Rail Research UK
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Modelling and Detecting Damage (Wear and RCF) in Rails

Prepared for The Railway Safety and Standards Board

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Summary

This report summarises the work carried out at the University of Birmingham between January to May 2003. The main part of the work was to carry out a feasibility study on two methods for detecting rolling contact fatigue damage and microstructural changes in rails using non-contact sensors. Two sensor types were assessed, a multi-frequency electromagnetic (EM) sensor and an ultrasonic sensor (based on electromagnetic acoustic transducers, EMATs) using four rails with differing levels of damage. The test samples included a rail with severe gauge corner cracking, a rail with hairline cracks partially removed by grinding, a rail with no visible cracks but a microstructurally altered surface region (white layer) and an unused rail. It was found that the EM sensor could detect the severe gauge corner cracks through a difference in the phase angle measured at the highest frequencies. The design of the EM sensor was not optimised for rail and therefore did not have the resolution required for conclusively observing subtle changes in microstructure, although the initial results are promising and new sensors are being developed. The tests with the ultrasonic sensors clearly showed the system to be capable of detecting the severe gauge corner cracks. In addition differences in the normalised Rayleigh wave velocities measured suggest that the different surface microstructures of the rails, in particular the changes in microstructure around the rail head, could be differentiated. Again this sensor was not optimised for examination of rails and further work would be required to develop new sensor designs. In addition to the feasibility study on NDT sensors, links were established with Dr Ajay Kapoor's research group in Sheffield to discuss microstructural inhomogeneities in rails and to determine how these can be included in modelling of rail life.

Contents

1 Introduction

1.1 Aims / terms of reference

The work undertaken in the period January to May 2003 has been in two parts. The first section involved conducting a feasibility study on methods for detecting rolling contact fatigue in rails using non-contact sensor techniques potentially suitable for mounted vehicle use. The second section involved establishing links with Sheffield University (Dr Ajay Kapoor's group) to discuss metallurgical input into modelling rail life (project A2 in RRUK portfolio of research projects) and starting to develop a database of rail samples for the project.

1.2 Background

Rolling contact fatigue in rails has become a major safety and economic issue on the rail network. Although there are a number of techniques that allow detection of such cracking, none is currently suitable for use at normal train running speed and thus all require the work to be undertaken during track possessions, often at antisocial times of the day, which makes the process slow, expensive and prone to errors. The microstructure of the railhead material is a crucial precursor to head cracking. In order to optimise rail maintenance strategy accurate modelling of the development of damage in rails is required. In addition to detection of cracking, modelling the development of damage provides a valuable tool for the maintenance of the rail infrastructure. The Whole Life Model, developed by Dr Ajay Kapoor, is able to accurately reflect the interaction between wear and fatigue at different service conditions, however, further research is required to include detailed microstructural and mechanical property data for the steels of interest at the micron (x 10^{-6}m) and nanometer (x 10^{-9}m) scales.

Electromagnetic techniques have been used for NDT applications for several decades, exploiting a variety of EM effects such as detecting the fringing fields from surface breaking cracks or monitoring changes in the electrical and magnetic properties of the test piece using induced eddy currents. There is a mature market of EM NDT products and services across many industrial sectors, with instruments typically employing single frequency AC or pulsed excitation. EM sensors are particularly suitable for detecting surface breaking cracks and monitoring variations in near surface microstructure because the eddy currents induced in the target tend to circulate on surface layers due to the finite depth of penetration of the EM field, which is widely known as the skin effect. Generally, EM sensors must be relatively close to the target surface, although depending on the application the separation or lift-off can be several mm's or even cm's. In addition, there are proven techniques for avoiding the errors caused by variations in lift-off. In the rail industry, EM sensors are routinely used. Examples include production, (steel producers, such as Corus, use custom designed rotating sensors) and inspection and maintenance (hand held EMFaCIS device by Alstom based on the Newt Lizard system). Recently, pedestrian rail inspection systems have appeared commercially, and EM systems for measuring speed and distance have been reported. However, a vehicle mounted, fast rail inspection system is a key priority for rail inspection.

Contacting ultrasonic inspection such as the ‘Sperry Wheel’ device or other conventional water coupled piezoelectric transducers are routinely used in Europe and America to inspect rail tracks, usually for large planar defects in the head or weld. In recent years various attempts have been made to develop non-contact ultrasonic inspection techniques by a number of international researchers. These techniques have included laser based ultrasound (using lasers to generate and detect ultrasound), air-coupled ultrasound and electromagnetic acoustic transducers (EMATs). Laser based ultrasound is an elegant solution but can be relatively costly on the detection side. Another possible, less costly approach may be to use a hybrid system where a pulsed laser is used to generate the ultrasound and an EMAT detects the ultrasound. Air-coupled ultrasound does not appear to be sensitive or reliable enough to perform the tests. The use of EMATs alone however appear to offer a viable solution to many rail inspection problems.

1.3 Structure of the work

Dr John Garnham joined the rail research group in Birmingham in January 2003, to carry out the work. Dr Garnham completed a PhD on rail related research (wear of bainitic and pearlitic steels) and has considerable experience in rolling contact fatigue as well as in automotive engineering R&D involving failure analysis, project management, laboratory management, tribological test analysis and non-destructive testing. Valuable assistance to the project has been provided by Drs Peyton and Dickinson at Lancaster University (EM sensors) and Dr Dixon at Warwick University (ultrasonic sensors).

2 Results and discussion

2.1 Rail samples

Four rail samples were assessed; an unused rail and three rails taken out of service with different degradation levels (heavy wear, RCF cracks removed by grinding and severe RCF cracking). Sections from the four samples are presented in figure 1 showing different degrees of wear.

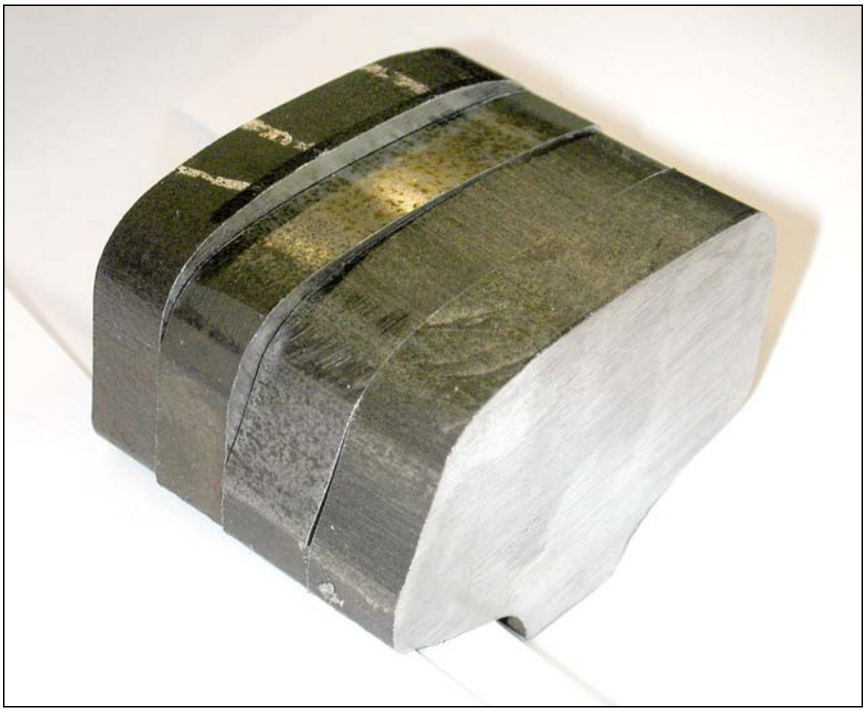

Figure 1. Transverse slices from rail samples A-B-C-D showing degree of wear.

Various types of inhomogeneities present in the rail steels have been noted, for example surface decarburisation, surface oxidation, mixed ferrite and pearlite microstructures (ferrite and pearlite have different mechanical properties), embedded oxides, inclusions (manganese sulphide and glassy silicates), heavily deformed surface microstructural layers (white etching constituent, deformed pearlite etc.). Example micrographs of key features are shown in figures 2-4. Work is now being starting on characterisation of the effect of the microstructural inhomogeneities on mechanical properties (e.g. nano-hardness testing).

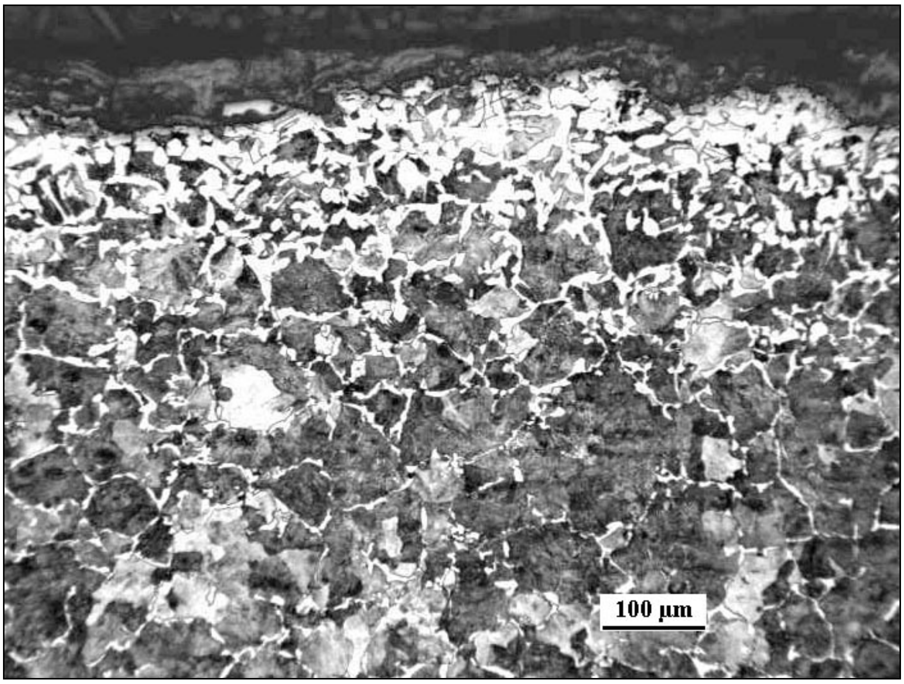

Figure 2. Unused rail sample showing surface decarburisation, surface oxide and mixed ferrite and pearlite microstructure.

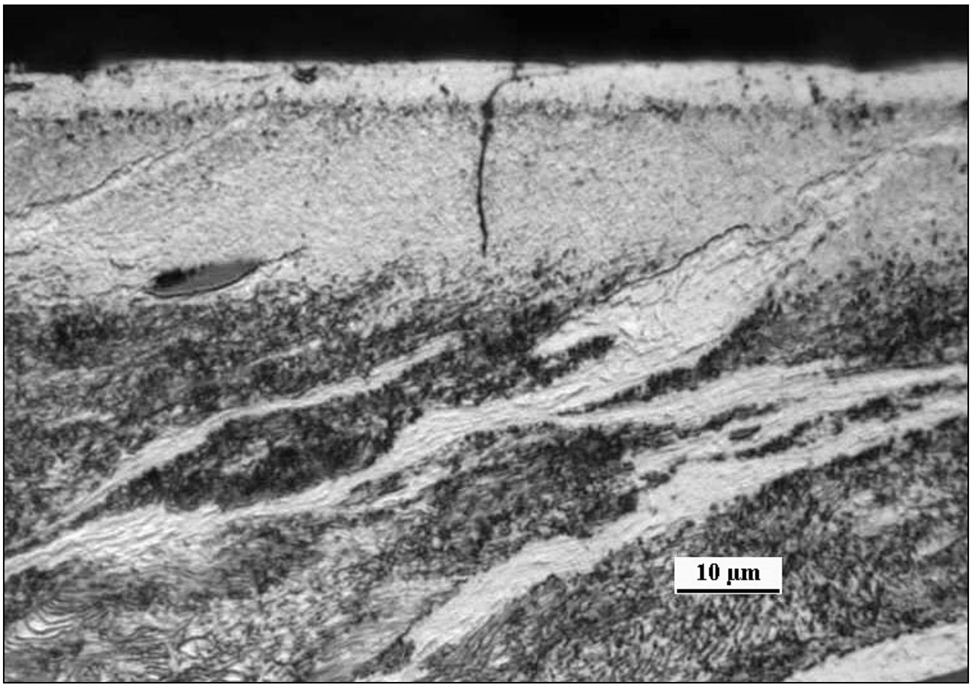

Figure 3. Heavily worn rail sample showing surface white etching layer (note two layer nature), manganese sulphide inclusion, deformed ferrite - pearlite (including ferrite region retained in part of the white etching region), and a surface crack.

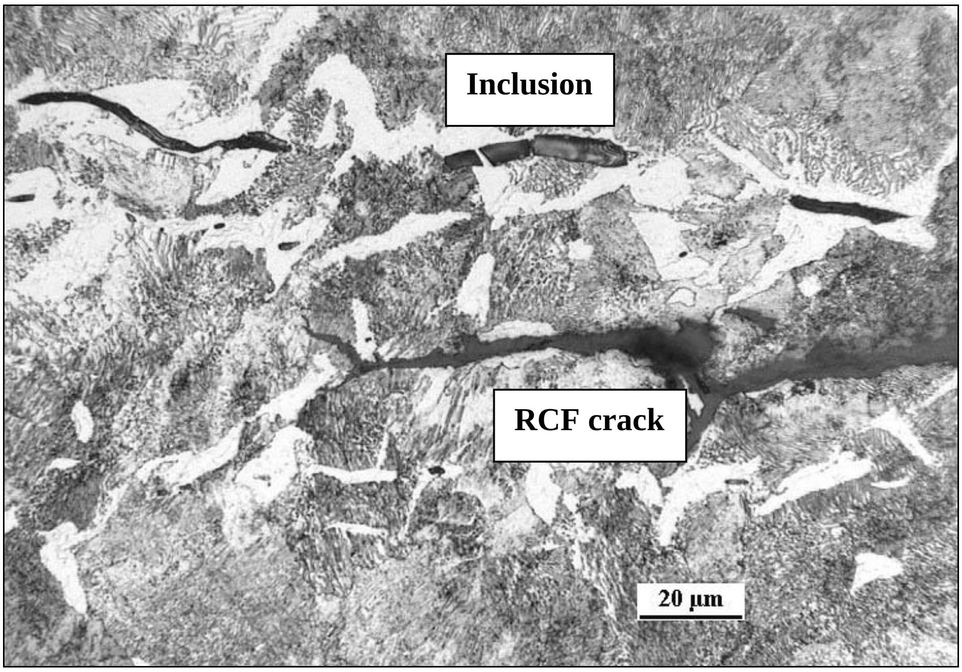

Figure 4. Worn rail sample containing severe RCF cracks showing the tip of an RCF crack which is fully oxidised and brittle glassy inclusions (one of which is cracked).

2.2 Electromagnetic sensors

The results for tests using an electromagnetic (EM) sensor with the sample rails are shown in figure 5. The different frequencies sample different depths of the material with the higher frequencies sampling the near surface regions. It can be seen that there is little difference in the phase angle values for rails A (unused rail) and B (heavily worn rail), although a small difference at the highest frequency may exist. A difference may be expected due to rail B having a deformed microstructure, however the sensor configuration was not set up for small scale changes to be detected, this would need to be developed further. However for rails C (RCF cracks removed by grinding) and D (rail containing severe RCF cracks) where sampling is carried out on the gauge corner side an increase in the phase angle is clearly seen for the higher frequencies which is likely to be due to the presence of a highly deformed material with fatigue cracks being present. The greater number, and size, of cracks in rail D is reflected in the large phase angle values.

The phase angle measured is insensitive to lift off (the distance between the rail and the sensor) within given limits, allowing the system to be used in a non-contact manner. The multi-frequency approach samples different material depths which may allow a 3-D analysis of the cracks to be measured.

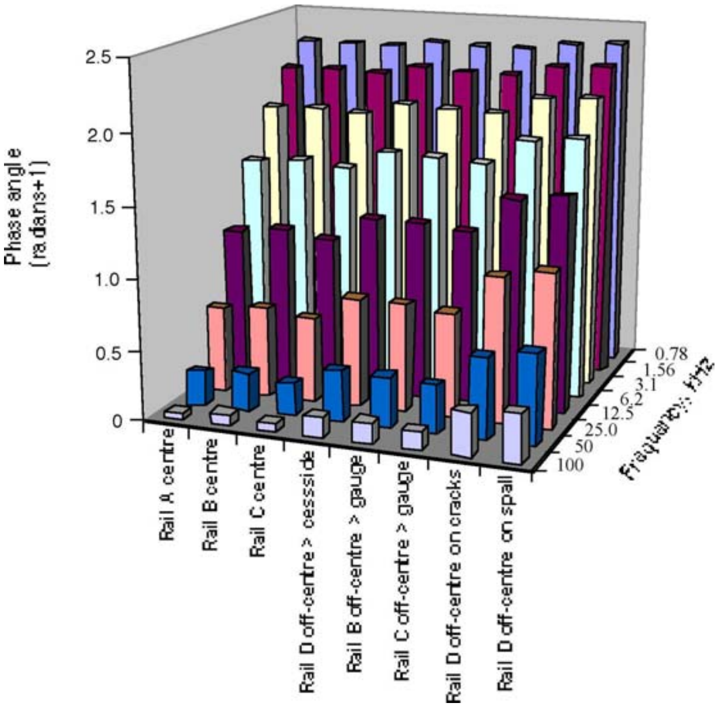

Figure 5. EM sensor results for four rail samples

2.3 Ultrasonic sensors

Results obtained using an EMAT-EMAT approach, for tests carried out at different positions around the profile of the rail samples, are shown in figure 6. The Rayleigh wave velocities were normalised to the velocity obtained on the centre and top of the head of sample A. This helps to demonstrate differences between surface wave velocities on each sample and relative variations between different samples. The results, shown in figure 7, indicate that there is little difference for rail A, as expected based on the rail being in the new condition where the microstructure would be relatively homogeneous. However, for the other rails significant differences can be seen in the normalised velocity, which will be caused by the differences in microstructure (due to the rails having different chemistries and differences in levels of deformation). It can also be seen that no reading was obtained for rail D in position 2, this is due to the presence of significant cracks being present at this position. This is a good approach to use in crack detection as conventional back-reflected inspection will not necessarily detect this type of crack. The HSE report of the Hatfield accident stated that the defects that caused track failure were probably ‘missed’ using conventional techniques.

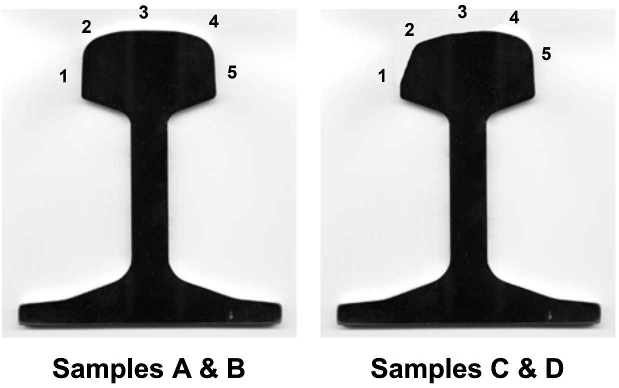

Figure 6. Schematic diagram of positions at which velocities were measured on the rail head down the length of the track.

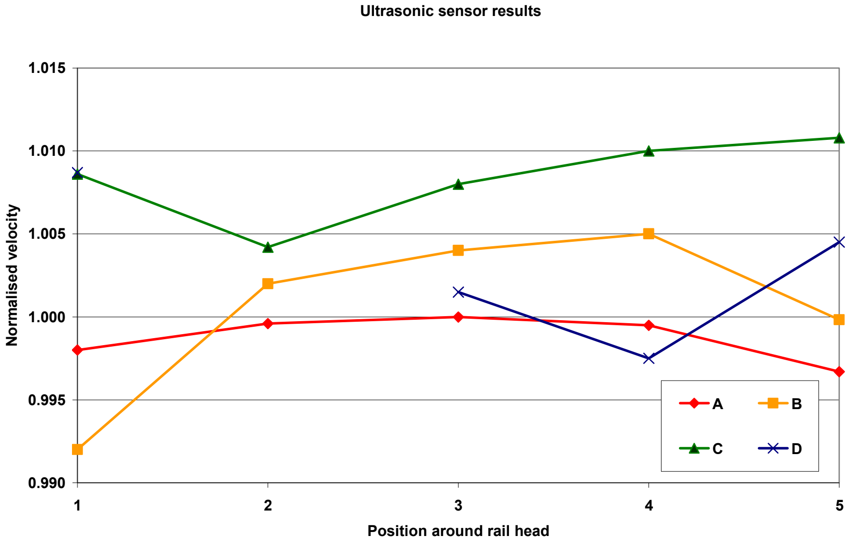

Figure 7. Ultrasonic sensor results for four rail samples.

Note that these are preliminary results and further tests showed slight variations in absolute differences between different samples, but good reproducibility on each sample.

2.4 Modelling rail damage

Discussions have been held with Dr Kapoor, and his research group, to determine the level of metallurgical detail required for the modelling work. Characterisation of a limited number of samples of rail has been carried out to determine the types of microstructural inhomogeneity that needs to be quantified for inclusion in the model. Further rail samples have been sourced to enable the microstructural development and inhomogeneity details to be assessed fully in rails with a variety of service histories. A literature review of current knowledge on microstructural aspects of rail contact is being carried out, including latest knowledge, from attendance at the 6th International Conference on Contact Mechanics and Wear of Rail/Wheel Systems in Gothenburg, Sweden, (June 10-13, 2003).

3. Safety implications

This research area is of significance to the rail industry as greater understanding and accuracy in detecting and modelling the fundamental causes of rail damage will aid the industry in planning the rail maintenance and renewal programme. Accurate rail life models allow the potential for cost savings from improved maintenance schedules (grinding and rail replacement) and the reduction in catastrophic rail failure accidents.

4. Conclusions and further work

4.1 Conclusions

1. Multi-frequency electromagnetic sensors were shown to detect the presence of severe gauge corner cracking through the measurement of a different phase angle values, particularly at high frequency. Small differences in phase angle were also noted for the different microstructures in the rail head.
2. The ultrasonic EMAT-EMAT sensors detected the presence of severe gauge corner cracking through the absence of a signal at the relevant position on the rail head. Differences in microstructure may be measurable through differences in the normalised Rayleigh wave velocities.

4.2 Further work

1. Further EM sensor design improvements need to be made to improve the resolution of the technique suitable for the application to rails.
2. A Laser-EMAT technique would also be suitable for use in detecting RCF cracks and microstructural changes, and may give better resolution and standoff between the rail and sensor. However, further development fixing detection and generation points to provide the necessary accuracy is required.
3. Measurement of the level of microstructural and mechanical property inhomogeneity on the micro- and nano-scale for the rail samples optically characterised. This will be used as input data to the Whole Life Rail Model.

5. Acknowledgements

Dr Tony Peyton and Dr Stephen Dickinson from Lancaster University are gratefully acknowledged for providing the EM sensors, conducting the sensor measurements and discussing the results. Dr Steve Dixon from Warwick University is gratefully acknowledged for providing the ultrasonic EMAT-EMAT sensors, conducting the sensor measurements and discussing the results.

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