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Modeling surface rolling contact fatigue crack initiation taking severe plastic shear deformation into account

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ABSTRACT

A new model for the prediction of rolling contact fatigue crack initiation at the surface of railway rails and wheels has been developed, which takes contact-related plasticity effects into account. The model assesses the propensity towards fatigue crack initiation based on microstructural crack paths in the severely shear-deformed, anisotropic material near the surface. The key to differentiate between situations favoring crack initiation accompanied by wear and situations where only wear prevails, is the distribution of plastic shear strain in combination with stress in a crack initiation layer at the surface, rather than the maximum values of the plastic strain or stress. The model predicts the formation of head checks at the gauge corner of rails and the corresponding damage pattern on wheels. It is parameterized based on results from a full-scale test rig experiment. The model can be coupled to multi-body systems simulations of railway vehicles to account for the effect of plastic shear deformation on rolling contact fatigue crack initiation in such simulations. This allows systematic studies of contact conditions, material properties and railway vehicle dynamics behavior with regard to rolling contact fatigue crack initiation.

1. Introduction

1.1. Motivation

Cracks and fatigue in rails were identified as the most important track maintenance problems by infrastructure managers based on their cost impact in the INNOTRACK project [1]. It has been estimated that rolling contact fatigue associated costs amount to around 300 million EUR in Europe [2]. In Germany, approximately 66 million EUR are spent every year for rail grinding and rail replacement due to rolling contact fatigue in the network of Deutsche Bahn [3]. Improved predictive tools for modeling rolling contact fatigue damage may thus contribute to significant cost reductions, for example by optimization of operating conditions and maintenance strategies, by improvements in railway vehicle design, and by development of new materials for rails and wheels.

1.2. Models for prediction of rolling contact fatigue

Various simulation approaches are employed in engineering practice to predict rolling contact fatigue damage: These include, for example, shakedown map-based predictions [4–6], the $T\gamma$-approach [6–8] and models based on the ratcheting failure mechanism [9,10]. In addition, various (multiaxial) crack initiation criteria [11,12] are used in combination with FEM-based simulation models [13–15]. Fracture mechanics approaches use the concept of configurational forces [16,17] for crack growth predictions. The influence of anisotropic surface layers on the propagation of surface cracks [18] has also been taken into account in the prediction of rolling contact fatigue.

Shakedown maps [4] are useful to identify the predominant material response and the associated failure mechanism due to contact loading. In case of elastic material response and elastic shakedown, failure due to high cycle fatigue may be expected, whereas in case of ratcheting, failure due to exhaustion of ductility is likely. Although shakedown maps do not provide data for a direct quantification of fatigue damage, different parameters have been derived from shakedown maps to assess the propensity for fatigue damage. These include the "surface initiated fatigue parameter" [5] and the "shakedown exceedance" [6].

The $T\gamma$-model [6,7] relates the wear number $T\gamma$ to fatigue damage. The wear number $T\gamma$ is calculated as the sum of the product of the tangential forces and the creepages in longitudinal and lateral direction. The wear number is linked to observed fatigue damage in track by means of an empirical damage

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function. The input data for the model is usually provided directly by multi-body system simulation results.

Accumulation of plastic strain is used for the prediction of rolling contact fatigue crack initiation in ratcheting-based models, in which failure is caused by the exhaustion of ductility of the material when a critical strain is exceeded [9]. This failure mechanism is the basis of engineering models like the "brick model" [10].

Crack initiation criteria and crack growth models, embedded in sophisticated FEM-based simulation models allow predictions of crack initiation and crack growth based on the complex elasto-plastic stress–strain material response. However, such approaches are hardly straightforward to use in practice, because they involve long calculation times, so that only a few loading cycles at specific locations in the railway network can be calculated in practice.

The literature survey shows, that there is a need for computationally efficient simulation models, which allow quantification of fatigue damage on the basis of the physical processes that govern fatigue crack initiation near the surface under rolling contact conditions. These points are addressed in a newly developed crack initiation model, referred to as "wedge model". It addresses the prediction of plastic shear strain-assisted crack initiation at surfaces under rolling contact loading.

Important applications of the wedge model include the prediction of surface initiated rolling contact fatigue affecting the gauge corner of high rails in curves in form of head checks, and the corresponding damage pattern on railway wheels, based on the results of multi-body simulations of railway vehicles.

2. The wedge model

2.1. Influence of the plastic shear deformation on microstructural crack paths

On a microscopic scale, both surface rolling contact fatigue crack initiation and delamination wear are governed by the growth of microscopic cracks in a severely shear-deformed layer near the surface [4]. This allows us to assess the propensity of different loading conditions towards macroscopic crack initiation and wear in one model on a common physical basis.

The basic mechanism of delamination wear [19] is the detachment of thin flakes of metallic debris from the surface by cracks developing parallel to the surface in a layer of severely shear-deformed material. This mechanism serves as the basis to explain the formation of (macroscopic) rolling contact fatigue cracks at the surface in the wedge model.

Large plastic shear deformation causes an elongation and an alignment of grains in the material. This is schematically illustrated in Fig. 1, where an initially isotropic grain-like structure is deformed to various amounts of angular shear strain parallel to the surface. The grain boundaries, depicted as black lines, increasingly align with the principal strain direction with increasing shear strain. The principal strain direction is visible as the predominant microstructural orientation in metallographic sections.

The resulting lamellar microstructure exhibits an anisotropy with respect to fracture toughness and fatigue crack growth resistance, which creates preferred crack paths: Cracks grow preferably parallel to the lamellae. The principal strain direction in the severely shear deformed material thus dictates the crack path. Because the principal strain direction is linked to the plastic angular shear strain, predominant crack paths in the severely shear-deformed material can be described in terms of plastic shear strain.

2.2. Assessment of the plastic shear deformation with respect to crack initiation

In the wedge model the plastic shear deformation is quantified by the plastic angular shear strain α which is related to the displacement due to plasticity u^p in case of simple shear by [20]

$$\tan\alpha = \frac{du^p}{dz} \tag{1}$$

Fig. 2 shows a square, which is sheared by plastic angular shear strain α parallel to the x-direction. The origin of the coordinate system on rail and wheel is located at the surface, with the positive x-direction pointing in rolling direction parallel to the longitudinal axis of the rail. The positive z-direction coincides with the surface normal and points into the body. The y-direction is determined based on a right-hand coordinate system. The surface on both rail and wheel is located at depth $z=0$.

The plastic angular shear strain due to contact loading is calculated with an approximate model [21]. In this model, the material volume affected by the contact patch is approximated by two-dimensional sub-models, each representing the contact of a cylinder with a plane. Based on linear-elastic contact stresses at the surface and the relative motion between the contacting surfaces, the plastic shear strains in longitudinal and lateral direction of the rail are calculated. Effects resulting from surface roughness and from temperature rise due to frictional heating are empirically taken into account by amplifying the stresses near the surface.

Fig. 3 shows two different distributions of plastic angular shear strain $\alpha(z)$ in a "crack initiation layer". The crack initiation layer is defined as a layer of finite thickness z_c at the surface, where the physical processes leading to crack initiation and wear take place. The displacement trajectories $u^p(z)$ are calculated by integration of Eq. (1) with respect to z. These displacement trajectories indicate the predominant local orientation of the microstructure in case of large shear strain.

The plastic angular shear strain $\alpha(z)$, shown as Case A in Fig. 3 (dashed line) results in a displacement trajectory $u^p(z)$, which runs

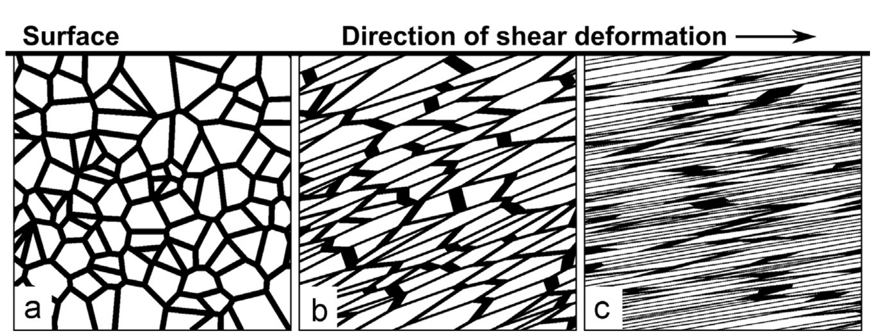

Fig. 1. Formation of an anisotropic lamellar microstructure by increasing alignment of grains and grain boundaries with increasing plastic angular shear strain α. (a) Undeformed, $\alpha=0°$; (b) $\alpha\approx 60°$; (c) $\alpha\approx 80°$.