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Characterization of deformed pearlitic rail steel

Dimitrios Nikas, Knut Andreas Meyer and Johan Ahlström

Department of Industrial and Materials Science, Chalmers University of Technology, SE-412 96 Gothenburg, Sweden

E-mail: nikas@chalmers.se

Abstract. Pearlitic steels are commonly used for railway rails because they combine good strength and wear properties. During service, the passage of trains results in a large accumulation of shear strains in the surface layer of the rail, leading to crack initiation. Knowledge of the material properties in this region is therefore important for fatigue life prediction. As the strain is limited to a thin surface layer, very large strain gradients can be found. This makes it very difficult to quantify changes in material behavior. In this study hardness measurements were performed close to the surface using the Knoop hardness test method. The orientation of the pearlitic lamellas was measured to give an overview of the deformed microstructure in the surface of the rail. Microstructural characterization of the material was done by optical microscopy and scanning electron microscopy to evaluate the changes in the microstructure due to the large deformation. A strong gradient can be observed in the top 50 µm of the rail, while deeper into the rail the microstructure of the base material is preserved.

1. Introduction

Carbon steels with a pearlitic microstructure are the most common materials for the manufacturing of rails today. Pearlite is a lamellar microstructure consisting of colonies of similarly oriented cementite lamellae embedded in a softer ferrite matrix. A large number of randomly oriented pearlitic colonies gives the material an isotropic behavior on the macroscopic level. This type of microstructure provides a good combination of wear and strength properties for railway applications and thus various types of such steel grades have been developed and used in the railways over the years. In this paper we consider the grade R260, which is one of the most common rail steel grades.

The surface layers of rails are subjected to very high rolling contact loads during their service life, which lead to large plastic deformation. As a result, material anisotropy develops, which strongly influences many of the defects that are observed in rails, such as pitting, shelling, spalling and head checks [1]. These defects are often denoted rolling contact fatigue (RCF) and are some of the main problems and sources for increased maintenance costs for the railway industry [2],[3]. The accumulation of strains has been investigated by e.g. [4] and [5] for rails and wheels respectively, where the strains were measured using the shear lines visible after etching. Micro hardness measurements also showed that the material had work hardened close to the surface, and in some cases [4], phase transformation to martensite had occurred (i.e. white etching layer formation).

The main goal of this study is to identify methods for determining microstructural quantities suitable for comparing different samples. To this end, measuring the reorientation of the pearlitic lamellar structure is considered in addition to the previously mentioned methods. By comparing

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two microstructures using these methods, it may be possible to determine if an artificially produced microstructure (e.g. through deformation of test specimens) is representative of the microstructures found in used rails. The benefit of creating a microstructure in the laboratory that resembles the one in the field, is that more extensive mechanical testing can be performed and gradients can be limited, giving more representative local properties.

2. Material and experimental

The material studied in this investigation is the railway rail steel grade R260. The microstructure of this material is almost fully pearlitic with nominal composition as shown in table 1.

Table 1. Chemical composition of R260 rail material, maximum levels, in wt% [6]

C	Si	Mn	P	S	V	Cr	Al	N	O	H
0.80	0.60	1.25	0.03	0.03	0.03	0.15	0.004	0.01	0.002	0.00025

2.1. Sample extraction

Samples for characterization were extracted from a rail section at Jonsered Station in Sweden. The rail was installed in 2005 on the main line between Gothenburg and Stockholm, in a curve with a radius of 590 m. The rail exhibited a highly deformed profile shown in figure 1. Samples were taken from the top of the rail head (T) and gauge corner (G) (see figure 1) and were prepared for hardness measurements and microscopy. They were mechanically ground and polished to 0.04 µm using colloidal silica suspension. Etching was done using Nital (3% HNO_3 in ethanol).

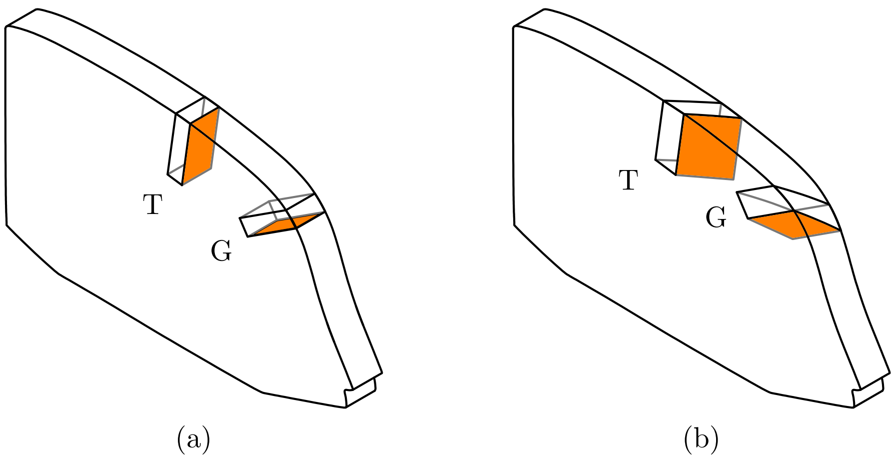


Figure 1. Samples extracted from the top of the rail (T) and gauge corner (G) with two orientations (90° (a) and 45° (b))with respect to the rail longitudinal direction. The orange colored sides denote the surfaces studied.

2.2. Hardness measurements

Both the Vickers and the Knoop method were used to evaluate the material hardness. Due to the strong gradients close to the surface, the Knoop method was chosen with a 10 g load (HK0.01), as this allowed for closer spaced indents with a sufficient size for optical measurement.

The measurements were conducted on an Struers DuraScan 70 hardness machine, using a 600× magnification. A global hardness map of the rail was obtained using a Vickers hardness indenter with a 10 kg load (HV10). This hardness measurement reduces scatter by averaging over a larger volume.

2.3. Optical flow lines
Three optical micrographs were taken using an optical microscope in the near-surface region to observe the shear deformation. The plastic shear strain was evaluated by measuring the angle α of the shear lines relative to the surface normal, see e.g. [4] and [5]. The angles α are obtained by manually tracing visible lines, and then using image analysis with linear regression to calculate the tangent direction of those lines at different depths. A measure of shear, γ, can then be calculated as $\gamma = \tan(\alpha)$.

2.4. Lamella orientation
The orientations of the cementite lamellae were evaluated from the gray scale gradient in SEM images, using the Sobel-Feldman operator [7]. While more direct methods that identify single lamellae give less noise in the data, they also produce less data per image, and hence more images are required to produce accurate distributions. This work mainly considers the variation with depth, and it was found that the differences in orientation distributions between the depths became more clear when using a gradient based analysis. Between 15 and 25 images per depth were used in this analysis. Fewer images were required close to the surface where the structure is very aligned, while more images were required to analyze the less aligned regions deeper in the rail.

3. Results and Discussion
A hardness map over the deformed railhead is considered in figure 2, to better understand the local variations closer to the surface. The hardness in the deeper parts of the rail show a small spread, and are mostly between 260 and 280 HV10. Closer to the surface a small increase in hardness is identified starting at a depth of about 5 mm.

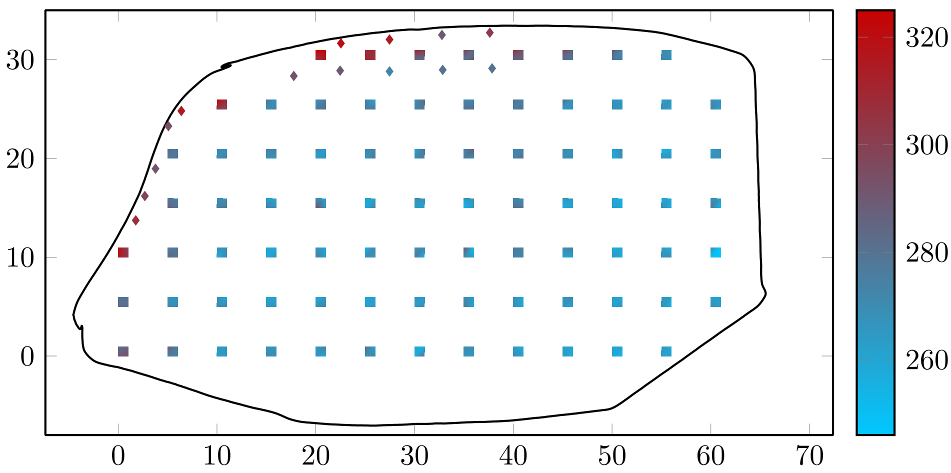


Figure 2. Vickers HV10 hardness overview of the deformed rail head (axis dimensions in mm). The grid points consists of 4 local points in a 1x1 mm grid, represented by the corners of the squares. The smaller diamond markers are additional single measurement points.

The critical area for fatigue in rails is the surface region close to the running band. We therefore consider the hardness variation with depth for the two regions in figure 1, measured on the 90° samples. The hardness results in figure 3 show that the hardness at the very top of the rail reaches around 550 HK0.01 and after about 100 µm it drops to 450. Deeper into the rail the hardness approaches the nominal value for the grade, as is shown by the Vickers overview map in figure 2.

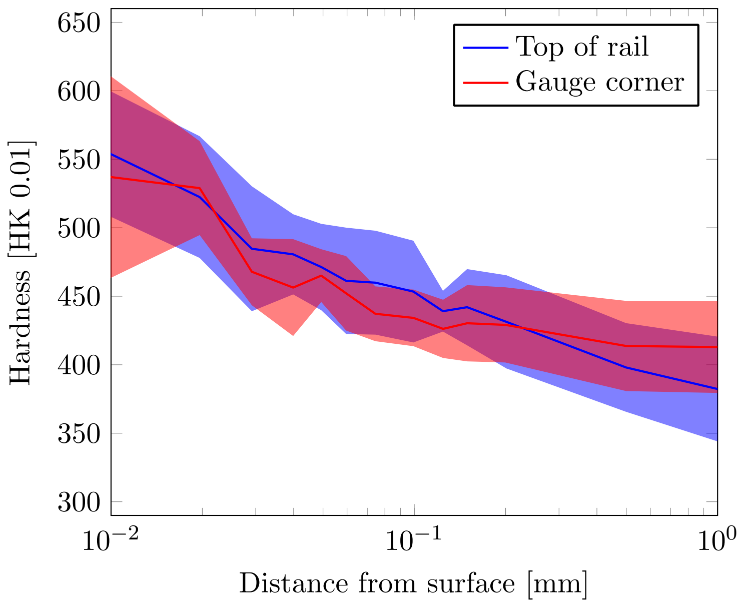
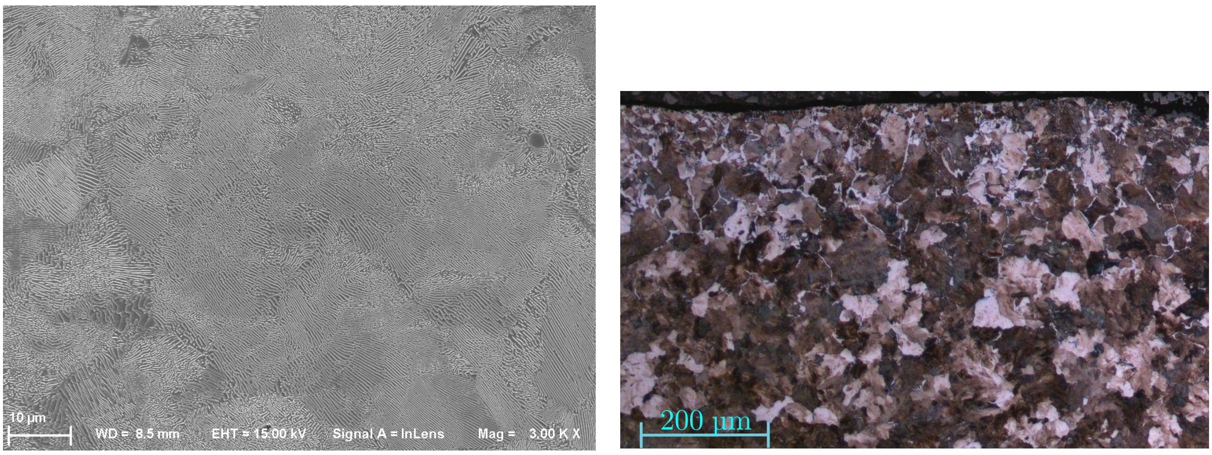


Figure 3. Hardness depth variation, filled region indicate ± one standard deviation.

The initial microstructure of the R260 rail steel is almost fully pearlitic, as shown in figure 4. In figure 4a the different orientations between the colonies are visible, and in figure 4b the grain refinement (but without any visible shear lines) close to the surface after rail rolling is visible.



(a) (b)

Figure 4. Initial microstructure of the R260 rail steel, depicted with an SEM image (a) and an optical micrograph (b)

During service the near-surface region becomes heavily deformed, as can be seen by the shear lines in figure 5a. The measure of shear strain γ shown in figure 5b shows a strong increase close to the surface. At the very surface some local shear effects resulted in a wave-like pattern and hence those values were excluded. The measurements are most accurate between a depth of 50 µm and 200 µm, where most lines could be identified.

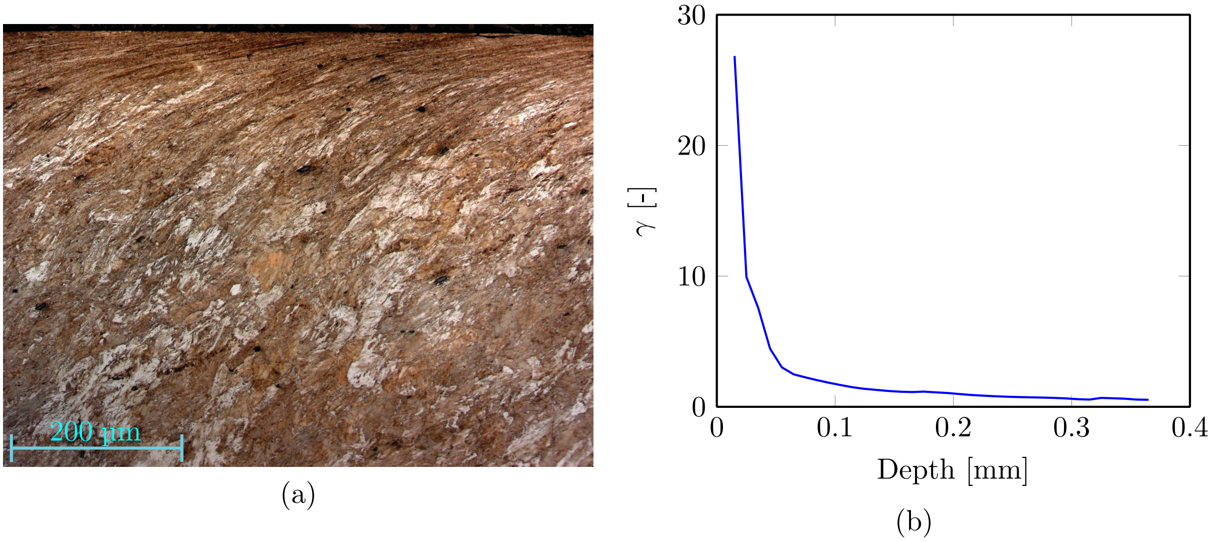


Figure 5. The deformation of the surface layer observed and measured using an optical microscope. (a) shows the deformed surface layer and (b) the measured shear strain γ as a function of depth

The SEM investigation also shows severe deformation close to the surface, where the lamellar structure becomes distorted such as seen in figure 6.

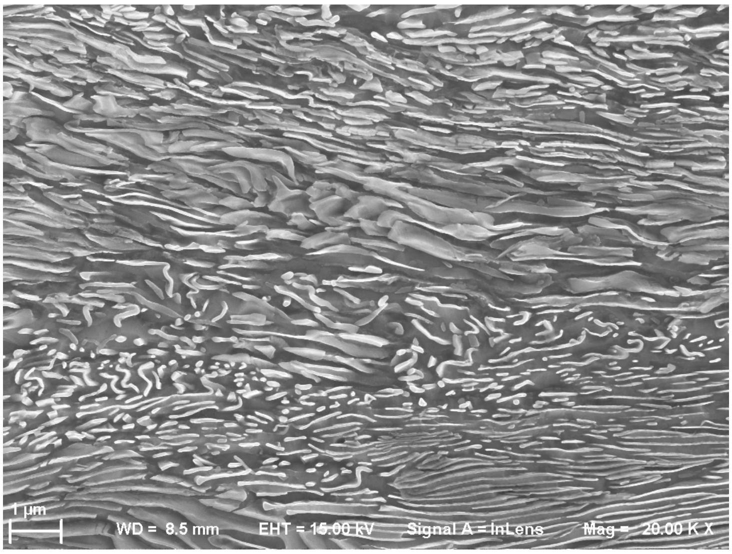


Figure 6. SEM images of the near-surface zone with the heavily sheared lamellas (taken from a depth of 20 µm).

The lamellar orientation distribution is calculated using images such as in figure 6 with a 20000× magnification. The results from this in figure 7 show a clear alignment of the microstructure close to the surface. Deeper in the rail the average angle increases, which implies smaller shear strains. The tails of the distribution also increase and the peaks decrease, indicating a less aligned structure.

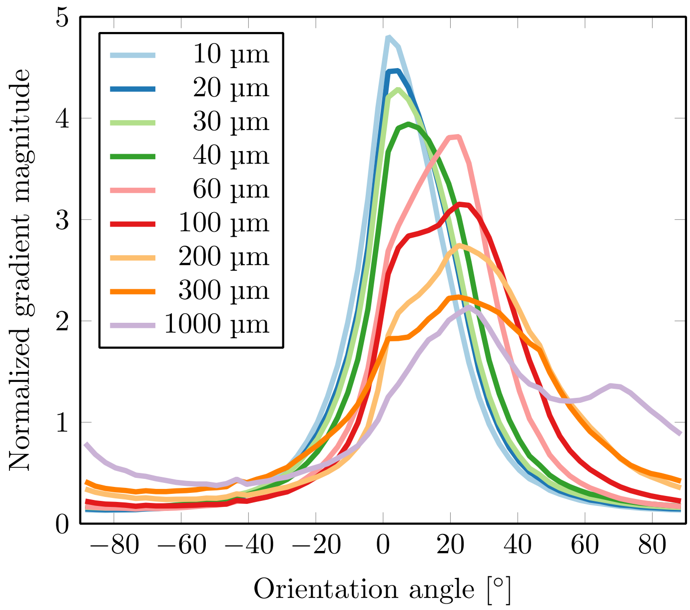


Figure 7. Pearlite orientation distributions obtained from SEM images

The main goal of the characterization in this paper, is to define a method in which some specific measurements can be used to compare the rail material with another microstructure created artificially in the laboratory. A biaxial machine will be used, combining compression and torsion to produce test bars that will also have a sheared microstructure. By using the method described in this paper these two microstructures can be compared. In case the microstructure created in the laboratory is similar, fatigue experiments can be run on those test bars to acquire the fatigue life and mechanical properties of a heavily deformed rail microstructure. Such tests are very important for the railway industry since testing directly on the deformed rail material is very difficult.

4. Conclusion

In this work a rail steel R260 was examined. Rail samples were extracted from an in-service section of railhead with large deformations present close to the surface. Hardness measurements showed a steep gradient with high hardness close to the surface (due to work hardening), reducing to the expected value for the base material deeper in the rail. The flow line method was used to give a measure of the strain close to the surface, showing that large deformations are present in the top layer of the rail. An alternative measurement of the strains has also been proposed, by considering the alignment of the microstructure using SEM images. Three quantifiable measurements of the microstructure have been used to evaluate the rail material. Using these methods to compare field samples with microstructures obtained through laboratory induced deformations, will make it possible to verify that the obtained microstructure is similar to that found in field samples. Hence, mechanical testing on these laboratory deformed specimens can be used to determine mechanical properties, such as constitutive behavior and fatigue life, of the deformed surface layer in rails.

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