

LA-UR-03-7128

Approved for public release;
distribution is unlimited.

| | |
|-------------------|--|
| <i>Title:</i> | THE MEASUREMENT OF RESIDUAL STRESS IN RAILWAY RAILS BY DIFFRACTION AND OTHER METHODS |
| <i>Author(s):</i> | J Kelleher (Manchester Materials Science Centre) Michael B. Prime (ESA-WR) D Buttle (AEA Technology plc) P M Mummery (Manchester Materials Science Centre) P J Webster (FaME38 at ILL-ESRF) J Shackleton (Manchester Materials Science Centre) P J Withers (Manchester Materials Science Centre) |
| <i>Details</i> | Journal of Neutron Research, 11 (4), 187-193, 2003. |



Los Alamos National Laboratory, an affirmative action/equal opportunity employer, is operated by the University of California for the U.S. Department of Energy under contract W-7405-ENG-36. By acceptance of this article, the publisher recognizes that the U.S. Government retains a nonexclusive, royalty-free license to publish or reproduce the published form of this contribution, or to allow others to do so, for U.S. Government purposes. Los Alamos National Laboratory requests that the publisher identify this article as work performed under the auspices of the U.S. Department of Energy. Los Alamos National Laboratory strongly supports academic freedom and a researcher's right to publish; as an institution, however, the Laboratory does not endorse the viewpoint of a publication or guarantee its technical correctness.

The Measurement of Residual Stress in Railway Rails by Diffraction and Other Methods

J Kelleher ^{*} ^a, M B Prime ^b, D Buttle ^c, P M Mummery ^a, P J Webster ^d, J Shackleton ^a, P J Withers ^a

- a) Manchester Materials Science Centre, Grosvenor Street, Manchester M1 7HS
- b) Los Alamos National Laboratory, Los Alamos, NM 87545, USA
- c) AEA Technology plc, Culham Science Centre, Abingdon, Oxfordshire OX14 3ED
- d) FaME38 at ILL-ESRF, Institute for Materials Research, University of Salford, Salford M5 4WT

ABSTRACT

Residual stresses have been measured in a new roller-straightened railway rail and a worn ex-service rail. Synchrotron $\{211\}$ lattice strain measurements at ID11 (ESRF) were used to map in-plane components of the stress tensor acting in cross-sectional rail slices. Stress maps made using laboratory X-rays and the magnetic measurement system MAPS, although coarser in detail, show similar trends. The validity of the measured data was examined using a stress balance requirement. Whilst generally true (to ± 15 MPa), stress balancing was worst (± 50 MPa) in regions with significant plastic deformation, suggesting that the measured $\{211\}$ lattice strain had become uncharacteristic of the bulk elastic strain. Attributable to plastic anisotropy, this is a well-established issue with diffraction-based stress determination. To complement the in-plane stress measurements, the contour method was used to map the longitudinal stress component in a similar new rail sample, this component being relieved in the slices. On the basis of this result, we show that the remaining unrelieved in-plane stresses in the rail slices are a suitable approximation of those in the original rail.

Keywords: residual stress; railway rails; plastic deformation; stress balance; contour method

* Corresponding author, joe@smartscience.co.uk

INTRODUCTION

Railway rails contain residual stresses arising from manufacture, in particular the roller straightening process. These stresses evolve during the service life of the rail, as a result of the wear and plastic deformation that occurs at the running surface. Changes in grain shape and texture are also observed. The most noticeable change in residual stress during service is the formation of a region near the running surface, extending up to about 20 mm into the rail head, which contains compressive residual stress in those directions parallel to the running surface. It is thought that this compressive layer provides some protection against fatigue crack growth. However, the compression is balanced by tension beneath this layer, and there is a danger that an internal material defect could be a nucleus for enhanced crack growth in this region or, if a crack originating from the surface does eventually grow through the compressive layer, its crack growth rate will increase when it encounters this tensile region.

Residual stress in rails has been measured with a number of techniques in recent years [1], in many cases on thin slices of rail. In a sufficiently thin slice (the exact thickness being dependent of the longitudinal stress distribution and rail geometry), the longitudinal stress is relieved and the remaining transverse and vertical stresses can be measured on the exposed surface of the slice. However, the relaxation of the longitudinal stress causes a change in these remaining stresses. If the original longitudinal stress is known, this change can be calculated using finite element methods. In this paper, a combination of synchrotron X-rays, laboratory X-rays and a magnetic stress system known as MAPS [2] has been used to measure the vertical and transverse stress in slices. By inputting contour method results for the longitudinal stress into a finite element model, it has been possible to assess the effects of stress relaxation caused by slicing and thereby show the measured in-plane stresses to be a good approximation of those existing in the original rail.

MATERIALS

Two rails were used for this study, a new roller straightened rail and a rail that had undergone 23 years of service. Both rails were BS 11 normal grade pearlitic steel with the standard 113A profile. The rail slices were cut to a thickness of 5 mm.

STRESS MEASUREMENT TECHNIQUES

Residual stress in rails is usually considered in terms of the individual stress components acting in the three orthogonal directions. We make the commonly used assumption that stress field varies slowly along the length of the rail, relative to the thickness of our slices. This implies that the longitudinal direction is very close to a principal stress direction. However, the transverse and vertical directions are not necessarily principal stress directions. Consequently, transverse, vertical and in-plane shear stress measurements were all made in the rail slices. Table 1 summarises the rail samples and stress components that were measured with each technique in this study.

Synchrotron strain mapping was applied on the ID11 beamline at the ESRF using X-rays of approximately 75.0 keV to determine the $\{211\}$ ($2\theta \approx 8.1^\circ$) lattice strains averaged through thickness in the transverse and vertical directions. A drift in the beam energy over time was monitored and subsequently corrected for by repeatedly measuring one particular area of the sample during the strain scanning. The synchrotron measurements were made in transmission geometry so that the strains were evaluated over a gauge of 500 μm in the direction of the strain vector and 750 μm in the in-plane direction at 90° to this, with the gauge volume extending equally out of each face of the sample over a total distance of about 7 mm. For each strain component of each sample, a single value for the stress-free lattice spacing d_0 was calculated that gave a stress of zero for the in-plane directions when averaged over the entire sample area. By calculating separate values of d_0 for each strain measurement direction, the effect of any small differences in beam energy between the vertical strain scanning runs and the transverse strain scanning runs was made negligible. A state of biaxial plane stress was assumed, and the vertical and transverse components of the stress were calculated using the elastic constants $E = 209 \text{ GPa}$, $\nu = 0.30$ in the stress-strain relation

$$\begin{aligned}\sigma_{transverse} &= \frac{E}{1-\nu^2}(\varepsilon_{transverse} + \nu\varepsilon_{vertical}) \\ \sigma_{vertical} &= \frac{E}{1-\nu^2}(\varepsilon_{vertical} + \nu\varepsilon_{transverse})\end{aligned}\quad (1)$$

Laboratory X-ray measurements were made using a Proto iXRD system (<http://www.protoxrd.com/ixrd.html>). Cr K α radiation was used to measure the {211} peak at $2\theta \approx 156^\circ$. The use of soft X-rays in a reflection geometry results in a sampling volume extending about 10 μm into the sample surface. The MAPS magnetic stress measurement system [2] was also used to map the in-plane stress, in our case with the sampling depth set at approximately 500 μm through the use of an AC magnetic field with a frequency of 252 Hz. Lateral spatial resolution was limited by the magnetic probe size to around 5 mm. The MAPS system relies on a combination of magnetic signals to derive the orientation and magnitude of the principal in-plane stresses [2].

In contrast to these in-plane measurements on thin slices having essentially zero longitudinal stress, the contour method [3], a destructive technique, was used to deduce the unrelaxed longitudinal stress distribution in a new roller straightened rail sample 70 cm in length. This technique involves making a planar wire electrodischarge cut completely through a rigidly held specimen. Upon cutting, the relaxation of the out of plane stress component causes the surface to deviate from planarity. By measuring the profile of the newly created surface, the original out of plane residual stress can then be uniquely calculated from a finite element model in which the distorted surface is forced back into a planar state.

RESULTS AND DISCUSSION

Residual macrostress (type I residual stress) is just one effect of plastic deformation in rails. Other effects can adversely influence stress measurement techniques to varying extents. In this instance, such effects of plastic deformation include

- Intergranular (type II) stress, which typically broadens diffraction peak widths but can cause peak shifts when the stress is grain orientation dependent [4]. Some peaks are more susceptible to shifts than others.
- Texture, which can affect the elastic constants and magnetic permeability (an issue for MAPS measurements [5]).
- Interphase (ferrite-cementite) stress [6]. Laboratory X-ray, synchrotron X-ray and MAPS measure only the ferrite, and if the stress in the ferrite is different from the overall stress, then assumptions about stress balancing and longitudinal stress relaxation may be invalidated. Furthermore, relaxation of any out-of-plane interphase stress at a surface can distort laboratory X-ray measurements of the in-plane stresses [7];

The transverse and vertical stresses retained in the new roller straightened rail slice, measured with synchrotron radiation, are shown in Figure 1 alongside the unrelieved longitudinal stresses found using the contour method. Adjacent to these maps is a plot of the vertical stress averaged across the rail slice, as a function of vertical position. This average should be zero in order to satisfy stress balancing requirements, and can be used to estimate the measurement error at different vertical positions. The average intensity (a function of texture) and average peak full width at half maximum (FWHM, an indication of type II stress) at each vertical position are also plotted. The average FWHM is clearly largest near the surface of the head due to plastic deformation. This corresponds well with the largest deviation from stress balance..

It is important that the longitudinal stress in the slices is completely relieved in order for the assumption of a biaxial stress field to be valid. Furthermore, the presence of any remaining longitudinal stress will be accompanied by a variation in the in-plane stresses through the thickness. If such a variation is present, the in-plane stresses measured by a technique will depend on the sampling depth of the technique used. This would cause an apparent disagreement between the techniques. To examine this potential problem, we used the unrelaxed longitudinal stress distribution determined with the contour method to predict the longitudinal stresses that would remain in slices of different thicknesses. It was found that a 5 mm thick rail slice would have a longitudinal stress of less than 3 MPa over essentially the entire volume of the slice,

with the longitudinal stress only becoming significantly greater in the sharp longitudinal stress gradients at the bottom of the rail foot.

The finite element model was also used to predict the difference between the transverse and vertical stresses in the rail slice and the same stress components in the original rail, before the slice was cut. The results showed that the residual stresses in the slice are a good approximation of the original transverse and vertical stresses. The difference between the rail slice stresses and the original rail stresses was no more than ± 30 MPa in most areas, and this difference varied slowly across the rail slice. Consequently, the positions and shapes of the features of the residual stress field in the slice are very similar to those that would have been present in the original rail, even if the magnitudes are slightly different. The effect of longitudinal stress relaxation in thicker slices was also modelled. It was found that as the thickness of the slice is increased beyond 5 mm, the in-plane stress field at the surface of the slice becomes a progressively poorer approximation to the transverse and vertical stresses in the original bulk rail. A difference of over 100 MPa between the stresses at the slice surface and the original in-plane stresses was found at some locations for slices over 50 mm thick.

Synchrotron X-ray results for the ex-service top-worn rail sample are shown in Figure 2. As anticipated, the main differences between this sample and the new rail occur near the running surface. The discrepancies revealed by the stress balance plot are in the same locations as for the new rail, but with the sign of the imbalance suddenly changing near the running surface. Over the whole height of the rail, variations in both the average FWHM and the average intensity appear to correlate with the average unbalanced vertical stress. This suggests that plastic deformation from manufacture and service has introduced both intergranular stress and texture. As a result, the measurement error revealed by stress imbalance cannot be definitely attributed to a single cause. The correlation between the average vertical stress, peak widths and peak intensities suggests that unrelaxed macroscopic longitudinal stress, even if it exists, is probably not the main source of the stress imbalance in the data. However, it is possible that interphase stress is contributing to the apparent stress imbalance. Because interphase stress is introduced through plastic deformation of the ferrite, which would also introduce intergranular stress and texture at the same

location, it would be expected that any stress imbalance due to interphase stress would correlate with the FWHM and intensity variations. Therefore, intergranular stress, texture and interphase stress should all be regarded as possible causes of the stress imbalance in the data.

The head of the ex-service rail was also measured with the MAPS magnetic system and laboratory X-rays. The results, including the principal stress directions, are shown in Figure 3.

Both techniques confirm the presence of transverse compression near the top of the rail. In agreement with the synchrotron results, this region has a near constant depth of about 8 mm below the contact surface and the magnitude of the compression is slightly greater near the corners. However, there is some disagreement on the distribution of the balancing sub-surface tensile stress. The synchrotron results show two small highly tensile spots, at opposite sides of the rail head. The laboratory X-ray results show larger tensile regions of lower magnitude, which are sufficiently close together that no clear distinction between them can be seen. The MAPS results are intermediate in each of these respects. It is possibly significant that the MAPS measurements were also intermediate in sampling depth. Similar patterns have been observed for MAPS and laboratory X-ray results in other rails. This suggests that the measured in-plane stresses vary with depth. Whilst incomplete relaxation of the macroscopic longitudinal stress may explain this, the effect is also consistent with the presence of interphase stresses [6]. The latter is considered to be more likely, as the longitudinal stresses would vary most sharply (and hence be more prone to incomplete relaxation in the slice) near the running surface of the rail, but in this region the agreement between techniques is better. The techniques also disagree on the magnitude of the vertical stress within the bulk of the head, this being mostly over 100 MPa tensile in the MAPS results, up to 100 MPa tensile for the synchrotron results and slightly less than zero in the laboratory X-ray results. The laboratory X-ray and MAPS results show good agreement for the principal stress directions, however. The MAPS results more clearly show the trend that the principal directions are generally aligned with the nearest free surface in the rail.

CONCLUSIONS

The different stress measurement techniques generally agree on the shape of the compressive layer near the contact surface, and the approximate magnitude of the compressive stresses. The main differences occur within the head where the balancing tensile stresses occur, these differences being qualitatively dependent on the sampling depth of the technique. The measured stress fields generally satisfy stress balancing requirements to within only small error. This error is correlated with the peak widths and intensities, suggesting the error arises from a micromechanical or microstructural effect of plastic deformation. The use of the contour method for finding longitudinal stress, in combination with measurements of the in-plane stresses in rail slices, was found to be an experimentally convenient approach for determining the full stress tensor in a rail.

ACKNOWLEDGEMENTS

The authors would like to thank Fame38 for assistance and the European Synchrotron Radiation Facility for provision of synchrotron radiation facilities, G B M Vaughan for assistance in using beamline ID11 and Corus R D & T for their sponsorship of JK. PJWi acknowledges the support of a Royal Society-Wolfson Merit Award.

REFERENCES

1. O. Orringer, J. Orkisz and Z. Swiderski, *Residual Stress in Rails Volume 1: Field Experience and Test Results*, [Kluwer Academic Publishers, Dordrecht, 1992]
2. D. J. Buttle, W. Dalzell, and P. J. Thayer, Non-destructive residual stress measurement in rail heads and rolling contact fatigue, *Insight*, **44** (6), pp. 364–368 (2002)
3. M. B. Prime, Cross-Sectional Mapping of Residual Stresses by Measuring the Surface Contour After a Cut, *J. Eng. Mater. Technol.*, **123**, pp. 162-168 (2001)
4. M. R. Daymond, M. A. M. Bourke, R. B. Von Dreele, B. Clausen and T. Lorentzen, Use of Rietveld refinement for elastic macrostrain determination and for evaluation of plastic strain history from diffraction spectra, *J. Appl. Phys.*, **82** (4), pp. 1554-1562 (1997)

5. D. J. Buttle and C. Scruby, Residual Stress: Measurement using Magnetoelastic Effects, *The Encyclopaedia of Materials: Science and Technology*, Pergamon Press, Elsevier Science (2001)
6. M. L. Martínez, C. R. Borlado, F. J. Mompeán, R. L. Peng, M. R. Daymond, J. Ruiz and M. García-Hernández, Neutron strain scanning in straightened eutectoid steel rods, *Appl. Phys. A*, **74**, pp. S1679-S1682
7. H. Ruppertsberg, Stress fields in the surface region of pearlite, *Mater. Sci. Eng.*, **A224**, pp. 61-68 (1997)

Table 1 The stress components and rail samples measured with each technique.

| | Stress measurement technique | | | |
|-----------------------------------|-------------------------------------|--|--|-------------------|
| | Synchrotron X-ray | Laboratory X-ray | MAPS | Contour method |
| Stress components measured | Transverse Vertical | Transverse Vertical In-plane shear | Transverse Vertical In-plane shear | Longitudinal |
| Rail samples measured | New Ex-service | Ex-service | Ex-service | New |

Figure 1 Longitudinal (before slicing), transverse and vertical (after slicing) components of the residual stress in a new roller straightened rail sample. A plot of the vertical stress averaged across the width of the rail as a function of vertical position is shown (right). The corresponding FWHM and integrated intensity variations are also shown.

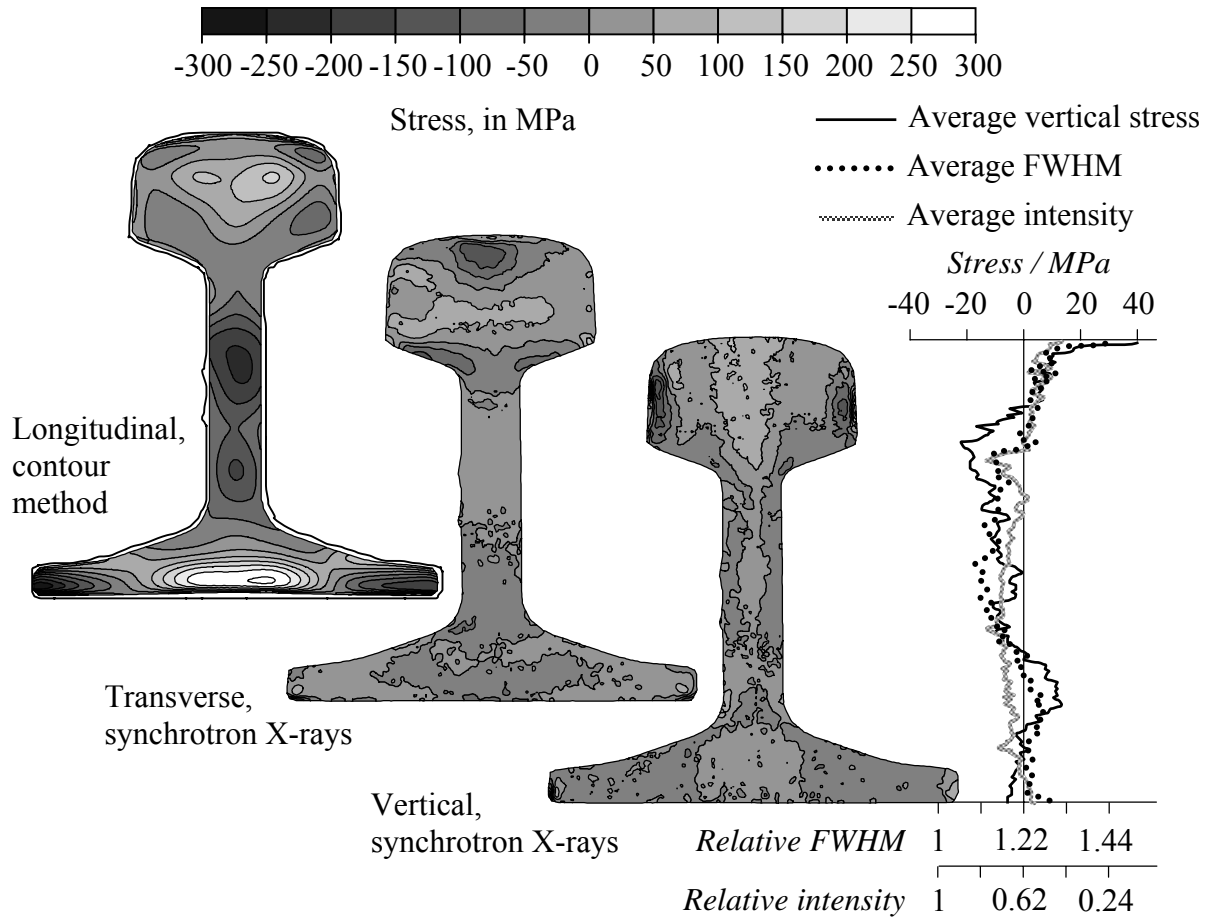


Figure 2 Transverse and vertical components of the residual stress in an ex-service rail sample worn from the top surface. A plot of the average vertical stress at the corresponding vertical position is shown (right). The FWHM and integrated intensity variations are also shown.

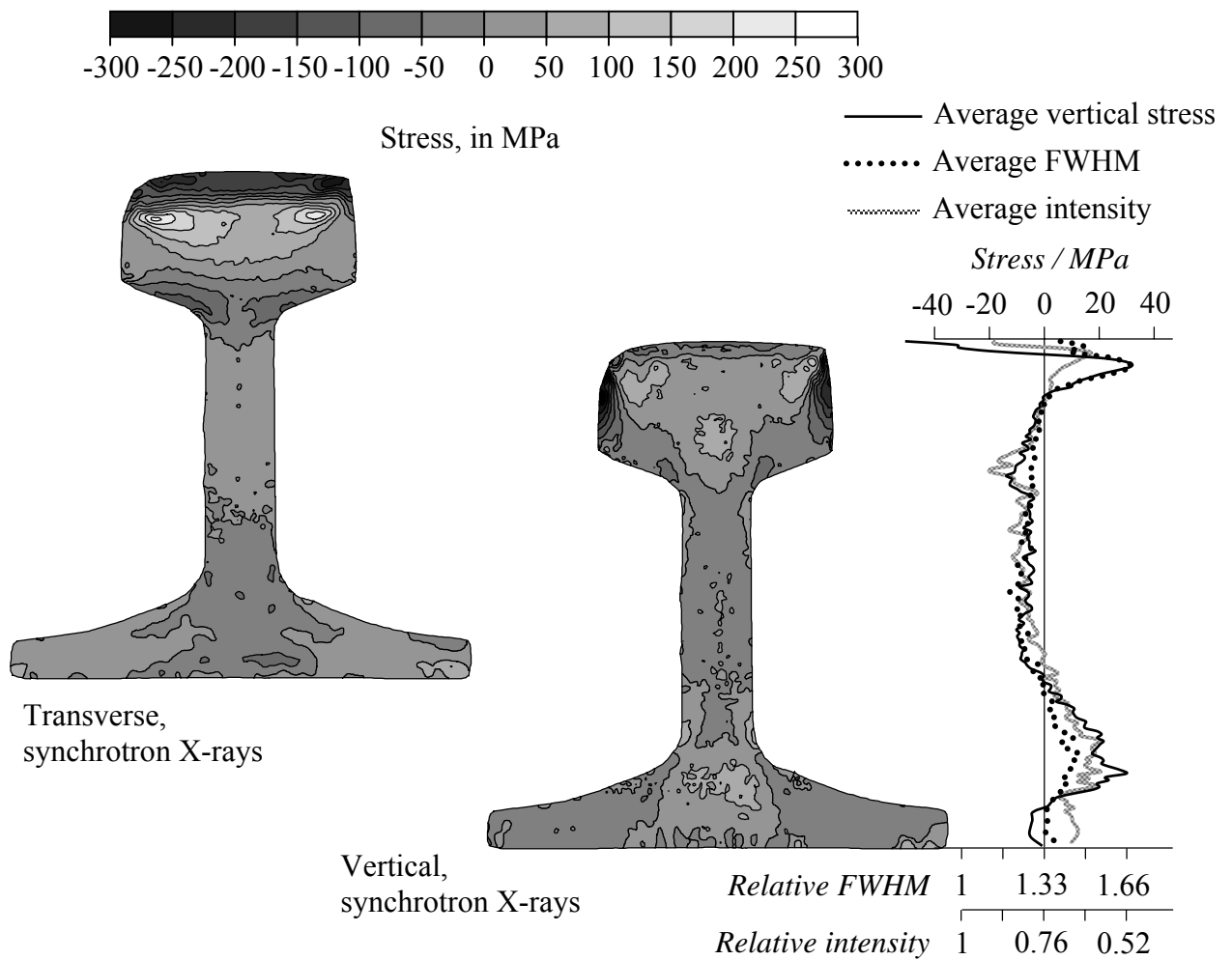


Figure 3 Residual stress in the ex-service rail sample, as measured with MAPS and a laboratory X-ray system. Transverse and vertical components are shown by the contour plots. Arrows at the measurement locations indicate the directions and relative magnitudes of the principal stresses.

