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Author(s):

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)

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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 radiation at ID11 (ESRF) was used to map components of the stress tensor acting in cross-sectional rail slices. Residual stress was deduced from the {211} lattice strain measured in the vertical and transverse directions. 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 the requirement that the average stress acting normal to any cross-sectional plane through a residually stressed body is zero. Whilst generally true (to ±15 MPa), stress balancing was worst (±50 MPa) in regions with significant plastic deformation, suggesting the measured {211} lattice strain had become atypical of the bulk elastic strain. Attributable to plastic anisotropy, this is a well-established issue with diffraction-based stress determination. The contour method was also used to map the longitudinal stress component in another new rail sample, this component being relieved in the slices. On the basis of this result, we show that the remaining unrelieved 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 though 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 of rail, 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, synchrotron X-rays, laboratory X-rays and a magnetic stress system known as MAPS [2] have been used to measure the vertical and transverse stress in slices. The results are compared and possible causes for some discrepancies are considered. By inputting contour method results for the longitudinal stress into a finite element model, the similarity between the stresses in the slices and the stresses in the original rail is examined.

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.

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 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. The transverse and vertical directions are not necessarily principal stress directions, however, and hence the shear component in the transverse-vertical plane was measured with some techniques. Transverse, vertical and 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 to determine the {211} ($2\theta \approx 8.1°$) lattice strains averaged through thickness in the transverse and vertical directions. From these values, together with the assumption that the longitudinal stress averaged through thickness was zero, the corresponding vertical and transverse components of the stress was calculated using the elastic constants $E = 209$ GPa, $\nu = 0.30$.

Laboratory X-ray measurements were made using a Proto iXRD system (http://www.protoxrd.com/ixrd.html). Cr Kα radiation was used to measure the {211} peak at $2\theta \approx 156°$. 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. In contrast to these in-plane measurements on thin slices having essentially no 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.

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 affects diffraction peak widths but can cause peak shifts when the stress is related to grain orientation [4];
- Texture, which can affect the elastic constants and magnetic permeability (an issue for MAPS measurements [5]);
- Interphase (ferrite-cementite) stress, which can distort laboratory X-ray measurements [6];

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 with an offset and linear scale chosen to give a subjective fit to the average vertical stress. The FWHM shows similar trends to the average vertical stress.

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 in almost 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 up to $\pm$ 30 MPa in most areas, but this difference varied slowly across the rail slice. Consequently, the positions and shapes of the features of the residual stress field in the slice would be very similar to those in the original rail, even if the magnitudes may be slightly different. The effect of longitudinal stress relaxation in thicker slices was also modelled. It was found that as the thickness of the slice increases beyond 5 mm, the stress field at the surface of the slice becomes a progressively poorer approximation to the transverse and vertical stresses in the original rail, in comparison to the 5 mm thick slice. A difference of over 100 MPa between the stresses at the slice surface and the original in-plane stresses was seen at some locations for slices over 50 mm thick.

Synchrotron X-ray results for the top-worn rail sample are shown in Figure 2. As anticipated, the main differences between this sample and the new rail sample 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, 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, and hence the measurement error revealed by stress imbalance cannot be definitely attributed to a single particular cause. The correlation between the average vertical stress, peak widths and peak intensities suggests that unrelaxed longitudinal stress, even if it exists, is probably not the main source 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 thickness of about 8 mm 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, 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.

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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. The FWHM and integrated intensity variations are also shown with an arbitrary offset and units.

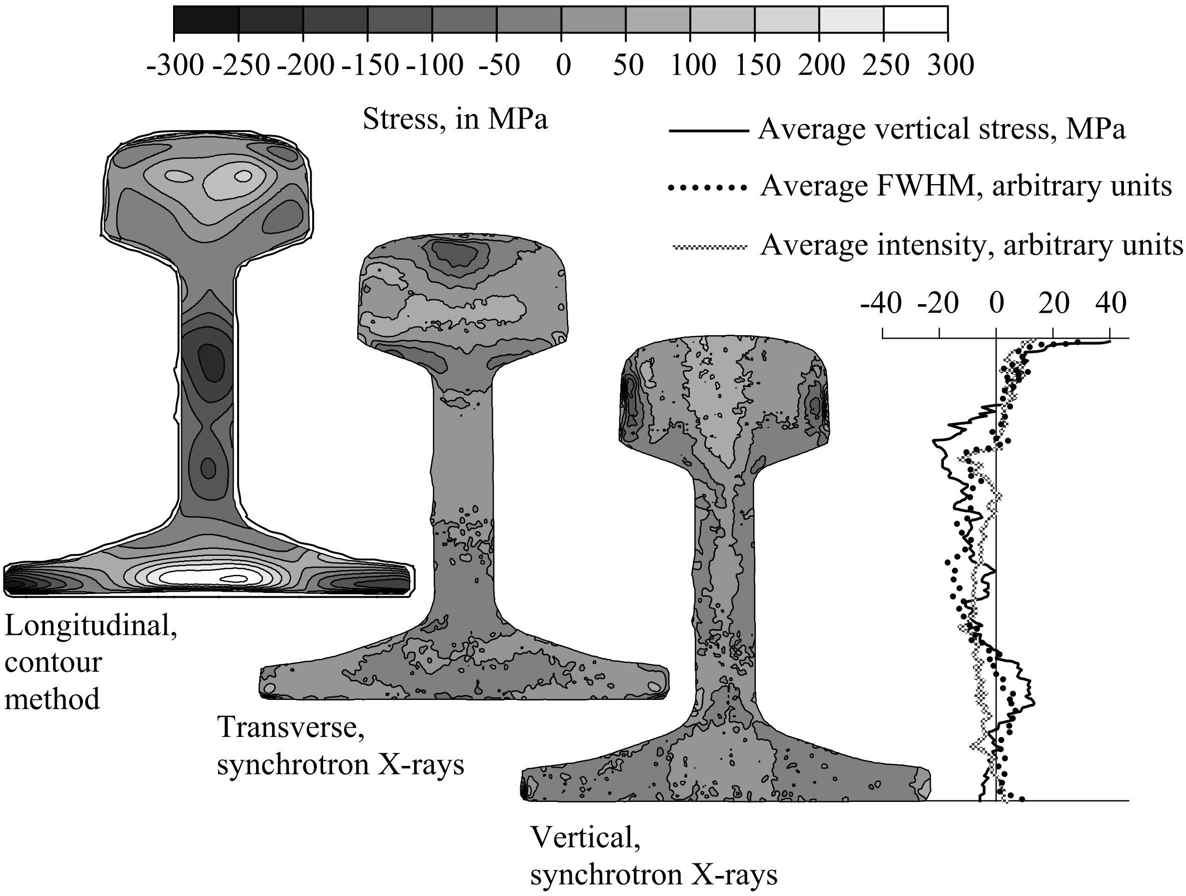

Figure 2 Transverse and vertical components of the residual stress in an ex-service rail sample worn from the top surface. A plot of the average vertical stress at the corresponding vertical position is shown. The FWHM and integrated intensity variations are also shown with an arbitrary offset and units.

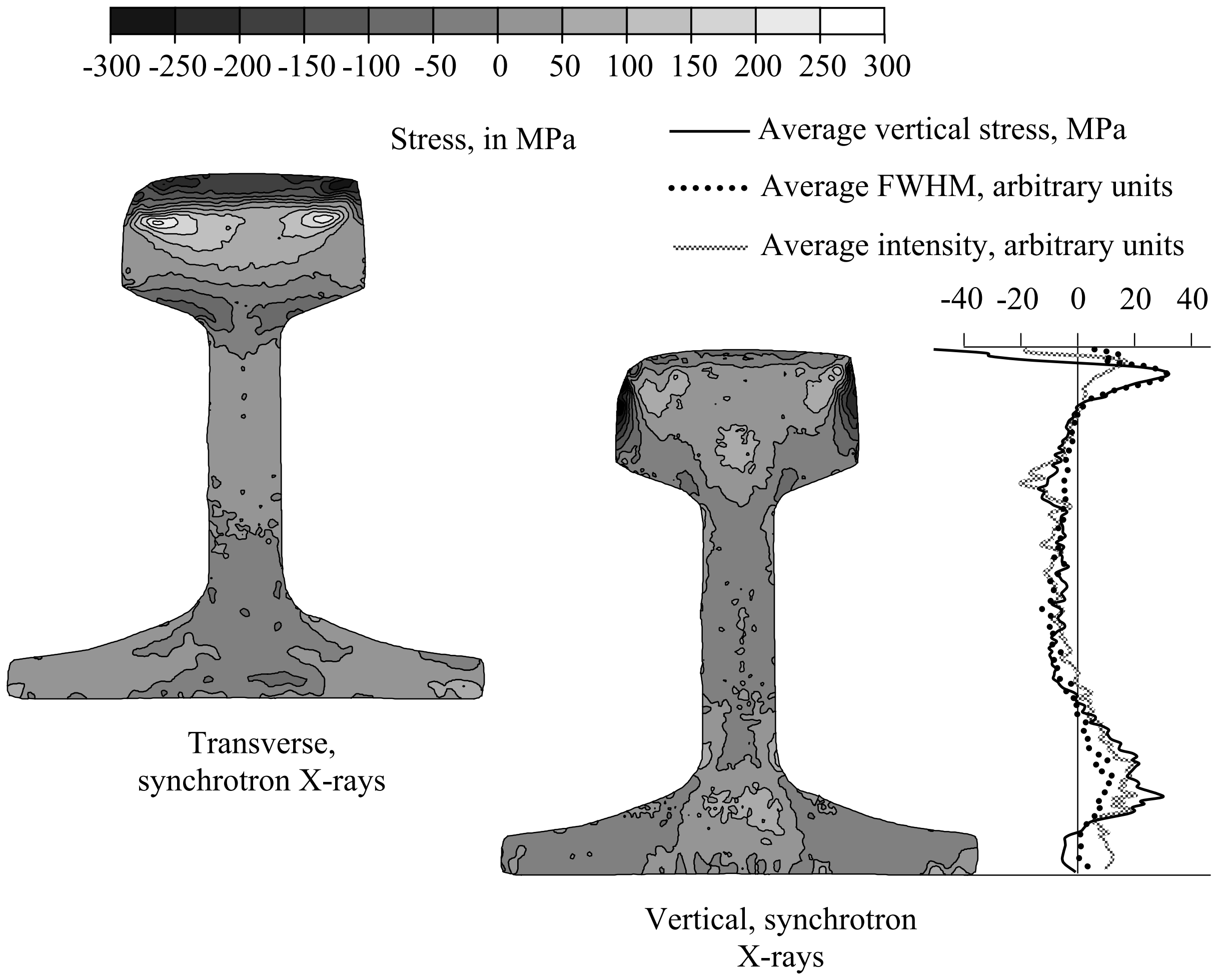

Figure 3 Residual stress in the ex-service rail sample, as measured with MAPS and a laboratory X-ray system. Arrows at the measurement locations indicate the directions and relative magnitudes of the principal stresses.