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On the modeling of anisotropy in pearlitic steel subjected to rolling contact fatigue

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THESIS FOR THE DEGREE OF LICENTIATE OF ENGINEERING IN SOLID AND STRUCTURAL MECHANICS

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Abstract

One of the main sources of damage caused by Rolling Contact Fatigue (RCF) in railway components is the large plastic deformations that accumulate in the surface layer of these components. Large plastic deformations in components made of pearlitic steel induce anisotropy in the mechanical properties of the material. The objective of this thesis is to investigate the effect of this anisotropy on the RCF properties of pearlitic steel components by utilizing material models and computational analysis.

The first paper aims at formulating a material model for predicting large irreversible deformations in components made of pearlitic carbon steel. On the microscopic level, pearlitic steel is a two phase material consisting of cementite lamellas and a softer ferrite phase. Large plastic deformations in pearlitic steel lead to a re-orientation and alignment of cementite lamellas in the microstructure. This is believed to be the main reason for evolution of anisotropy in the material. Therefore, a macroscopic model formulated for large strains is proposed that captures this re-orientation and its influence on the macroscopic yielding of the material. Thereby, the re-orientations lead to distortional hardening of the yield surface. The proposed material model is calibrated against experimental results from cold drawing of pearlitic steel wires reported in the literature.

In the second paper, the influence of the anisotropic surface layer on the propagation of cracks in pearlitic rail steel is investigated. Experimental results in the literature have reported significant degrees of anisotropy in fracture toughness and fatigue crack propagation rate in heavily deformed pearlitic structures. Indeed, such an anisotropy should be taken into account when trying to predict the fatigue life of components subjected to large deformations. This anisotropy can also be attributed to the alignment of cementite lamellas in the pearlitic microstructure which results in changes in the resistance against crack propagation in different directions. Micrographs of the surface layer of pearlitic steel rails, tested in a full scale test rig, show a transition from a fully aligned microstructure (a high degree of anisotropy) at the surface, to a randomly oriented lamellar structure (isotropy) at some millimeters from the surface. Based on these observations, an anisotropic fracture surface model is proposed to capture the anisotropic resistance against crack propagation and its dependence on the depth from the surface. The fracture surface model is employed in a computational framework for simulation of propagation of planar cracks. The framework is based on the concept of material forces where the propagation rate is linked to a crack-driving force. The results of simulations show that the characteristics of the surface layer have a substantial influence on the crack path.

Keywords: Anisotropy, pearlitic steel, plasticity, Rolling Contact Fatigue, crack propagation, material forces

In the memory of
Mohammad Larijani (1925-2011)
who was my first great teacher:

فرداست که در بطن زمین خاك و سرابیم

"And tomorrow a mirage is left from us ..."

Preface

The work presented in this thesis was carried out at the department of Applied Mechanics at Chalmers University of Technology within the project MU19 ”Material anisotropy and Rolling Contact Fatigue in rails and switches”. The project is part of the activities within the Centre of Excellence in Railway Mechanics (CHARMEC) and is supported by industrial partners voestalpine Schienen, Trafikverket and SL Technology.

First of all, I would like to thank my main supervisor Professor Magnus Ekh for his guidance, encouragement and especially his endless patience and understanding. I would also like to express my gratitude to my co-supervisor Associate Professor Anders Ekberg for his support and the rewarding discussions we had. I am very grateful to my co-authors Jim Brouzoulis and Martin Schilke for the exchange of knowledge and our cooperation. Furthermore, I want to thank my colleagues at the divisions of Material and Computational Mechanics and Dynamics for being extremely helpful and creating a pleasant working environment.

Most importantly, I would like to thank my lovely family in Iran for their strong long-distance support through these years and also Tayyebeh Larijani and Naser Rajabi for being my second family in Sweden. Last but not least, I wish to thank Martin Schilke, this time as my boyfriend, for his help, patience and most of all, his amazing sense of humor which made even the longest working days memorable for me.

Nasim Larijani
Göteborg, May 2012

Thesis

This thesis consists of an extended summary and the following appended papers:

Paper A N. Larijani, G. Johansson, and M. Ekh. Hybrid micro-macromechanical modeling of anisotropy evolution in pearlitic steel. *Submitted for international publication* (2011)

Paper B N. Larijani, J. Brouzoulis, M. Schilke, and M. Ekh. The effect of anisotropy on crack propagation in pearlitic rail steel. *To be submitted for international publication* (2012)

The appended papers were prepared in collaboration with the co-authors. The author of this thesis is responsible for the major progress of the work in papers i.e. taking part in planning the papers and developing the theory, developing the numerical implementations and carrying out the numerical simulations.

Contents

Part I
Introduction

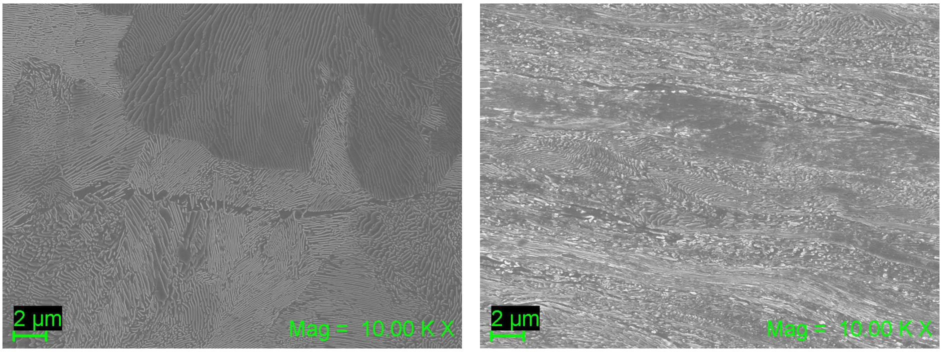
1 Motivation and Background

In railway components, subjected to Rolling Contact Fatigue (RCF), the material yields during the first few loading cycles and plastic deformations start to accumulate. This is mainly due to the high contact loads and the small contact patch between railway-wheels and rails. Large plastic deformations that accumulate in the surface layer are the source of many defects and consequently failures in railway components, cf. [8, 10, 12]. Hence, the mechanism of accumulation of plastic deformations, changes in the microstructure and mechanical properties of the material in the surface layer of railway components have been the topics of many studies in the railway field, cf. [1, 5, 9]. Specifically, in components made of pearlitic steel, which is the most common railway steel, accumulated large deformations induce anisotropy (directional dependence) in the mechanical properties of the material, cf. [2, 3, 13]. Pronounced anisotropy in the material properties like yield stress, ultimate tensile strength, fracture toughness and fatigue threshold, found in heavily deformed pearlitic structures (see e.g. [3, 11]), have a crucial effect on the fatigue life of these components.

The aim of this thesis is to investigate the effect of anisotropy on the deterioration of pearlitic steel railway track components subjected to RCF. To reach this goal some models have been proposed to include anisotropy in computational frameworks for simulation of these deteriorations.

2 Anisotropy in Pearlitic Steel

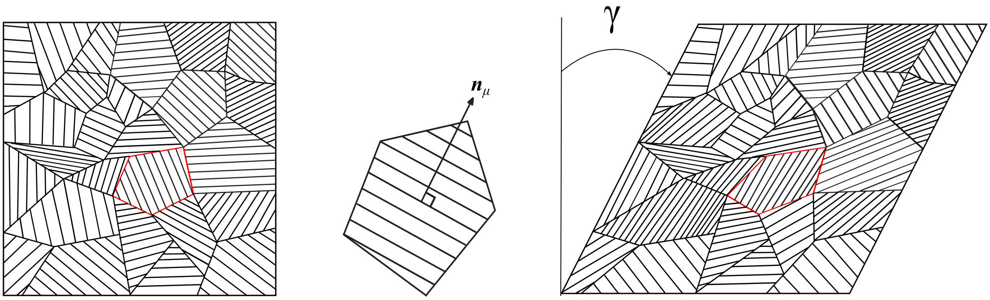
Changes in the mechanical properties of pearlitic steel, subjected to large plastic deformations, is attributed to the changes in its lamellar microstructure. Pearlite is a two-phase material consisting of bands of cementite and ferrite. Since the percentage of the ferrite phase is much higher than of the cementite, pearlite's distinctive structure under a microscope (see Fig. 2.1a), is usually described as cementite lamellas embedded in a ferrite matrix. The domains in which the cementite lamellas are aligned in one preferred direction, are denoted as colonies. Random orientation of the colonies in an undeformed pearlitic structure, accounts for the isotropy in its mechanical properties on the macroscopic length scale. Under deformation, however, the individual colonies start to align in the principal direction of deformation, cf. [4, 11, 13]. This is shown schematically for a Representative Volume Element (RVE) under simple shear deformation in Fig. 2.2. This alignment evolves markedly in the microstructure by increasing the deformation. At very high deformations, the microstructure of the main part of the RVE is fully aligned. This transition in the microstructure can be clearly seen in the micrographs of the pearlitic structure, at two different distances from the rail surface, illustrated in Fig. 2.1. The micrographs are obtained from the surface layer of a piece of rail, tested under wheel-rail



(a) (b)

Figure 2.1: *SEM micrographs of the pearlitic structure in the surface layer of the rail at the depth of (a) 2* mm*; (b) 100* µm.

operational conditions, by using a scanning electron microscope (SEM). At a depth of

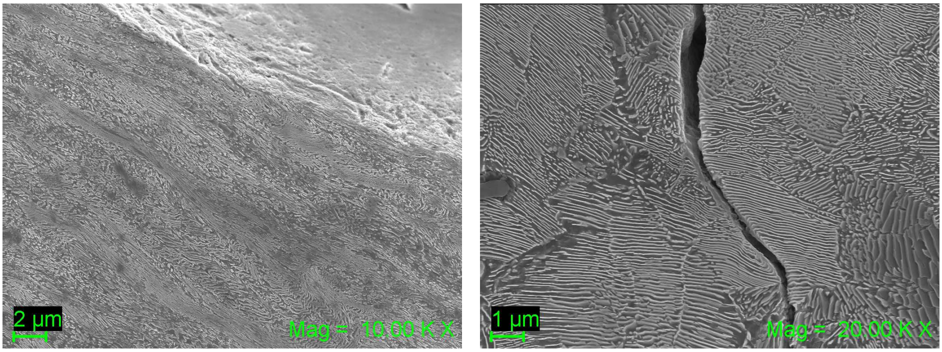


(a) (b) (c)

Figure 2.2: *(a) A two dimensional representative volume element (RVE) of an undeformed pearlitic structure; (b) a single colony with aligned cementite lamellas with the normal* $\boldsymbol{n}_\mu$*; and (c) a two dimensional RVE of a pearlitic structure deformed by pure shear.*

2 mm (Fig. 2.1a), the colonies have a random orientation representing a non-deformed isotropic microstructure. Closer to the surface, however, the microstructure can be heavily deformed. As can be seen in Fig. 2.1b, at a depth of 100 µm, the pearlitic structure is entirely aligned and the lamellas that originally lay unfavourably with respect to the traction (shear) direction are bent and broken.

Studies on the changes in the mechanical properties of heavily deformed pearlitic rail steels, by equal channel angular pressing and high pressure torsion (HPT), show a significant degree of anisotropy in fracture toughness and fatigue crack propagation rate, cf. [3, 13]. Fracture toughness has been found to be lower for a crack propagation parallel with the aligned microstructure than perpendicular. On the other hand, fatigue crack propagation rate values are much higher for a propagation parallel with the alignment of the microstructure than perpendicular. Micrographs along the path of the cracks found at the rail surface, are in agreement with these results (see Fig. 2.3). The cracks



(a) (b)

Figure 2.3: *SEM micrographs along the path of a crack in the surface layer of the rail at the depth of (a) 100* μm*; (b) 900* μm.

propagate parallel to the aligned lamellas in the deformed microstructure close to the surface. However, when the crack grows deeper into the rail, the propagation path is along the colony boundaries and even through the colonies. This implies that the weakest path in an undeformed structure is more random and even propagation through the cementite lamellas is occasionally preferred. In contrast, in the deformed microstructure closer to the surface, there is evidently less resistance against crack propagation parallel to the aligned cementite lamellas.

In order to include the effect of anisotropy in an analysis, in the context of numerical prediction of RCF, different approaches can be proposed. Anisotropy in the material, in this context, can be interpreted as directionally dependent strength at the material points. A constitutive model that takes this directional dependence into account develops the so-called *anisotropic state of stress* at the studied material points. Thereby, the effect of anisotropy is included in the analysis. This is the approach chosen in **Paper A**. In this paper, a macroscopic material model is formulated to predict the evolution of anisotropy in pearlitic steel. Another approach for including the effect of anisotropy, is to identify the material properties that affect the analysis once they become anisotropic. Models can then be formulated to include the directional dependence of these material properties in the analysis. Choosing this approach in **Paper B**, an *anisotropic fracture surface* model is proposed to study the effect of anisotropy on crack propagation in pearlitic rail steel.

3 Summary of Appended Papers

- **Paper A: Hybrid micro-macromechanical modeling of anisotropy evolution in pearlitic steel.**
  Large shearing and/or stretching of pearlitic steel leads to a re-orientation and alignment of cementite lamellas on the microscopic level. In this paper a macroscopic model formulated for large strains is proposed for pearlitic steel that captures this re-orientation by adopting an areal-affine assumption. The re-orientation of the cementite lamellas influences the macroscopic yield function via homogenization of the normals to the cementite lamellas. Thereby, the re-orientation leads to a distortional hardening of the yield surface. Additionally, the model is formulated in a large strain setting by using the multiplicative split of the deformation gradient and includes non-linear isotropic as well as kinematic hardening. The proposed model is implemented by using a backward Euler technique for the evolution equations together with the integration on the unit sphere to compute homogenized quantities. Finally, numerical results are evaluated and compared to experimental results for wire drawing of pearlitic steel reported in literature.

- **Paper B: The effect of anisotropy on crack propagation in pearlitic rail steel based on material forces.**
  One of the main sources of damage caused by Rolling Contact Fatigue (RCF) in railway components are the large plastic deformations that accumulate in the surface layer under rolling contact loading. Large irreversible deformations in components made of pearlitic steel induce anisotropy in mechanical properties of the material in the surface layer. In the present work the influence of the anisotropic layer on propagation of cracks in rail head is investigated. Based on the concept of material forces, a computational framework for simulation of propagation of planar cracks is formulated where the propagation rate is linked to a crack-driving force. An anisotropic fracture surface model is employed to capture the effect of changes in the resistance against crack propagation in different directions and depths in the surface layer. Results of simulations for cases with different characteristics in the surface layer show that the anisotropic layer has a substantial influence on the crack path.

4 Conclusions and Outlook

In **Paper A**, a hybrid micro-macromechanical model was developed to predict the evolution of anisotropy in pearlitic steel. The model is formulated in a thermodynamical consistent framework for large deformations. The proposed model is calibrated against experimental data on wire drawing from [11]. The evolution of the yield limit in these experiments is predicted by the model with a good precision. However, the hardening stage in the stress–strain curves is not predicted as accurately. The capability of this model to predict the yield stress and stress–strain response is of critical importance considering simulations of cases with a significant degree of anisotropy e.g. evolution of anisotropy due to wheel–rail contact loading in the surface layer of rails. This motivates calibration of the model against experiments on samples that have been heavily deformed in shear. For example, calibration of the model against uni-axial tension tests of samples pre-deformed by high pressure torsion (HPT) can lead to a significant improvement in the material model's formulation. Additionally, employing the model in analyses to study the effect of anisotropy on initiation and propagation of cracks are listed as future work in this project.

In **Paper B**, a fatigue crack propagation law based on the concept of material forces for linear elastic material behaviour was extended to include the effect of anisotropy. Based on the microstructural investigations, an anisotropic fracture surface model was proposed to account for the changes in the resistance against crack propagation in different directions. This was formulated by defining the fracture threshold as a function of the degree and orientation of alignment of cementite lamellas in the microstructure. Parametric studies of crack growth simulations, in a simple two dimensional model of a wheel-rail contact, showed that the degree of anisotropy in the surface layer has a significant influence both on the path and the rate of propagation of the cracks. The results obtained are in good agreement with field observations. Further improvements can include, simulation of propagation of shorter cracks with lower initial inclinations from the surface and also including more realistic loading conditions (such as bending and thermal loading). This will possibly improve the prediction of crack paths so that they closely resemble the cracks usually found in the surface layer and at the gauge corner of railway-rails. An important extension for these simulations is including a more realistic material model that takes into account plasticity, hardening and anisotropy evolution. The model developed in *Paper A* can be a good candidate for this task.

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Part II
Appended Papers A–B

Paper A

Hybrid micro-macromechanical modeling of anisotropy evolution in pearlitic steel

Paper B

The effect of anisotropy on crack propagation in pearlitic rail steel