Wear 314 (2014) 57–68

Contents lists available at ScienceDirect

Wear

journal homepage: www.elsevier.com/locate/wear

The effect of anisotropy on crack propagation in pearlitic rail steel

Nasim Larijani [a,*], Jim Brouzoulis [a], Martin Schilke [b], Magnus Ekh [a]

[a] Department of Applied Mechanics, Chalmers University of Technology, 412 96 Gothenburg, Sweden
[b] Department of Material and Manufacturing Technology, Chalmers University of Technology, 412 96 Gothenburg, Sweden

ARTICLE INFO

Article history:
Received 8 November 2013
Accepted 24 November 2013
Available online 3 December 2013

Keywords:
Anisotropy
Rolling contact fatigue
Crack propagation
Material forces

ABSTRACT

One of the main sources of damage in railway components is 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.

1. Introduction

One of the major problems in the railway industry worldwide is Rolling Contact Fatigue (RCF) associated damages in rails and wheels. Rail failure caused by RCF is currently one of the largest risk factors causing increased maintenance costs for infrastructure holders, cf. [1,2]. Optimization of maintenance and operational conditions requires accurate ways for prediction of fatigue life of rails.

The fatigue life of components subjected to RCF is often determined by their resistance against crack initiation and propagation in the surface layer. The extremely high loads applied to rail and switch components during their service life lead to irreversible deformations in these components. In particular, the surface layer of rail and switch components is subjected to large plastic deformations that accumulate during the wheel–rail contact loading, see e.g. [3]. The heavily deformed surface layer in rails is the origin of most usual defects like head checks, cf. [4]. Studies have been carried out on the change in the microstructure, the accumulation of plastic deformation and the strain hardening in the surface layer of railway tracks, cf. [5–7].

The behavior of pearlitic steel, which is the most common railway steel, under large plastic deformations is dominated by the changes in its lamellar microstructure. Pearlite is a two-phase material consisting of colonies with preferred directions of cementite lamellas embedded in a softer ferrite matrix. Each individual colony can therefore be considered as transversely isotropic. Random orientation of the colonies in an undeformed structure accounts for the isotropy in mechanical properties on the macroscopic length scale. After considerable deformation, the individual grains tend to align in the principal direction of (inelastic) deformation, cf. [8]. In components made of pearlitic steel, accumulated large deformations induce anisotropy in mechanical properties of the material in the surface layer, cf. [9]. Among all other material properties, pronounced anisotropy in the elastic limit and the fracture toughness found in heavily deformed pearlitic structures (see e.g. [10,11]) have the most crucial effect on the fatigue life of the components. This is due to the re-orientation and alignment of cementite lamellas in the pearlitic microstructure which has a strong influence on initiation and growth of fatigue cracks in the component, cf. [10,12–14].

This work aims at studying the effect of the anisotropic surface layer on propagation of surface cracks in the rail head. Anisotropy in the material, in the context of numerical prediction of RCF, can be interpreted as directionally dependent strength at the material points. Therefore the effect of anisotropy can be included in a mechanical analysis if the state of stress is calculated at the studied material points, taking this directional dependence into account. This calls for a material model which provides the simulations with the so-called *anisotropic stress state*, cf. [15]. However, in this paper another approach is proposed by introducing a so-called *anisotropic fracture surface* i.e. considering anisotropy by accounting for the difference in resistance against crack propagation in different directions. This approach is especially useful when the focus is on studying the effect of anisotropy on crack propagation.

---

[*] Corresponding author. Tel.: +46 31 772 1586; fax: +46 31 772 3827.
E-mail addresses: nasim.larijani@chalmers.se, nasim.larijani@gmail.com (N. Larijani).

0043-1648/$ - see front matter © 2013 Elsevier B.V. All rights reserved.
http://dx.doi.org/10.1016/j.wear.2013.11.034

A 2D crack propagation model, formulated in terms of a *crack-driving force* based on the concept of material forces (see e.g. [16,17]), is employed in a computational framework for simulation of crack propagation, cf. [18,19]. In the current study the propagation criterion is modified in order to account for the anisotropic fracture resistance in the material. Based on the propagation model, the growth of a single head check-like crack in a piece of rail is simulated under RCF loading conditions employing a 2D Finite Element model. The crack behavior is studied for cases with and without an initially anisotropic surface layer in order to investigate the effect of anisotropy. Parametric studies on the amount of evolved anisotropy in the surface layer and the thickness of the anisotropic surface layer are carried out and the results are qualitatively compared with field observations.

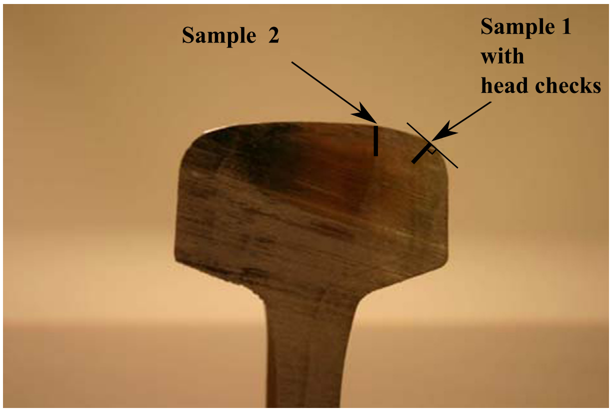

Fig. 1. Transverse cross-section of rail head showing the points the samples for microstructural investigations were taken from.

2. Measurements and experimental results

Studies on the changes in the mechanical properties of pearlitic rail steel R260 deformed by equal channel angular pressing and high pressure torsion (HPT), carried out at Erich Schmid Institute for Material Science, show a significant degree of anisotropy in tensile strength, fracture toughness, and fatigue crack propagation rate, cf. [11,12]. This anisotropy is attributed to the changes in the microstructure and the deformation induced alignment of cementite lamellas in the pearlitic structure. Specifically, fracture toughness and fatigue crack propagation rate values depend on the orientation of the crack with respect to the aligned microstructure of pearlite. It is observed that the cementite lamellas tend to align in the principal direction of the (inelastic) deformation i.e. the drawing direction in heavily drawn steel wires as shown in [10] and the shear plane in HPT tests according to [8,12]. This alignment of the lamellas evolves markedly in the microstructure by increasing the strain and at high strains ($\varepsilon_{\rm vM} \approx 8$), except for only some areas, the microstructure is almost fully aligned.

Consequently, investigation of the change in the microstructure of pearlitic rail steel due to the wheel–rail operational loading conditions is considered as the first step towards studying the effect of anisotropy.

Samples were taken from a rail segment produced by voestalpine Schienen GmbH and tested in a full scale test rig designed by the same company. In the test rig, a rail segment is moved under a full wagon wheel and simultaneously pressed against it. As a result both vertical and lateral forces can be generated. The test rig provides the possibility to simulate different operational wheel–rail conditions through adjustment of parameters like angle of attack, friction at the wheel–rail contact and the rail inclination. The rail piece used for microstructural investigations in the current study, was tested with 23 t vertical and 4 t lateral force for 100 k wheel passes with no rail inclination and no angle of attack. The material is the pearlitic rail

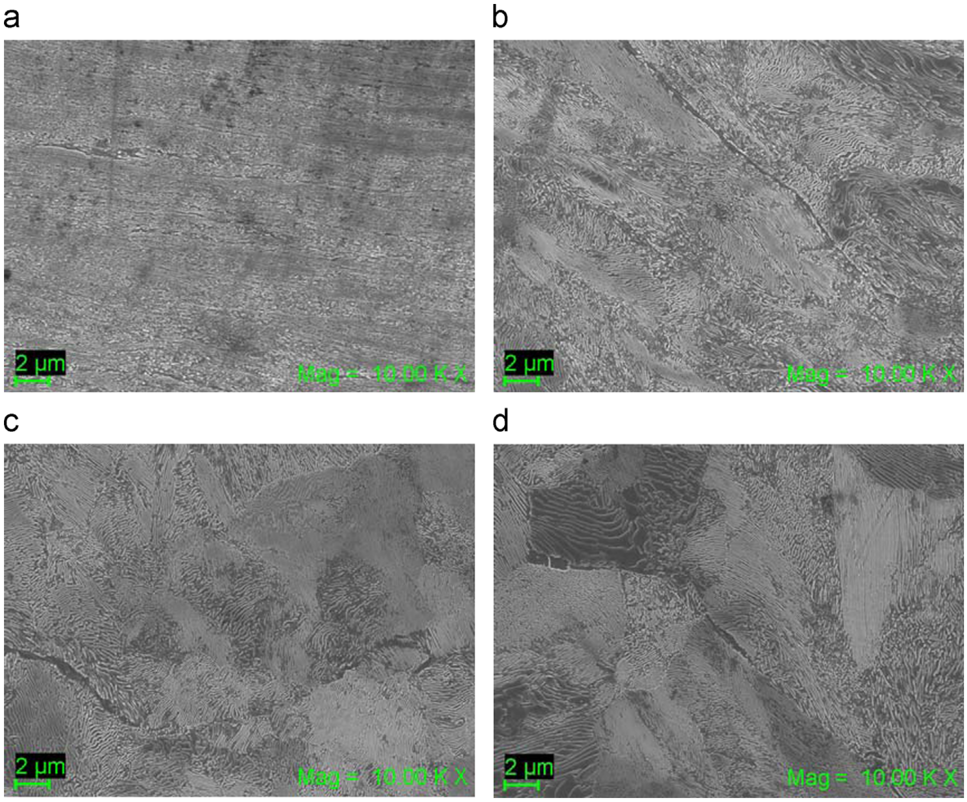

Fig. 2. SEM micrographs of microstructure at the gauge corner at the depth of (a) 20 μm; (b) 100 μm; (c) 700 μm; (d) 1 mm.