An advanced ultrasonic inspection tool for rapid volumetric examination of aluminothermic rail

Lu ZHAO 1, John RUDLIN 1

1 NDT Section, TWI Ltd; Granta Park, Great Abington, Cambridge, UK
Phone: +44 1223 899000, Fax: +44 1223 890952; e-mail: lu.zhao@twi.co.uk, john.rudlin@twi.co.uk

Abstract
There are millions of aluminothermic field welds on Europe's rail network. Occasionally flaws develop during and shortly after welding that can lead to early failure and this can cause train derailment, disruption to train services and costs to the rail network, train operating companies and maintenance operators. The welds are made as a casting and are more difficult to inspect than joints made by other welding processes. The inspection tool, Railect, was developed to provide quick and easy inspection of the full weld body. The latest prototype is more robust, easier to deploy, and more importantly compatible with 4 types of rail profile, including 56E1, 54E1, 54E2, and 60E1. The first three are widely used in European rail industry, which allows the product to penetrate the European market.

This paper presents the operations of the inspection tool and shows how it has been made compatible with different profiles. Once deployed, defects on the head, web, and foot can be picked up by different sensors within a minute. Comparison trials are also described. In the recent trial, it has also been demonstrated Railect can easily detect foot flaws that were often missed by conventional UT.

Keywords: multiple track profiles; thermic weld; phased array; semi-automated inspection;

1. Introduction

The majority of field welding in the railway industry is carried out using the aluminothermic technique. Such welds are primarily associated with replacement of rail or weld defects, installation of insulated rail joint and track construction activities. In the UK, it is estimated that Network Rail produces over 65,000 Thermite welds per year and they have approximately 1.5 million welds installed on track.

Thermite welding is an effective, highly mobile and cost effective casting method of joining heavy steel structures such as rail; however this is also a very skilled welding process which requires experience and expertise. The many process steps can be altered by the welder and/or the environmental conditions and can therefore result in poorer weld performance and in creation of defects within the weld.

Up until this date; only a few techniques of inspection have had some limited success to control the quality of these welds. For instance; manual ultrasonic and radiography techniques are sometimes carried out on the welds but this is not commonly used in the railway industry. Most of the time, only visual inspection is performed. Every new weld is inspected using visual techniques for weld defects, profile and geometry. Although there is no requirement to inspect rail welds using ultrasonic, MPI or DPI techniques, there is a conventional ultrasonic standard EN 14730-1:2006 Annex C [1] developed specifically for the inspection of rail welds. This standard describes a relatively long and complex inspection. It involves the use of many conventional ultrasonic probes and the deployment of time consuming scans because of the complex weld profile geometry, making this technique only used occasionally.

As the welds use a casting process, these can be more difficult to inspect than joints made by other welding processes and as a result visual inspection is currently the only technique regularly used to inspect aluminothermic rail welds; which is often not reliable enough and involves the removal of potentially non-critical aluminothermic welds.

Rail flaw detection has an important part to play in ensuring the safety of railroads. Recent accidents such as the Hatfield disaster in the UK in 2000 caused by broken rail have focused
attention on the technologies that enable the detection of flaws in rails and rail welds. This paper describes a novel and semi-automated method of inspecting the full weld volume using phased array technique.

2. Method

2.1 Rail Profiles and Weld Dimensions

The latest prototype has been designed to be compatible with 4 different rail profiles, CEN60E1, CEN56E1, CEN54E1, and CEN54E2, as shown in Fig. 1. Those are the most dominant UK/European rail profiles and aluminothermic welds. As the prototype is designed, it is able to accommodate any rail sizes that fall in the range.

In summary, the range of rail height is from 158mm to 172mm; range of foot width 125mm to 150mm; range of head width: 67mm to 72mm; and range of head height 49mm to 51mm.

Fig. 1 Rail profiles of (left to right, top to bottom) CEN54E1, CEN54E2, CEN56E1, and CEN60E1

2.2 Defect Types

The project focused on three types of defects namely porosity, lack of fusion and shrinkage, as shown in Error! Reference source not found.2. These defects were considered the most common type of defects leading to potential failure of the rail weld when in service and hence critical to rail safety. The rail foot was more predisposed to the lack of fusion defect whereas the shrinkage defect was more likely to be located in the web of the rail. Unlike porosity, lack
of fusion and shrinkage were more likely to be found in specific areas of the rail weld. These observations were critical features to take into account for the design of the ultrasonic phased array system.

![Image of defects](image.png)

Fig. 2 The three types of most common defects (from left to right) porosity, lack of fusion, and shrinkage

### 2.2 Industrial Requirements

Following discussion with end-users, a number of industrial requirements were defined. General considerations about the overall device were investigated and specified. Indeed, as the system was planned to be mostly used on-site, it needed to be portable, easy to operate, quick to deploy, functional in inclement weather and give clear indications of defective welds. Furthermore, additional specifications about the joint geometry were defined prior to develop the system. The geometry considered would show a normal gap width of 25mm (± 2mm each rail) ranging from 26 to 80mm and the finish cast of 35mm ranging from 35 to 90mm. Finally, the distance between two sleepers being in average around 340mm, the inspection system would have to fit within those limits taking into account that the weld is not always centred between two sleepers.

### 3. Development of UT Phased Array System

#### 3.1 Modelling

In order to choose the most appropriate design, the design needed to provide the most effective coverage of the weld area and a design where data acquisition and analysis could be feasible and relatively fast. The other objective was to minimise the amount of scanning operations in order to maintain an easy application and analysis of the signal. The coverage of the weld area was investigated using both modelling and experimental tests. The modelling work investigated primarily the coverage of the weld, and the response from different defect types. This was carried out using both ESBeam tool and CIVA software. Fig. 3 shows some examples of the modelling output in which a 32 element phased array probe was considered for the purpose of the modelling experiments. The probe and focal law parameters were varied during the modelling experiments so that the most appropriate settings for full volumetric weld coverage could be identified.
Fig. 3 Modelling experiments using CIVA software showing beam coverage.

Fig. 4 presents some of the results obtained for the optimisation of the foot area coverage. In this particular case, a 16 elements phase array probe was implemented and positioned on the foot in order to investigate the ideal scanning parameters.

Thus, it was shown that one phased array probe could be used to cover the whole of the web and the central part of the weld foot from one side, and that another set of probes were needed to cover each side of the foot. In total, eight probes were necessary to carry out the inspection from one side of the weld centreline. Note that in order to perform a full volumetric inspection of the weld, data were collected from both sides of the weld centreline.

Various probe frequencies were investigated in the modelling work but the selection of the most appropriate frequency for the present application was carried out during the experimental testing.

Fig. 4 Modelling experiments using CIVA software for the detection of two 2mm diameter side drilled holes separated by a 2mm gap in the ankle of the rail foot.

### 3.2 System and Prototype Design

For the purpose of data acquisition and analysis, commercially available phased array instrument and software were used jointly to carry out the inspection and the recording of the
data. The focal laws were developed during the laboratory trials and optimised prior to being set up and saved in the instrument. Initially each law would be loaded and used at a time but their application could be controlled to enable an automatic sequencing to facilitate an automated inspection of the joint. The data output were collected for analysis.

In order to deploy the PAUT probes correctly around the rail joint, a specific prototype design was developed based on the modelling and laboratory trials. This system was clamped to the side of the railhead and combined all the PAUT probes necessary for a volumetric inspection. Those were then held in place around the rail profile by means of clamping mechanisms (Fig. 5). The overall weight of the mechanical design is under 15kg, and designed to be carried along the track manually. The design is also rugged for rough site conditions. With the design experience up to this date, we will be able to adapt the design concept to customised applications, including additional rail profiles, additional requirements on weight etc.

Fig. 5 The Latest Prototype Deployed on 60E1 Rail, with the Data Acquisition Being Carried out by Phased Array Instrument

4. Trials

4.1 Lab Trials
Laboratory trials were carried out to verify the correct operation of the focal laws and the detection of defects. Some of the results are shown in the Fig. 6 and Error! Reference source not found. 7.

Fig. 6 shows the validation of the model described in Fig 4 related to the inspection of the rail foot. The two 2mm diameter side drilled holes were detected using the probe and focal law parameters given by the model. Moreover, it was also possible to distinguish them even though they were only distant by 2mm.
Fig. 6 Sectorial scan performed on the ankle of the rail foot containing two 2mm side drilled holes in the rail foot.

Fig. 7 shows the scan obtained for the inspection of the web of the rail weld. In this case, the scan is obtained by the probe located on top of the rail at a selected probe offset with regards to the rail weld centreline. Both non defective and defective welds are illustrated on the figure below. One might notice that the bottom of the rail weld was easily seen on the scan due to the irregular surface finish underneath the rail foot. These indications could be used as a reference position when carrying out the inspection.

Fig. 7 (a) Sectorial scan of web with no defects (b) sectorial scan of web with porosities
Moreover, the presence of porosity (see Fig. 7b) was easily detected using the RAILECT system when compared with a reference sample (see Fig. 7a). In general, the RAILECT system covered a wider range of defect than the manual UT technique described in the standard [1]. This is explained by the fact that phased array technique was tailored to a specific profile by means of various focal laws.

4.2 Field Trials

The first prototype system was successfully tested on the Network Rail test track (see fig. 8) at the Rail Innovation and Development Centre in High Marnham where positive reactions were received from the project end user, Network Rail. More details can be found on Railect website [2], including a video recording the site trial.

![Fig. 8 Field trials on Network Rail test track with the second prototype](image)

Another trial using the latest prototype was carried out in Belgium (see figure 9).

![Fig. 9 Field trial in Belgium with the latest prototype](image)
5. Conclusion

The ultrasonic phased array inspection capability has been demonstrated and well received by end users. That proved the feasibility of an automated phased array system for inspection of rail welds. Modelling studies were validated by the experimental trials. Probe locations and parameters such as focal laws were investigated and optimised so that the maximum volumetric coverage of the rail weld could be achieved. The latest prototype has been shown to be able to fully inspect the aluminothermic weld in less than 10 minutes and robust for site inspections. In the latest comparison against conventional ultrasonic inspection, it has been shown that for the target flaws, it had a higher probability of finding them and can characterize and locate the defects in the weld much better than conventional ultrasonic. When adopted by the railway industry, the system will be one of the first automatic systems of inspection allowing rapid and simple detection of defects in rail welds. It will not only enhance rail safety significantly but also help railway operators reducing repair costs considerably.

6. On-going Work

The latest prototype shown in Fig. 5 is now undergoing more field trials to demonstrate its compatibility with multiple profiles and its conformance with existing standards. TWI is also actively gathering feedbacks about the latest design. With the experience TWI has gathered so far, customized designs with new requirement can be made to suit different needs of clients.

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