to weaknesses due to a reduction in cross-sectional area in the rail profile, and increases the probability of a full rail fracture, particularly when track stresses arising from other factors such as repairs, re-railing or wheel flats are experienced.

To improve safety, reliability, and assurance, London Underground decided to investigate the possibility of using a phased array ultrasonic inspection device to verify the internal integrity of welded joints, both in the head and the foot of the rail, in addition to the current visual inspection.

This paper discusses the initial investigations, the decisions that were made and the implementation of the equipment and inspection process.

These new processes have now been in use since the start of the year and continue to give greater confidence in the integrity and reliability of both new and existing welds. These have been implemented into TFL documentation, and both ongoing and site specific inspections are being rolled out across the business, giving additional assurance to stakeholders throughout LUL.
1. Introduction

The London Underground system has been steadily expanding since the Metropolitan Railway, consisting of eight stations and 6 km of track each way, opened in 1863. Currently it contains around 270 stations, and 400 km of operational track. It is estimated that this track contains around 50,000 welds, many produced using the Aluminothermic process.

![Figure 1 Expansion of London Underground Network](image)

This process uses a mixture of metal oxides and additives in a crucible above a mould formed around the region to be welded. The mixture is ignited, and an exothermic reaction occurs, causing superheated metal to run into the mould. Whilst this process is extremely reliable, manufacturing defects can sometimes occur.

With so many joints it is inevitable that there will be a few fractures. However recent changes to 24 hour running on Fridays and Saturdays on some lines, which reduces the time available for repair and inspection work, and the introduction of digital signalling, have increased the reliability requirement significantly. Heavier and more frequent trains have increased the load on the track substantially.

Analysis of weld related track breakages has shown that:

1. Defect origination mechanisms are typically either weld porosity, or cracking resulting from weld induced stresses, a particular cracking issue was ‘hot tears’ i.e. movement of the joint before the weld had fully cooled.

2. Some of the broken welds had been in use for years before failing. Often these breakages are associated with nearby track work, which has changed the stresses on welds.

Currently all new welds carried out on the underground network are independently inspected within 28 days of cast. The existing procedures include both visual and dimensional checks. While cracking or porosity are cause for rejection where visible on the surface, this approach cannot find ‘hidden’ defects.

A programme was initiated in 2016 to improve performance in these areas, initially by investigating the possibility to incorporate additional requirements into the weld inspection procedure.
LUL owned, and were familiar with, Sonatest Prisma phased array instruments. The author had provided training to LUL while working at Sonatest, and was asked to assist with additional training and assistance in developing procedures.

2. Constraints

1. Like all railways track access has very limited hours, and safety is paramount. It is necessary that any potentially unsafe situation can be identified immediately, so that appropriate precautions (e.g. clamping track and/or imposing speed restrictions) can be implemented before trains must run.

2. Existing Welding Inspectors are qualified and experienced welders, but are not ultrasonic NDT personnel. It is desirable that procedures are reasonably simple and robust, allowing them to carry out the work with limited additional training.

3. It is desirable that the weight and bulk of equipment is minimised so that the NDT equipment, along with the other equipment required for weld inspection, can be carried by one member of staff. Access to the inspection location may involve walking some distance, and use of long flights of stairs is frequent.

4. It was necessary to comply with many LUL and railway standards such as track standards and equipment approval etc. Trade Unions also needed to approve changes in working practice, this presented some disagreements as their representatives, whilst very supportive, needed to be kept involved and satisfied.

3. Initial investigations.

Three different approaches were evaluated

![Figure 2 proposed scan locations](image)

3.1. Shear-wave angle beam scan of the foot of the rail.

This was really the only method considered for this region – It is a reasonably straightforward test, similar in many ways to a conventional butt-weld inspection. The Rail Foot is approximately 20mm thick and tapers slightly. This taper does mean that
multi-skip testing will give inconsistent positioning, across the width of the rail foot, but did not appear to affect defect detection significantly. The geometry of a ‘good weld’ gives minimal spurious indications.

Reflections from the underside of the rail outside the weld region were sufficiently reliable to find defects at the top of the weld using a ‘skip’ technique.

A number of probe types were evaluated for this, while there would have been a preference for using a probe with a replaceable wedge the ones tried were a bit too large to be easily manipulated in the critical region. A 4MHz 16 element array probe was used (8x9mm, with an integral wedge in a standard size housing).

Results were generally unambiguous – once operators had seen a ‘real crack’ they were unlikely to be confused by surface geometry and similar indications.

3.2. Shear wave angle beam scan for weld porosity

While this was initially expected to be a promising technique it was found that:

1) Work–hardening and similar effects on the top of the rail made it very inconsistent on installed rails.
2) The normal level of ‘weld noise’ varied significantly and thus it was difficult to create criteria to reliably distinguish scattered porosity defects from normal welds, especially without very consistent calibration.

3) A ‘skip’ technique resulted in a long path length; small variations in material attenuation could greatly affect sensitivity. Without skipping it was difficult to test the upper region of the weld.

4) In a few cases there were bolt holes obstructing regions of the weld, making it difficult or impossible to inspect them. These were always present where suspect welds had been clamped. This effectively meant that no weld that had failed or was suspect (and had been subsequently clamped) could be inspected, making technique validation almost impossible.

Although this technique has some advantages it was felt that without complicating the procedure to ensure very consistent calibration, results were likely to be difficult to interpret.

3.3. **Longitudinal wave ‘zero-degree’ scan for weld porosity**

This is the approach that was eventually selected. A 16 element probe was used with a scan over +/- 20 degrees. Because the probe was used without a wedge or delay line, protective tape was specified.

This gave a ‘clean’ response on a good weld, it was thus much easier to evaluate, and identification of defects did not require a precise calibration.

![Figure 5 Longitudinal wave scan for weld porosity](image)

Tests were carried out on a number of samples containing defects due to porosity.

The rail in Figure 6 had been in use for some years before it broke: Because the weld is ‘full’ of porosity the energy is all reflected at the top of the weld and the lower section is ‘quiet’. Operators are taught to recognise this as a sign of gross porosity.
Isolated indications present in a more familiar manner. Attempts were made to induce deliberate porosity in this weld. After investigation it was milled down to investigate the indications.

4. Procedure development.

Once the approach had been agreed outline procedures were developed. As noted in the constraints, weight is a critical aspect for the practical implementation, so calibration / verification procedures were developed using the lightweight CB87M calibration block already in wide use in the railways.
N.B. this block weighs approximately 1.2 kg with its protective case. There would be some scope for reducing this weight further by using a custom test block, but it was felt that this was not justified.

A standard kit was developed containing all phased array inspection related items. This was issued to operators along with the phased array instrument. A key point was to simplify the procedure so that it could be used by relatively unskilled (in NDT) operators. Accordingly:

- ‘Standard’ probes were used. Using several different probes of the same type it was confirmed that the probes were sufficiently consistent, and that a standard configuration file was acceptable for the required test.

- After selection of probe and configuration file, correct operation is verified using the CB87M block. Other than checking correct operation no attempt was made to ‘fine calibrate’ the test.

- Reporting is intended to be simple process – pass, fail or ‘monitor’ actions are applied (typically the monitor category applies to minor porosity or indications where the operator felt uncertain about ‘minor’ indications). The procedure specifies that all ‘fail’ or ‘monitor’ indications are to be recorded, screen images taken and emailed to LUL NDT experts, and, in the case of a ‘fail’ appropriate track protection and minimum actions are to be taken immediately.

5. Implementation.

After testing and investigation of new, suspect and in-service welds by LUL NDT specialists, the approach detailed previously was integrated into updates in the relevant LUL procedures and welding specifications. The internal work instruction for aluminothermic weld inspections was also updated. These documents are mandatory for all aluminothermic welds carried out on the underground network.

Reporting forms ‘Aluminothermic weld inspection report’ (completed for all welds) and ‘Report of noncompliant weld’, were also updated to include new sections for the ultrasonic reporting.

Once this had been done (see Figure 9) the procedure was ready to be rolled out as part of the routine weld inspection. Welds are inspected visually and dimensionally at the time of manufacture, and must have an independent final inspection within 28 days of being placed into service, this now included phased array inspection.

During the first phase internal LUL personnel were used. However much of the welding and inspection work is carried out by external sub-contractors, so it was necessary to develop a standardised training and certification procedure to ensure that weld inspectors carrying out the Phased array inspection are approved to do so.
6. Operator Training

Level X currently provides “equipment familiarisation” training for users of phased array equipment. The existing course was adapted and additional content added for the rail inspection requirement.

As noted, most of the weld inspection personal have minimal ultrasonic knowledge or experience, so it was necessary to develop an appropriate course assuming minimal prior knowledge, and giving what was necessary to follow the procedures.

The course that was developed contained the following components:
- Classroom training covering theory, use of the equipment and the detailed procedures. A brief exam was included.
- On track practical / mentoring comprising one night with instruction as necessary and one night with minimal assistance to confirm competence.

Subject to adequate examination and practical performance trainees are approved to carry out the inspection work and issued with a credit-card size approval ‘ticket’. This, in conjunction with their LU access pass and other relevant approvals, demonstrates competence to inspect welds in accordance with the LUL procedures.

London Underground now have greater confidence in all new welded joints and expect to see positive performance improvements as the new procedures are introduced throughout the network.

N.B. An update on the project will be given at the time of presentation, for more information please contact the primary author or refer to the ‘papers’ section on www.levelxndt.com