New Methods of Rail Axle Inspection and Assessment

John RUDLIN\textsuperscript{1}, Angélique RAUDE\textsuperscript{1}, Uwe VÖLZ\textsuperscript{2}, Antonietta LO CONTE\textsuperscript{3},

\textsuperscript{1}TWI Ltd, Granta Park, Abington, Cambridge, CB21 6AL, UK Phone +44 1223 899000 Fax +44 1223 890952
\textsuperscript{john.rudlin@twi.co.uk; angelique.raude@twi.co.uk; \textsuperscript{2}BAM, Germany, uwe.voelz@bam.de; \textsuperscript{3}Politecnico de Milano, Italy antonietta.loconte@polimi.it

Abstract
Three alternative methods of crack detection and corrosion assessment for railway axle inspection have been proposed in the WOLAXIM (Whole Life Rail Axle Assessment and Improvement) project. One method is for the exposed body of the axles (intended primarily for freight wagon or passenger trailing axles) and can be carried out automatically, as the vehicles pass an inspection station that could be installed in carriage sidings or marshalling yards. A second method is specifically for the hollow axles of high speed trains and aims to improve the speed of the inspection and improve crack detection reliability. This could be deployed while the train is in the depot overnight and without dismantling the wheel set. The third method is to improve the measurement of corrosion and therefore the sentencing of corroded axles. This will be linked to newly developed corrosion fatigue assessment models by reliability methods.

This paper describes the main principles of these methods and gives some preliminary results.

Keywords
rail axles, thermography, corrosion fatigue, phased array, ultrasonics.

1 Introduction

The European rail network is targeting a considerable expansion of passenger and freight traffic by 2020. In order to achieve this, increased reliability and availability of rolling stock is necessary whilst maintaining the same or a better level of safety. The axle life is a crucial part of both the safety and economic performance of the vehicles and the axle deteriorates through its lifetime by means of fatigue and corrosion mechanisms. Periodic inspection is used to ensure that these mechanisms have not compromised the axle safety; however inspection which takes a vehicle out of service impacts on the economic aspects of train operation.

1.1 Inspection of Train Axles for Fatigue Cracks

The WIDEM (Wheelset integrated design and maintenance) project \cite{1} carried out a survey of axle inspection methods and their performance in terms of probability of detection (POD).

Production inspection of axles is carried out by surface inspection methods (dye penetrant and MPI) and ultrasonics for solid axles. Inspection of hollow axles is by automated ultrasonics with a group of rotating probes.

In service, axles can be inspected either in the depot (while still on a train) with limited access, or at overhaul when worn wheels are removed and there is good access to the surface. At overhaul there is no additional disruption of the train service for inspection and generally this time for inspection is preferred by the train operating companies. However currently it is not usually possible to extend the inspection period to overhaul times and some depot inspections are still necessary.
Methods of inspection in service, and degrees of automation, vary from country to country. In Germany highly automated phased array ultrasonic methods are used for high speed train axles at overhaul [2], whereas in the UK surface inspection methods (particularly MPI) have been introduced at overhaul since the Rickerscote accident in 1996[3] for accessible areas. Eddy current methods have also been introduced for depot inspection and are very effective [1] but still require manual intervention.

Where a crack could initiate from an inaccessible surface (e.g. fretting cracks under a wheel) the inspection is by ultrasonics. The methods adopted for solid axles are generically known as the high angle scan (applied from the axle body), the near end scan and the far end scan both of the latter being applied from the axle end.

Hollow axles are also used, and the ultrasonics used in this case is an angled beam scan from a rotating probe in the bore, as in manufacturing. This inspection is mechanized, this requires incrementing and rotating the probe, a very slow process. Portable devices for use in depots have been manufactured but these tend to be unreliable due to the long reach and sensor rotation required. There is also some uncertainty in their capability for crack detection in the radius between the axle body and the wheel seat. An inspection performance trial in the WIDEM Project indicated that a 90% POD may only be achieved for cracks of 10mm depth or greater using this method.

Ultrasonic methods of inspecting the wheel seats of hollow axles (using high angle scans manually deployed from the axle body) have also been introduced. This has the advantage of carrying out the inspection without removal of the end caps.

Manual methods are regarded with some suspicion in some circles because they are dependent on the operator, and human factors in ultrasonic inspection are known to be the most significant factor in the performance capability of the techniques. This was studied for axle inspection in WIDEM [1] and for ultrasonic testing more generally by the UK Health and Safety Executive [4]

An inspection tool using laser ultrasound to detect cracks was patented by TTCi and Tecnogamma. This is aimed at detecting cracks as the vehicle passes the inspection station [5], in the same way that the proposed AC thermography method below is planned to be used.

1.2 Method of Corrosion Assessment for Axles

The current state of the art for this seems to be only visual inspection, at best supported by a pit depth gauge or similar device. Corrosion can be measured in the laboratory by optical methods to a high degree of accuracy but these measurements tend to be slow, requiring precision scanning of small areas and do not give a suitable output for sentencing. There is no instrument that can be used directly for the quantitative on-site inspection of axles. For corrosion assessment generally there are a number of standards for the measurement and classification of pits, but these are not related to high cycle fatigue.

1.3 Corrosion Fatigue in Rail Axles

Some bibliographic notes report cases of axle failures due to crack propagation from corrosion pits. Hoddinott [6] reports that about five mid-span failures of in-service axles occurred in the UK from 1996 to 2003, four of which have been connected to the presence of
diffuse axle surface corrosion and corrosion pits. The Transportation Safety Board of Canada [7] reported one axle failure to have been caused by corrosion pits under the journal bearing. It also mentions another seven similar failures occurring between 1998 and 2000.

The effects of corrosion on fatigue properties can firstly be observed as a number of surface defects or pits which obviously reduce the fatigue strength of the axle body (this seems to be the effect described by Hoddinott in one case). There is also considerable experimental evidence [8-11] showing a detrimental effect of the environment upon the S-N diagram.

Recently, investigations have been carried out to assess the effect of corrosion upon fatigue properties of A1N, a steel widely adopted for railway axles [12],[13]. Rotating bending corrosion fatigue tests on both smooth and micro-notched specimens machined from axles were performed. The S-N data for complete failure of the specimen have shown that corrosion has a significant influence on the fatigue life especially at high cycles (>10\(^7\) cycles) where the absence of a fatigue limit seems to be confirmed.

1.4 Proposed Methods

The methods described in this paper are, AC thermography, phased array internal bore inspection and an optical corrosion assessment method. The principles of the methods are described below.

1.4.1 AC Thermography

The idea of this method is shown in Figure 1. When the axle passes over the inspection station a high frequency electric current is passed through it, causing it to heat slightly. Near a crack the current flow is distorted and this results in a different heating pattern. If the right conditions can be reached, the method is very sensitive and capable of detecting cracks of 0.8mm deep [14]. It has been shown by some workers that the heat is generated at the crack corners formed between the metal surface and the crack [14], whereas others [15] show a pattern is similar to the current distribution assumed by the AC Field Measurement (ACFM) technique, giving a lower temperature at the crack centre and hot spots at the crack ends.

To deploy it through the wheel using a direct application of the current rather than induced current solves the problem of the inducing coil being in the way of the camera, but introduces some additional technical problems, described in Section 2.

Figure 1 Principle of AC thermography technique
1.4.2 Phased Array Bore Inspection
The idea of this device is to replace the rotating probe methods used to inspect hollow axles by a phased array probe that rotates the ultrasonic field electronically. This enables a much faster inspection and could reduce the inspection time of a hollow axle from around 20mins to 5 mins. The system allows ultrasonic testing of transverse cracks in the axle surface with full coverage. The concept of the ultrasonic inspection system is to scan a complete hollow axle with a fixed beam angle in the axial direction of approximately 45° and an electronic rotation of the sound field by sweeping the active element groups around the circumference (Figure 2). The system will consist of a phased array device with a probe as described above, a motor driven linear axis for moving the probe axially inside the bore and a PC for device control.

![Figure 2 Principle of the conical phased array probe](image2.png)

1.4.3 Corrosion Inspection
Study of the sample surfaces from corrosion fatigue experiments has led to knowledge concerning the corrosion and crack propagation relationship, particularly at the crack initiation stage. It was observed that the crack growth occurred in specific stages that could be identified and related to the sample lifetime. An example of an image of small corrosion fatigue cracks on a corroded surface is shown in Figure 3. It is planned that analysis of microscope images will enable classification of corroded areas.

![Figure 3 Image of corrosion fatigue cracks and pitting corrosion](image3.png)
2 AC Thermography Method

Several aspects of the technique have been investigated

1) Frequency and amplitude of the required current
2) Methods of generating the high current needed
3) Sensitivity and field of view of the thermal camera

The frequency and amplitude of the required currents to display the flaws has been investigated by modelling. Initially 2D models were set up using COMSOL. Later 3D models were generated.

The methods of generating the current and to test the validity of the models were investigated initially with small scale tests. 3 samples of 20mm diameter steel bar were manufactured with different size fatigue cracks (4mm, 1.3mm and 0.7mm deep, as measured by ACPD). Currents were passed through them by various means including an MPI bench, a modified induction heater system and a 500W power amplifier.

A 2D model showed that there would be an indication from the crack. (Figure 5(a)). However this does not give the full picture. A 3D full size model (Figure 5 (b)) shows an indication after a very short period (for processing reasons) from of a 2mm deep crack 20mm long. It is just visible that the pattern follows the expected surface currents, and that there is a temperature rise at the crack itself (corresponding to the 2D case). This also shows that the crack end temperature rise is much stronger that from the central area.

Examples of the modelling output are shown in Figure 4

![Figure 4 Modelling of temperature changes close to cracks](image)

A result from the small scale sample is shown in Figure 5. The indication as observed in the model can be seen although it is slightly distorted by interference from the system and some reflections.
The field of view of the camera was also investigated. Figure 6 shows an image from a 1mm diameter insulated wire, heated by finger friction, on an actual axle. It shows that the camera could view all the axle length between the wheels with a sensitivity to detect heat sources provided they were above 1mm in size.

3 Phased Array Hollow Axle Inspection

3.1 Modelling

The phased array internal bore inspection system has been extensively modelled to establish the expected performance. These models optimised the frequency, angle and number of elements. Figure 7 shows the effect of the number of elements activated on the circumferential resolution and the signal strength from different numbers of elements activated.
3.2 Initial Experiments

A first mock-up of the conical probe with 10 elements was manufactured to carry out tests for probe sensitivity. Figure 8 shows the probe adapted to a bore diameter of 65 mm. The results confirm the theoretical expectations. The echo of two corner reflectors (saw cuts) with 2 mm and 1 mm depth at the surface of a test block with a diameter of 237 mm is shown in the A-scans (Figure 9). A good signal to noise ratio (greater than 12 dB) is attainable with these ideal test flaws. In practice, the reflectivity of natural cracks may be lower due to tilted and rough surfaces of the cracks.

Copyright © WOLAXIM 2012
4 Corrosion Assessment

4.1 Corrosion Fatigue Crack Initiation and Growth

A large number of small scale rotating bending fatigue tests using specially designed equipment have been carried out and are providing information for the S/N curves and Paris equations for fatigue crack growth in corrosion conditions in A1N and A4T axle steels. This has enabled classification of the crack growth into 4 stages:

1. Pitting only (similar to corrosion without fatigue) and crack initiation from pits
2. Formation of microcracks (Figure 10(a))
3. Coalescence of microcracks (when depth exceeds about 0.3mm) (Figure 10(b))
4. Growth of macrocracks detectable by NDT

Table 1 shows how crack length data builds up in a single specimen as time goes on. The ML numbers refer to tests after each period. The crack length with a probability of occurrence of 50%, $L_{50}$, (determined by plotting a Weibull Distribution) reaches successively higher peaks when the crack numbers decrease, due to coalescence (at ML5, ML7 and ML9). This picture is more complicated in specimens with different load levels but the effect is clear.

Table 1 Progress in crack numbers and lengths for single sample under corrosion fatigue

<table>
<thead>
<tr>
<th>Specimen</th>
<th>ML3</th>
<th>ML4</th>
<th>ML5</th>
<th>ML6</th>
<th>ML7</th>
<th>ML8</th>
<th>ML9</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cycles (x10³)</td>
<td>200</td>
<td>300</td>
<td>400</td>
<td>500</td>
<td>600</td>
<td>700</td>
<td>800</td>
</tr>
<tr>
<td>Number of cracks</td>
<td>40</td>
<td>81</td>
<td>56</td>
<td>68</td>
<td>46</td>
<td>50</td>
<td>33</td>
</tr>
<tr>
<td>$L_{50}$(µm)</td>
<td>133</td>
<td>143</td>
<td>257</td>
<td>223</td>
<td>308</td>
<td>372</td>
<td>488</td>
</tr>
</tbody>
</table>

This evidence suggests that in order to be sure about the situation in the axle as far as corrosion fatigue is concerned, we need to be able to either improve conventional surface NDT to quantify the microcrack status or carry out a microscopic evaluation of the surface.
(or a combination of methods). Optical and eddy current methods were considered. The eddy
current work is covered elsewhere [16], and this paper deals solely with the optical method.

The optical approach uses a microscope camera with image analysis. For the laboratory work
the rust was removed from the samples by using a solution at 75°C for 20 minutes. This is
not a procedure that can be used on site so rust remover solutions for site use were also
tested.

Three images taken from the samples have been used in an initial analysis (Figure 11).
Different rust removal methods were used for each sample so the colour is slightly different.

Sample 1 is from a heavily rusted plate which has been processed using the site procedure.
Sample 2 is a sample from the edge of a corroded area with additional corrosion in salt water.
Sample 3 is from the centre of a corroded area using the laboratory rust removal method.

![Sample 1](image1.png) ![Sample 2](image2.png) ![Sample 3](image3.png)

**Figure 11 Examples of surface images**

Table 2 shows image analysis was able to identify and grade the three images, although this
does need further development. For example, using this method if the percentage of objects
filtered is greater than say 8%, then it is likely that cracks are developing; if less than 6% the
corrosion is relatively benign at the time of testing.

<table>
<thead>
<tr>
<th></th>
<th>Image 1</th>
<th>Image 2</th>
<th>Image 3</th>
<th>Image 1</th>
<th>Image 2</th>
<th>Image 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>No of objects</td>
<td>1487</td>
<td>147</td>
<td>253</td>
<td>%</td>
<td>%</td>
<td>%</td>
</tr>
<tr>
<td>Example analysis(filter) result</td>
<td>90</td>
<td>15</td>
<td>36</td>
<td>6</td>
<td>10</td>
<td>14</td>
</tr>
</tbody>
</table>

**5 Conclusions**

Three new approaches to the inspection of rail axles are being developed, and show
considerable promise for the inspection and sentencing of axles.

(1) The AC thermography method appears to be able to detect cracks in axles but the
engineering aspects are challenging.

(2) The phased array rotating probe appears to offer potential for faster and more reliable
inspection from the bore of hollow axles.

(3) The optical method shows promise for the sentencing of axles subject to corrosion
fatigue but more image analysis and classification work is needed.
Acknowledgements
This work was funded by the European Union under the FP7 Capacities programme Grant Agreement No FP7-SME-2010-1-262442 monitored by the Research Executive Agency (REA).

The support and permission of the other partners in the project (Applied Inspection (UK), CGM (Italy) Diatek (Germany), RCP (Germany) Lucchini UK, ATM (Italy) is gratefully acknowledged.

References
5. TTCi, ‘Remotely Detecting Cracks in Moving Freightcar Axles’ TTCi Report SAFETY-08 August 2006