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Published in:
Materials Science and Technology

Link to article, DOI:
[10.1080/02670836.2020.1852749](https://doi.org/10.1080/02670836.2020.1852749)

Publication date:
2021

Document Version
Peer reviewed version

[Link back to DTU Orbit](#)

Citation (APA):
Dhar, S., Danielsen, H. K., Xu, R., Zhang, Y., Grumsen, F. B., Rasmussen, C., & Juul Jensen, D. (2021). Residual strain-stress in manganese steel railway-crossing determined by synchrotron and laboratory X-ray. *Materials Science and Technology*, 37(1), 6-13. <https://doi.org/10.1080/02670836.2020.1852749>

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Residual strain-stress in manganese steel railway crossing determined by synchrotron and laboratory X-ray

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Abstract:

The residual stress within the nose of a worn manganese steel railway crossing was investigated. The macroscopic residual stress at the running surface was determined in areas with and without visual faults by laboratory X-ray. To get information about the penetration depth of the residual stress, synchrotron X-ray diffraction was used to map the distribution of *local* (within grain) residual strains below the running surface. The laboratory X-ray measurements revealed significant compressive stress on the rail running surface. The synchrotron measurements documented that local strains exist through the entire depth investigated. Relations between residual stress, plastic deformation and crack formation are analyzed leading to discussion on potentials/limitations of the two experimental methods for investigations of residual stress in large engineering components.

Keyword: Residual Stress; Differential Aperture Synchrotron Diffraction; X-ray diffraction; Manganese Steel; Switches and crossings (S&Cs); Rolling contact fatigue

1. Introduction:

The presence of residual stress in materials and components is often overlooked, although it may be significant, and affect the mechanical properties both in a positive and negative way of any metallic component.

The present work deals with residual stress in a rail component: namely the nose of a manganese steel railway crossing which has been in service for five years in the Danish rail network and is heavily damaged. For rail components, in particular the fatigue life and the dimensional stability are affected by the presence of residual stress. Both these properties are critical for safe operation of the railway. Whereas many experimental and theoretical studies have been published on residual stress in straight rails made of pearlitic steel e.g. [1-7], to the authors' best knowledge, residual stress in used Switches and Crossings (S&Cs) made of the more complex Hadfield manganese steel has not been

studied before. The nose of the S&C, i.e. the pointed rail part onto which the train wheels shift from one running direction to another, is in particular interesting as the nose is exposed to both contact friction and impact stresses which lead to much more severe wear and rolling contact fatigue than what straight rail is exposed to [8-9]. Furthermore, preliminary measurements indicate that significant stresses are present even deep in the nose [10].

In the present work, two X-ray techniques are applied to quantify the residual stress in the selected nose. The conventional laboratory X-ray $\sin^2\psi$ vs d method is used to determine the global macro stress at the running surface while differential aperture synchrotron X-ray diffraction is used to determine the local micro strains within selected grains at four different depths down to 15mm below the rail surface. The magnitude of the residual stresses in the different positions of the worn nose are analyzed and related to the plastic deformation and to the crack formation in the nose. Whereas the data give valuable information about certain aspects of the strains within the nose, our primary motivation for the work was to evaluate the potentials of the synchrotron method for recording local strains below the surface in a heavily deformed real-life component (instead of in idealized model samples which most often are investigated by synchrotron methods), and to relate these results to what can be obtained by standard laboratory based X-ray techniques. Thereby illustrating potentials and limitations of the 2 methods for the present type of investigations.

2. Experimental procedure:

In a renewal program the Danish rail infrastructure provider, Banedanmark, secured the crossing part of a worn S&C. The crossing was in service in the railway network for five years and had both freight and passenger traffic through it. The approximate annual traffic density was around 14 MGT. Visual inspection of the crossing reveals severe spallation and cracks. The crossing is made of the austenitic manganese steel also known as Hadfield steel. The nominal chemical composition is given in Table

1.

[Insert Table 1 here]

The undeformed manganese steel has a hardness of 220 Hv, yield strength of 363 MPa and elastic modulus of 203 GPa [9]. The undeformed microstructure is composed of large equiaxed austenitic grains with an average grain size of 500 μm . The surface of the nose receives the maximum deformation and the microstructure here contains a large number of deformation induced bands. The density of the bands is maximum at the surface and decreases through the depth, see Figure 1.

Three specimens were cut from the nose for the X-ray measurements, referred to as specimens A, B and C. The sizes of the specimens are given in Figure 2. These three specimens were chosen for the following reasons: B is as close as possible to the nose tip with A just a bit further away. Both specimens contain cracks, which were clearly visible when the transverse section (TD/ND) was polished. A larger specimen, C, was extracted to ensure no significant stress relaxation at the central measurement position due to the cutting out of the specimen. There is visual spallation at the running surface of specimen C but the measurements were taken away from this position.

[Insert Figure 1 here]

2.1 Synchrotron Measurements:

Synchrotron measurements were conducted on the transverse (TD/ND) surface of specimen A at beam line 34-ID-E at the Advanced Photon Source (APS), USA. The specimen was 5mm in thickness and measurements were made at various depths along the longitudinal direction (running direction) at four sampling positions (see Figure 2b). The transverse surface was electropolished to avoid mechanical stresses induced due to cutting and polishing. The specimen was mounted on a holder with its surface normal at an inclination of 45° to the incoming X-ray beam. The synchrotron beam thus penetrates along the direction sketched in Figure 2c. A polychromatic beam was used first to determine the

orientations of the matrix grains. The focusing of the beam was done with the help of non-dispersive Kirkpatrick-Baez (K-B) focusing mirrors. The resulting microbeam has a Lorentzian profile and a full-width half maximum of $\sim 0.5 \mu\text{m}$. The Laue diffraction patterns from the scanned volumes were recorded on a detector mounted in 90° reflection geometry at a distance of 510.3 mm from the specimen. A Pt-wire was used as a differential aperture to obtain diffraction patterns at different depths [11]. The Laue patterns at each depth were reconstructed by LaueGo software [12]. The patterns were indexed, from which the (hkl) indices of the individual spots as well as their corresponding X-ray energies were determined. A spot with high intensity and from a grain with the diffraction vector normal to the specimen surface was then selected for monochromatic energy scans to determine the lattice spacings, d , at the selected positions using a method described in [13]:

The strain was calculated as

$$\varepsilon = \frac{d-d_0}{d_0} \dots\dots\dots (1)$$

where d is the lattice spacing at the measured position and d_0 is the lattice spacing of the specimen in stress-free state. This spacing (d_0) was obtained by synchrotron microdiffraction using a specimen taken from the base of the nose at a depth of 20 mm from the running surface. In previous studies, hardness measurements have indicated that the plastic deformation was confined within 10 mm from the running surface [9]. Therefore, the d_0 was measured at a depth of 20 mm from the running surface which is stress free. Optical microscopy also suggests that at this depth there is little effect of deformation due to wheel rail interaction (see Figure 1b). The d_0 of the $\{220\}$ plane was determined to be $1.2802 \text{ \AA}$. d_0 measurements were also performed by laboratory X-ray diffraction at a similar depth from the running surface as that for the synchrotron measurement. Both methods gave the same d_0 values within the experimental accuracies.

The local micro strains within the selected grains are determined in one direction. In the present experiment, at the depth of 3 mm, the chosen diffraction spot was (426) (i.e. from a grain with (426) diffraction vector close to the specimen normal), while at depths of 4, 6.5 and 15 mm, it was the (446), (517) and (626) spots respectively. It is in principle possible to obtain the complete strain/stress tensor by measuring the diffraction vectors for at least three diffraction spots using microdiffraction [14]. However, in practice it is very time consuming and challenging, in fact almost impossible for heavily deformed as the present. We thus decided to measure only one strain component for different grains more precisely, rather than to determine less reliable strain/stress tensor in a single grain.

[Insert Figure 2 Here]

2.2 Laboratory X-ray Diffraction measurements:

The laboratory X-ray measurements of the macro (Type I) stress were done using a Bruker X-ray diffractometer operated in the Bragg-Brentano configuration applying Cr-K α radiation. X-ray diffractograms were recorded with a step size of 0.07° in 2 θ , a voltage of 35 kV and exposure time of 10 s in the angular range of 2 θ 122°-133° to record the austenitic (220) peak. One may speculate if the heterogeneous banded deformation microstructure (see Fig 1b) may lead to asymmetric diffraction peaks as for example observed in [15]. However, in the present work almost fully symmetric peak profiles were observed and the peaks were thus fitted with the sliding gravity method. For Specimen A, measurements were made on the transverse section at 5 locations from the running surface at 3, 6, 9, 12 and 15 mm from the surface. For Specimens B and C, the measurements were made on the running surface. The standard $\sin^2\psi$ vs d technique [16-18] was used for all specimens with 9 tilts(Ψ) from 0 to 65° along the two directions (Φ) of 0° and 90° for specimen C whereas both positive and

negative ψ tilts were performed for specimen A. The diffraction peaks were fitted with a Lorentz profile and from the peak positions the interplanar spacings, were calculated. The inter-planar spacings, d are then plotted as a function of $\sin^2\psi$. If a linear fit is observed with no psi splitting, it indicates absence of shear stresses. The stress is then calculated as $\sigma = \left(\frac{E}{1+\nu}\right) \frac{m}{d_0}$ (2)

where m is the slope of the d versus $\sin^2\Psi$ curve, E is Young's Modulus and ν is Poison's ratio. For the present material $\nu = 0.28$ and $E = 203$ GPa. The method assumes there is no shear stresses present [16]. This corresponds to zero stress at $\sin^2\psi = 0$. If a linear fit cannot be obtained or psi splitting is observed in the d versus $\sin^2\Psi$ curve, presence of shear stresses is confirmed. An elliptical curve fit is used in that case. The curve is fitted with $d = m (\sin^2\psi) + t (\sin 2\psi) + r$. The parameters (m , t and r) are determined using the non-linear least square approach . The stress values are then calculated from the parameters with the help of the equations given below [18]:

$$a_1 = \frac{d_{\phi\psi+} + d_{\phi\psi-}}{2d_0} - 1 = \frac{1+\nu}{E} \{ \sigma_{11} \cos^2\phi + \sigma_{12} \sin 2\phi + \sigma_{22} \sin^2\phi - \sigma_{33} \} \sin^2\psi + \frac{1+\nu}{E} \sigma_{33} - \frac{\nu}{E} (\sigma_{11} + \sigma_{22} + \sigma_{33}) \dots\dots\dots (3)$$

$$a_2 = \frac{d_{\phi\psi+} - d_{\phi\psi-}}{2d_0} = \frac{1+\nu}{E} \{ \sigma_{13} \cos\phi + \sigma_{23} \sin\phi \} \sin(2\psi) \dots\dots\dots (4)$$

σ_{33} is considered zero at the free surface.

X-ray diffraction (XRD) measurements were also performed using a Xstress 3000 G2R diffractometer equipped with a Cr $K\alpha$ X-ray source on specimen B at two positions to verify the Bruker measurements. The Xstress measurements were made with 9 tilts from -45° to $+45^\circ$ along three directions of 0° , 45° and 90° . The operating conditions were: voltage 30 kV, current 6.7 mA and exposure time 60 seconds. Again, the (220) austenitic peak around $2\theta = 128^\circ$ was chosen. The incident X-ray beam was collimated to a diameter of 1.5 mm. The diffraction peaks were fitted using the Stress

Tech Xtronic software, using a cross relation method with a linear background [19] and the same procedure was followed as described above.

3. Results:

3.1 Synchrotron Measurements:

[Insert Figure 3 Here]

For specimen A, Figure 3 gives the overview of all the measured strains at the four selected depths from the running surface. The figure reveals that there are significant residual micro strains at all depths, which are mostly compressive, and that the strains are fairly constant as a function of distance from the TD/ND specimen surface down to 75 μm below this free surface. It is remarkable that the compressive residual strain at 15 mm from the running surface is twice as large as the strains at 3, 4 and 6.5 mm; this shall be discussed below. At 15mm the residual strain values are around 0.001.

3.2 Laboratory X-ray Diffraction Measurements:

For the large specimen C, the $\sin^2\psi$ vs d plots are given in Figure 4. Nice straight lines are observed in both cases indicating absence of shear stresses. Based on the slopes, the stress values calculated are -360 MPa and -499 MPa respectively. This means that very large compressive residual stresses are present at the running surface in both the transverse and longitudinal directions.

[Insert Figure 4 Here]

Whereas these measurements were done on specimen C taken at some distance from the tip of the nose (see Figure 2a) and at a position away from any visual crack and spallation, similar measurements were performed on specimen B which is much nearer the nose tip. It should be noted

that a large crack is present in this specimen extending to a depth of 2-3 mm. Measurements were taken in an area away from, but still near, the crack network. The $\sin^2\psi$ vs d plots obtained from measurements at the center of the running surface for the two directions are given in Figure 5. No straight line can be fitted to these data, expressing that the stress state here, near a large crack, is not biaxial. On the contrary the data are nicely fitted to an ellipse expressing that shear stresses are present. Just using the standard software of the X-ray system, normal stress values were calculated to be -70 MPa in the transverse direction and -112 MPa in the longitudinal direction. The same specimen was also characterized using the Xstress 3000 G2R equipment and the measurements were performed both at the middle of the running band and at the gauge corner, the results are reported in Table 2. The two set of results largely agree. The $\sin^2\psi$ vs d plots obtained from measurements obtained from Xstress 300 G2R equipment for the two directions are given in Figure 6. Psi splitting can be observed, and the data are fitted nicely by an ellipse. The difference in the elliptical fit between the figures 5 and 6 although from the same specimen is likely to be due to minute changes in the measurement location when using the two X-ray equipments but the stress values calculated are almost identical.

The results reported in Table 2 reveal that the residual stresses at the running surface are similar in magnitude to those at the far less loaded gauge corner. The observed difference in stress values in different directions at different locations may relate to the difference in wheel rail contact when a train passes over the nose. The area of contact of the wheel on the nose will affect the stresses developed.

When compared to specimen C it is obvious that the stresses in specimen B have been significantly reduced and the stress state has changed because of the crack formed here.

[Insert Figure 5 & 6 Here]:

[Insert Table 2 Here]

Laboratory X-ray measurements were also performed for specimen A on the transverse sample section at five different depths from the running surface (3, 6, 9, 12 and 15 mm). At all these depths the resulting $\sin 2\psi$ vs d plots show only points which are too scattered for the standard software to determine any stress values. Reasons for this shall be discussed in the following.

4. Discussion:

Residual stress is present in essentially all engineering components originating from the manufacturing processes and such stress evolves during in-service operations. For freshly manufactured straight rails, residual stress up to 250 MPa is generally accepted [20] and values in the range 300-500 MPa for rails which have been in operation in the track have been reported [21-22]. In the present work, the residual stress present in the nose of a crossing made of manganese steel which has been in operation for five years and experienced 14 MGT yearly traffic density from both passenger and freight trains has been characterized.

Using laboratory X-ray measurements very large compressive macro stresses of values up to -500 MPa were measured at the running surface. This stress is much higher than the yield stress of 363 MPa of this material. However, the metal will be deformed during operation, it will thus strain harden and its yield stress will increase significantly. The deformation hardening is reflected in the microstructural subdivision by bands in a regular pattern, i.e. in a characteristic deformation structure subdivided by low and high angle boundaries. The yield stress of the hardened steel parts puts an upper limit to the residual stress. For manganese steel deformed by explosion hardening, yield values as high as 660 MPa has been reported [23]. It is therefore realistic that a residual stress of 500 MPa as found in the present work can be present in a severely deformed crossing near the nose where the largest impact forces and rolling contact fatigue occurs.

Crack formation and growth are critical for the railway crossings. Residual stress contributes to this unfortunate event and when a crack is formed the residual stress previously present nearby may be relieved. Effects of cracks on residual stress relaxation were investigated in the present study by measuring the residual stress present in a specimen taken at a location where a large crack has evolved (specimen B). For this specimen, the macro residual stresses were found to be significantly reduced compared to that far away from a crack, to values in the range -50 to -180 MPa at the running surface and the stress state was converted to include shear components. The latter is not surprising due to the presence of the crack. At the gauge corner, residual stress values of -80 to -113 MPa were observed. It is therefore clear that cracks can relax the residual stress built up during operation, however of course with the unacceptable effect that the nose is damaged.

Another important parameter is how deep into the rail the residual stress extends to, which we tried to investigate using laboratory X-rays. A specimen was cut out (specimen A) and the measurements were performed on the cut-out transverse section. However, this attempt was unsuccessful. Stress relaxation occurring near the surface when the transverse surface becomes free during the cutting out of the specimen is the most likely explanation. Instead synchrotron X-ray of 21 keV was used which readily penetrates 75 μm in iron to measure the residual stress below the cut out free transverse surface as a function of depth from the running surface. Figure 3 reveals that micro compressive residual strains are present at all measured depths. The micro residual stresses, of which only one component was measured, can of course not be directly compared to the more conventional macro stresses determined by the $\sin^2\psi$ -d method using laboratory X-rays, because the micro strain only represents a given grain (or subgrain). The present micro strain results however document that the residual stress is not only at the running surface but on the contrary extends to significant depths. For the present data (Figure 3), it is of interest to note that the largest micro strain exists at a distance of 15mm from the running surface and the micro strains at e.g.4mm are about half of that. As the

micro strains are measured locally for four different grains with different orientations at the four depths from the running surface, one may speculate if this could be the reason. However, all the four selected grains have similar directional Young's modulus, in the range 209-257 GPa [24], and the grain at 15 mm depth have $E = 235$ GPa, which is in the middle of the range. That the variation in Young's modulus is not the only reason for the observed difference in micro strain is further substantiated by the fact that the three curves measured at 3, 4 and 6.5 mm are largely identical. It is well known that impact related residual stress is typically not maximum at the surface, but somewhere below [25]. For the present nose, it is thus suggested that the micro residual strain profile is related to the complex interplay between impact forces, plastic deformation and crack/spallation formation.

The depth profiles of residual stresses are of importance when interpreting crack propagation. The measured micro strains are compressive except very near the (artificially) free transverse section surface. Clearly of course, these compressive strains must be counterbalanced by tensile strains elsewhere. However, for essentially all the measurement positions chosen here, only compressive strains were recorded. Such strains are actually beneficial and contribute to crack closure. That the compressive strains are largest in the grain at significant depth may contribute to explaining why cracks formed near the surface of the nose typically evolve to a certain depth and then move parallel to the running surface instead of moving further into the material, as for example reported for a nose in [9]. However, it has to be underlined that the present micro strain measurements are for individual grains and in one direction only. Many more measurements are needed if the aim is to get a complete map of the local strain distribution and to relate it directly to the evolution of a crack network.

5. Conclusions:

The residual elastic stress in the nose of a Hadfield manganese steel crossing extracted from the Danish rail network after five years in operation was studied. Both standard $\sin^2\psi$ -d laboratory X-ray

measurements of macro stress as well as synchrotron X-ray measurements of micro strains were performed. It was found that:

- The macro residual stress at the running surface of the crossing nose can reach 500 MPa in compression. This is higher than the yield stress of the undeformed material. High deformation by rail wheel contact has however hardened the top layers as witnessed by the presence of a typical deformation microstructure here. The yield strength is thereby increased to a level above the measured 500 MPa residual stress.
- When cracks at the surface are present, the residual stress is observed to be lowered to about 200 MPa in compression.
- Micro residual stress extending to a depth of 15mm below the running surface can reach about 150 MPa in compression determined for four selected grains.
- The complexity of the residual stress profiles in the nose of a crossing suggests that such stresses both on the macro and the micro scale are to be taken into account in component design and failure analysis. Furthermore, it is documented that the synchrotron X-ray method is a very valuable technique for measurements of stress in the bulk of large engineering components.

Acknowledgments:

The authors would like to thank Interreg ESS & MAX IV: Cross Border Science and Society (Project number DTU-009) for supporting this research. Use of the Advanced Photon Source was further supported by the U.S Department of Energy, Office of Basic Energy Sciences, under Contract No.DE-AC0206CH11357. The authors would also like to thank Dr. Mallipeddi from the Department of Materials and Manufacturing Technology at Chalmers University of Technology, Sweden for help doing the laboratory X-ray measurements. DJ and YZ further wish to acknowledge support from the European Research Council (ERC) under the European Union's Horizon 2020 research and innovation programme (grant agreement No 788567-M4D).

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Figure 1: Optical micrographs of the microstructure of the Hadfield manganese steel nose. (a) Specimen taken at the running surface showing a deformed microstructure with deformation induced bands; (b) specimen taken 20mm below the running surface showing large equiaxed grains.

Figure 2: Photo and schematic diagrams showing where specimens A, B and C were cut out from the nose. (a) Photograph showing the nose studied. (b) Schematic diagram of specimen A. The

positions of the synchrotron X-ray diffraction measurements are also shown. (c) Sketch showing the experimental synchrotron X-ray set up for specimen A and the points of measurement. (d) Schematic diagram of specimen B for laboratory X-ray diffraction scans showing the measurement positions at the running surface and at the gauge corner. (e) Schematic diagram of specimen C used for laboratory X-ray diffraction scans showing the measurement position.

Figure 3: The residual strain along the longitudinal sample direction measured non-destructively as a function of the distance from the TD/ND specimen surface at different depths from the running surface (3, 4, 6.5 and 15 mm).

Figure 4: The $\sin^2\psi$ vs d plot measured on the running surface of specimen C for two directions, (a) transverse and (b) longitudinal.

Figure 5: The $\sin^2\psi$ vs d plot (with elliptical fit) for the laboratory X-ray measurements on running surface of specimen B at the center of the running band (center of the specimen): (a) transverse (b) longitudinal.

Figure 6: The $\sin^2\psi$ vs d plot (with elliptical fit) for the laboratory Xstress measurements of specimen B (center of the specimen): (a) transverse (b) longitudinal.

Table 1: Chemical composition of the manganese steel

Element	C	Mn	Cr	Si	Cu	Co	P	Ni	Fe
Wt %	1.17	12.7	0.12	0.5	0.044	0.010	0.031	0.062	Balance

Table 2: Stress values obtained at different directions in two locations of specimen B measured using the Xstress laboratory X-ray system.

Location	Stress at $\varphi=0^\circ$ (MPa)	Stress at $\varphi=45^\circ$ (MPa)	Stress at $\varphi=90^\circ$ (MPa)
Centre	-59.78	-180.25	-121.99
Gauge corner	-113.34	-103.79	-82.48