

The work described in this *Technology Digest* was performed by Transportation Technology Center, Inc., a subsidiary of the Association of American Railroads.

Key Findings:

- One new and three worn rails were cut to allow surface mapping and analysis of residual stresses. Results show how initial stress distribution in a new rail changes over time as the rail is subjected to wheel-rail contact forces causing wear and plastic deformation. In every case, the compressive stresses are balanced by tensile stresses generating an overall complex map of residual stress distribution.

Determining Residual Stresses in Rails using Contour Method

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[Transportation Technology Center, Inc. \(TTCI\)](#) recently generated estimates of residual stresses in railroad rails. Results from using the recently-developed contour method were used to create plots of residual stress distributions within the cross sections of a new rail and three rails of differently worn head profiles. Analysis of the compressive and tensile residual stresses of the rail cross sections are being used to predict likely areas of highest tensile stresses in the rails.

BACKGROUND

Residual stress estimation has been a challenging area of research over the last few decades. X-ray and neutron diffraction measurements of atomic lattice spacings, interpreted as residual strains¹ have been used on rails as shown in Figure 1a, while other methods have used direct measurement of residual strains by instrumenting the rail cross section with strain gages^{2,3} and recording strain changes by sectioning the sample as shown in Figure 1b. The X-ray and neutron diffraction methods lose resolution as the beams undergo considerable scatter before they reach the center of the rail head travelling through the rail. Strain gage methods involve cumbersome and time-consuming efforts in attaching small strain gage rosettes on the rail cross-sectional surface; which can be subject to measurement errors.

TTCI has previously performed research on residual stress estimation on a variety of metal components such as wheels, joint bars, and welds. The results gave good indications of compressive and tensile stress distributions on the external surfaces, but no stresses within the cross sections were determined from this approach.^{4,5,6} In all cases, the strain gage method was used as shown in Figure 2. Strain gages are shown as small rectangles in Figures 2a through 2c, respectively. An alternative method was attempted to measure stresses on wheels using the slitting method, but this method is limited to one-dimensional residual stress profiles.⁷

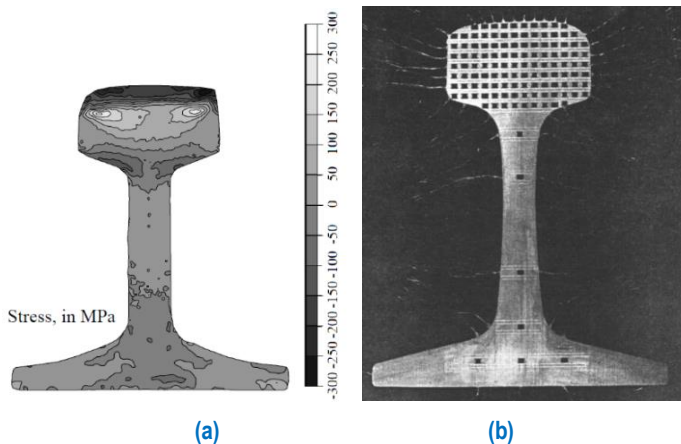


Figure 1. (a) X-ray measurement of residual stresses in transverse direction of a worn rail¹, (b) Strain-gage rosettes on rail head, web and base for residual strain measurements^{2,3}

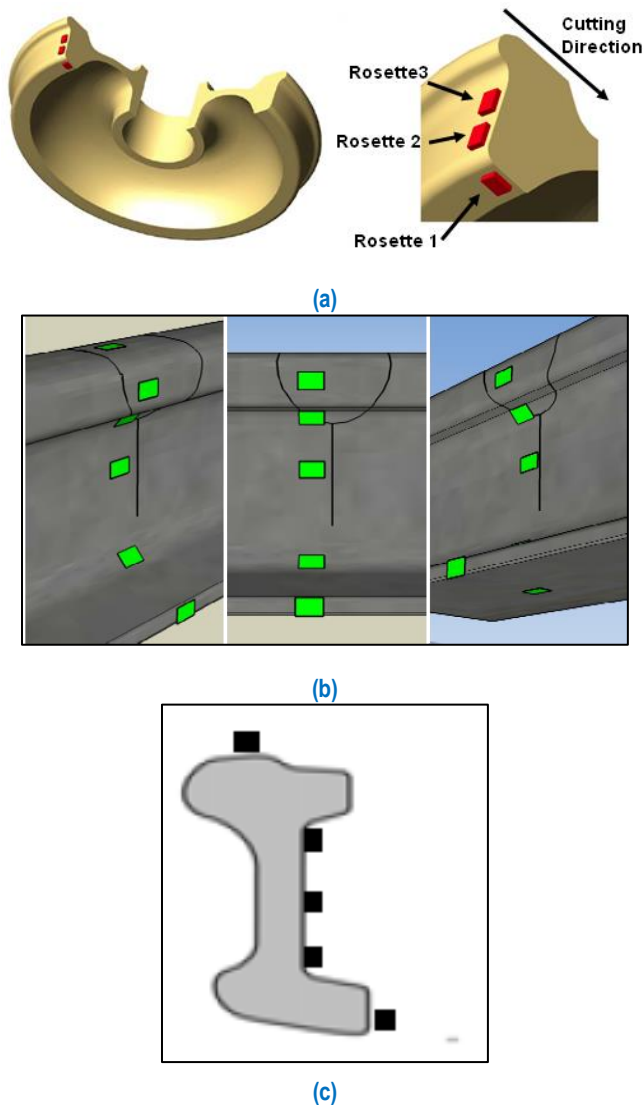


Figure 2. Strain-gage rosettes on (a) outer circumference of wheels,⁴ (b) outer surface of a weld⁵ and (c) a joint bar⁶

CONTOUR METHOD

The contour method is a fairly new method of estimating residual stresses. The technique involves cutting a specimen into two pieces and measuring the resulting deformation. The measured displacement data results are used to compute residual stresses through an analysis that involves an FEA model of the specimen.⁸ The output is a two-dimensional map of residual stress normal to the measurement plane.

The original sample has a stress distribution of compressive and tensile stresses. These deformations at the cut surfaces are converted to strains for calculating stresses that were present before cutting.

Four rail samples were tested in two phases for this residual stress analysis. The first set of specimens sent for analysis was comprised of a new rail that was received from a manufacturer and had never been laid on track, and a worn rail with significant gage face wear that had been used in tests on the High Tonnage Loop at the Transportation Technology Center, Pueblo, CO. The second set of specimens was comprised of rails received from revenue service that had experienced substantial head wear.

Cutting the Rail Samples

Rail samples were longer than 24 inches to ensure that the location of the contour method measurement was mechanically remote from any other cut surfaces.

The wire electrical discharge machining (EDM) process is the preferred cutting method as the wire is electrically charged and spark erosion causes the cut without the cut surface coming in contact with the physical wire. The rail sample is submerged in temperature-controlled deionized water during cutting to minimize thermal stress effects. This process can achieve positional precision within a fraction of a micrometer for a straight cut.^{8,9}

Measuring the Cut Surfaces

As Figure 3a shows, the contour plane was chosen at the center of the sample and the wire EDM process cut each rail sample into two pieces. The two pieces now had deformed surfaces at the cut. The displacements at these new surfaces were measured at the micrometer scale using a laser-based scanning profilometer, shown in Figure 3b.

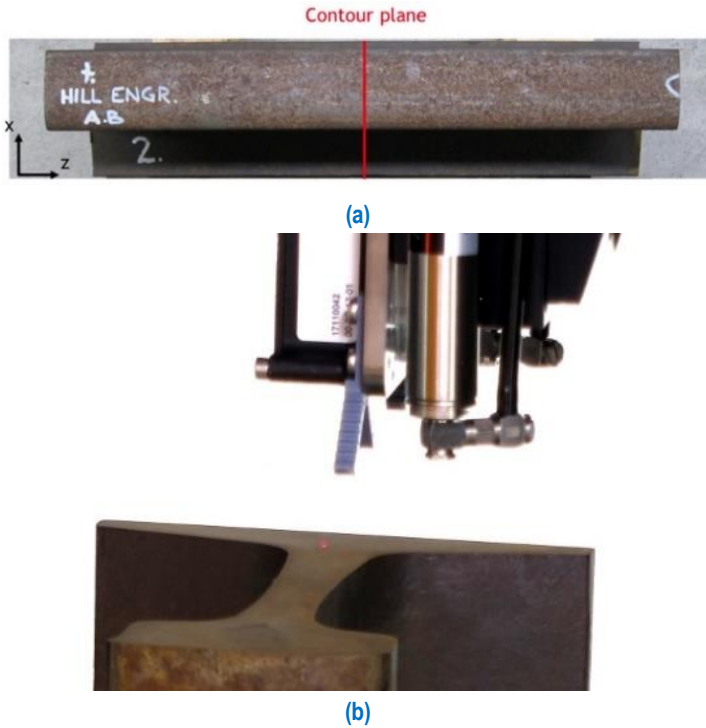


Figure 3. (a) Contour plane selected on a rail sample, (b) precision metrology equipment measuring surface heights of the surfaces after wire EDM process (Photo courtesy: Hill Engineering)

Finite Element Analysis (FEA) Model

An FEA model representing half of the rail sample was created using the measurements received from the metrology equipment and a finite element mesh was generated using that geometry. Displacement boundary conditions were applied to the model to recover the original flat surfaces at the cut. The resulting stress values obtained for all the points in the FEA model were used to create a map

of the estimated original residual stress distribution of the entire cross section of the rail sample.

RESULTS

Figures 4a through 4d show residual stress distribution maps of the four rail samples. Figure 4a shows the residual stress distribution in a new rail that has not been laid in track, and the stress distribution is caused by the manufacturing processes in forming the final shape of the rail from a cylindrical bloom. As illustrated, the manufacturing processes create compressive stress zones around the outer edges of the rail with the web having almost all compressive stresses. Tensile stresses are generated around the center of the base and the head with a gradual distribution of positive to negative stresses. In all images shown in Figures 4a through 4d, the scale varies from -40 ksi (dark blue) to +40 ksi (dark red) with the color spectrum changing from blue to red in between.

Figure 4b shows stress distribution in a rail with significant gage face wear. A small yellow tensile zone is at the bottom of the gage face where there has been metal flow forming a lip, and is a likely area for fatigue defect initiation. Figure 4c shows a slightly different stress distribution in the head than Figures 4a and 4b. It is expected that vertical and lateral forces play major roles in causing rail wear and subsequent changes in residual stress patterns. The tensile zone in the head is large and any defect growing fast in the tensile zone will see reduced growth rate once the residual stress becomes compressive.

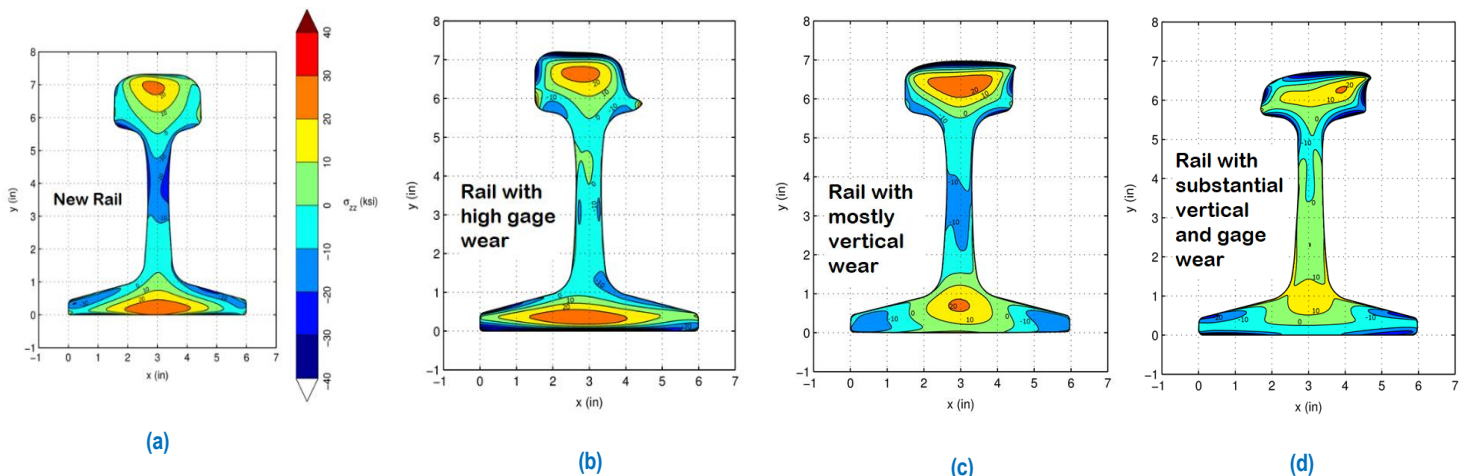


Figure 4. Residual stress distributions in (a) new rail with no tonnage, (b) rail with significant gage face wear, (c) rail with primarily vertical wear and (d) rail with both vertical and gage wear

Figure 4d is from a rail exhibiting substantial vertical and gage face wear. Comparisons of Figures 4b through 4d to Figure 4a indicate how the initial residual stress distribution after hot rolling in a new rail changes with different conditions of wheel rail wear.

ACKNOWLEDGEMENTS

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