Investigation of Residual Stress Distribution of Wheel Rims using Neutron Diffraction

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Abstract.
Damage accumulation due to fatigue significantly reduces the safety of railway vehicles. Shattered wheel rim failures are the result of large fatigue cracks that propagate roughly parallel to the wheel tread surface. The large stress, most likely due to wheel/rail impact or material discontinuity, is responsible for the initiation of shattered rims. The voids and inclusions of sufficient size in a stress field will also lead to failure of wheels. Significant improvements have been made in recent years to prevent the shattered rim failure. The ‘new’ wheels have a better resistance to the shattered rim failure, due to the fact that the circumferential residual stress on tread of a new wheel must be compressive to comply with requirements of international standard EN 13262. However, this may not necessarily apply for millions of ‘old’ wheels that are still currently in use. At the moment the residual stress measurements are carried out using destructive methods (such as slitting or hole drilling), or using quantitatively ultrasound method obtaining the average stress across the whole section. The main objective of this research was to apply non-destructive neutron diffraction method to quantitatively measure residual stress distribution of the wheel rim in as manufactured condition.

Introduction
Since the beginning of railroading in the 19th century, the optimization of the wheel/rail contact area has been a major challenge. Steel-on-steel contact accounts for a large reduction in rolling resistance compared with any widely diffused wheel/ground interaction (such as typically rubber tyres on asphalt). Furthermore, axle loads and speeds allowed by trains have steadily increased, and in consequence increase the possibility of inducing cracks in the bodies of both wheel and rail. This day to prevent the cracking phenomena in the steel rim wheels (Fig. 1), controlled compressive residual stress is implemented during the manufacturing process. This is obtained via repeated heat treatments. At very high temperatures radiation dominates the heat transfer but at lower temperatures convection plays an increasing role. During the cooling process different regions of the wheel cool at different rates depending upon shape, thickness and proximity to adjacent
radiating wheel and differential contraction and complex structural phase changes occur [1]. The new wheel when finished has a complex residual stress pattern as a result of the manufacturing process. Additionally, during the lifetime of the wheel some non-uniform plastic deformation occurs particularly in the rim and this involves changes in microstructure as well as in residual stress profile.

![Wheel crack](image1)

Fig. 1. Wheel crack [VOLPE National Transportation System Center]

Normative Standard document EN13262:2004 [2] which has been used until now in Europe for wheel acceptance completely defines the test procedures and the wheel characteristics to be measured. As defined in the Standard, four steel grades, ER6, ER7, ER8 and ER9 can be used; and it is applicable to solid forged and rolled wheels which are made from vacuum degassed steel and have a chilled rim. Procedure "rim-chilled" describes heat treatment of the rim, the aim of which is to harden the rims well as create compressive residual stresses. The level of compressive circumferential stresses measured near the surface of the tread shall be in the range 80 N/mm$^2$ to 150 N/mm$^2$. These stresses shall be equal to zero at a depth of between 35 mm and 50 mm. The stress distribution below the rolling contact line is shown in Fig. 2.

In the Standard the principles of the method to be used to calculate the residual stresses are mentioned. The method comprises cutting operations leading to the progressive relief of residual stresses present in the rim. The change in the state of residual stresses resulting from each cutting operation is evaluated at the surface by measuring local deformation using strain gauges. The change in state inside the rim is obtained by a linear extrapolation of the state evaluated at the surface. The evaluation is performed for one radial cross section because, based on experience, it is known, that the heat treatment induces effectively a uniform circular state of residual stress. Cutting operations are performed following a procedure that will not induce residual stresses [2].

![Range in variation of circumferential stress values](image2)

Fig. 2. Range in variation of circumferential stress values. [EN13262:2004 [2]]
However, the traditional sectioning method involves the measurement of strain relaxation and consequently destruction of the sample which limits measurements to a few well spaced points [3]. The residual stress patterns in wheels are complex and most of the details are missed by the destructive sectioning and can not be easily repeated due to the high cost of the sample. Neutron diffraction is the only non-destructive method suitable to provide information about the residual stress profile in three directions within the bulk [4, 5, 6]. Non-destructive measurements are vital to validate various prediction of those complex stresses which was presented in several finite elements studies [7, 8, 9].

In this research, we demonstrate the possibility of analyzing a train wheel with neutron diffraction method, in order to obtain the residual stress line scan. The analysis is concentrated on the most representative part of the wheel (namely the rim).

**Experimental methods**

Neutron diffraction is nowadays a widely used technique for accurate measurements of residual strains and stresses in metal artefacts [4]. The measurements on a new (“as manufactured”) wheel and on a stress-free reference sample were performed at the ISIS Rutherford-Appleton Laboratory on the ENGIN-X instrument [5]. On ENGIN-X, one can define a small measurement volume (gauge volume) in the sample in the order of a few cubic millimeters. This is achieved by collimating the incident beam (width x height), and by using a radial collimator in front of the detectors to accept only neutrons from a certain depth along the incident beam direction. As ENGIN-X utilizes a spallation neutron source, it is a time-of-flight facility and multiple diffraction peaks were acquired simultaneously. This enabled the lattice spacing to be obtained directly using a Pawley-Rietveld refinement of a time of flight profile.

For experimental planning and alignment of objects of such a due to the challenging size (diameter over 1m) and weight (500kg) of the high speed wheel, use of the SScanSS software package [6] and a CAD software to model the wheel was vital. The layout of the beamline in the virtual instrument during the experiments is depicted in Fig. 3 (please note that in ENGIN-X the direction along which the strain is measured is represented as a red and a blue line in Fig. 3.) In order to obtain strain components on the main directions (i.e. the radial, axial and hoop (tangential) directions of the wheel), it was necessary to align the sample twice in different orientations, with the use of purposely built heavy-duty supports.

![Fig. 3. Layout of beamline during the experiment within the virtual instrument (SSCANSS)](image-url)
The new high-speed train wheel has been provided by Lucchini RS (Italy), together with a stress-free reference sample. This investigation concentrated on the rim part of the wheel. Line scan measurements through the section of the rim were performed using a 4x4x4 mm$^3$ gauge volume. A cube (10x10x10 mm$^3$) has been measured as a reference. The cube was manufactured from the same material as the wheel under investigation but annealed in order to be completely stress free.

**Experimental results**

The residual stresses were derived from the elastic strain measurements (Fig. 4a) using Young’s modulus of 210 GPa, and Poisson’s ratio of 0.28. The residual strain has relatively uniform distribution across the measurements line. The highest tensile strain was observed in axial direction, around 170 microstrain. The radial component of strain was also tensile however its magnitude was approximately 100 microstrain smaller. The hoop directions was found to be highly compressive in the magnitude in a range from -600 to -700 microstrain. In Fig. 4b the residual stresses in the three principal directions is shown. The results show that axial and radial component are equal to zero or of small compressive magnitude, up to -20 MPa and up to -30 MPa, respectively. However the hoop component is highly compressive, in range from -125 to -160 MPa. This confirms that the manufacturing process was highly effective and the wheel compiles with the EN13262:2004 [2] standard. The residual stress values obtained are also in reasonably good agreement with the values predicted in several finite elements studies [7, 8, 9].

![Residual strain and stress distribution](image)

**Fig. 4.** The residual a) strain and b) stress distribution 5mm below the surface of the wheel rim. Comparison with current standard requirements EN13262:2004.

**Discussion**

This pilot study has demonstrated the possibility of using neutron diffraction as a non-destructive method for quantitative 3D residual stress analysis of large and heavy samples such as a train wheel. Desirable compressive residual stress was found close to the surface in the hoop (circumferential) direction of the new wheel. This investigation provided valuable feedback to the FEM modellers of the wheel manufacturing processes.
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