Tribology International 80 (2014) 147–155

Contents lists available at ScienceDirect

Tribology International

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

Multi-scale finite element modeling to describe rolling contact fatigue in a wheel–rail test rig

Martin Pletz [a,*], Werner Daves [a,b], Weiping Yao [a], Wilhelm Kubin [a], Stephan Scheriau [c]

[a] Materials Center Leoben Forschung GmbH, Leoben, Austria
[b] Institute of Mechanics, Montanuniversitaet Leoben, Leoben, Austria
[c] Voestalpine Schienen GmbH, Leoben, Austria

ARTICLE INFO

Article history:
Received 22 April 2014
Received in revised form
30 June 2014
Accepted 9 July 2014
Available online 17 July 2014

Keywords:
Finite element modeling
Rolling contact fatigue
Contact mechanics
Surface cracks

ABSTRACT

Finite element models on different length scales are presented for the loading of rails. A 3-D model of the full-scale test rig of the voestalpine company is developed. Results of the model include the full elastic–plastic deformations of rail and wheel, the contact pressure, shear stresses and slip. Results of this model are transferred to (a) a 2-D crack model that calculates the crack tip loading of an inclined surface crack and (b) a 2-D model with rough surfaces calculating cyclic near-surface deformations. On the rail profile two locations in the contact patch with different pressure/slip loads are analyzed separately in the 2-D models. The used multi-scale approach is essential for a realistic description of rolling contact related damage mechanisms.

1. Introduction

Over the last 20 years the demands on the railway track structure have increased seriously due to raising axle loads, higher velocities and higher total tonnages. In general, two main rail damage mechanisms are observed near the contact surface, namely wear and rolling contact fatigue—RCF. Wear is defined as the loss of material and is observed in curves and in the straight track, respectively. RCF such as head checks and/or gauge corner cracks is mostly seen in curves which have a typical radius between 1500 and 3000 m. As wear of the rail removes RCF cracks, such RCF damage is not seen in tighter curves with more wear. Hardness and microstructure of the rail material, contact pressure, slip and rail profile are several parameters which have a great impact on resulting contact loading and the characteristics of the crack pattern.

The repeated contact loading leads to plastic deformation of the rail surface. The result is a change in the rail profile over months or years. If the profile change exceeds certain limits, the slip in the wheel rail contact zone is often increased. The contact loading also leads to wear, crack initiation and crack growth. In Fig. 1, RCF cracks on a rail surface are shown. If surface cracks grow to a certain length, they may cause fracture of the rail. To prevent all these effects, the rails are regularly ground to a profile defined by the rail operator. For faster initiating and growing cracks these grinding intervals have to be more frequent to avoid a crack length that can be critical regarding rail breaks.

Track parameters for the loading of the rail are, e.g., the curve radius, the slope of the track and whether trains accelerate or brake in that part of the track. From given parameters, vertical and lateral contact forces and creepages can be calculated. Locally, these loads cause contact pressure, shear stress and slip.

From the evolution of contact pressure and slip, the frictional work in the rail surface can be obtained. According to Archard's wear law [1] this frictional work is proportional to the wear rate. The proportionality factor, however, depends on the slip rate. For a quantitative prediction of wear, lots of experiments have to be performed. There is an approach to predict whether RCF cracks develop based on shakedown diagrams [2]. For existing cracks the tendency of those cracks to grow can be studied with finite element models.

In the track it takes a long time to evaluate the performance of rails with new rail materials. Within some months, the rail profile might change due to wear and plastic deformation. In some cases also RCF occurs. Trains might go at different speeds, have different axle loads and have different wheel profiles. Usually those load parameters are not monitored which makes it harder to compare rails in the track in terms of arising damage. Laboratory tests of rails have the advantage of a defined loading of the rails.

For this purpose a full-scale test rig of the voestalpine Schienen GmbH was developed [3]. The wheel (with a certain vertical and lateral force) is pressed onto the rail and repeatedly rolled over the

---

* Corresponding author. Tel.: +43 3842 402 4115; fax: +43 3842 402 7702.
E-mail address: martin.pletz@unileoben.ac.at (M. Pletz).

http://dx.doi.org/10.1016/j.triboint.2014.07.005
0301-679X/© 2014 Elsevier Ltd. All rights reserved.

rail. In the test rig experiment that is modeled in this work, no traction is applied on the wheel (it rolls freely on the rail) and the angle of attack is set to 0. The test rig and the presented model use higher vertical forces compared to the track situation. The test rig experiments produce similar damage (RCF and wear in similar regions of the rail) as observed in the track.

The rail loading of the test-rig was modeled with a combined MBS/FEM/CONTACT model by Brouzoulis et al. [4], focusing on the profile development and on calibrating wear coefficients with measured profile changes in the test rig.

The work at hand, however, is not focused on profile change but on the local damage initiation and crack growth. Following that aim, a quasistatic three-dimensional finite element model is developed for the test rig. Its element size is about 1.5 mm and allows for a calculation of the contact pressure and the slip distribution, respectively. Also the plastic adaption of the rail to the load can be described at least for 10 cycles.

For certain points within the contact patches on the rail profile, the direction of sliding is calculated. A cut is made along these directions and the slips and contact pressures obtained along such directions are applied in two-dimensional micromodels. Such micromodels are used to investigate (a) crack propagation of a surface crack and (b) local plastic deformation on the scale of the surface roughness. Only a two-dimensional model allows the use of a sufficiently fine FE mesh for this needed modeling depth. For both the 3-D model and the micromodels the commercial FE package Abaqus [5] was used.

Using the crack model, the crack driving force of an existing crack that has a certain length and inclination (which can be obtained from experiments and metallographic investigations) can be calculated. If there are crack growth curves available, a prediction of the rate and direction of the crack growth can be made.

The near-surface shear deformation is one key point in the investigation of RCF and wear reported by Donzella et al. [6]. Of course the surface roughness plays an important role in near-surface deformation. The roughness model thus calculates the local stress fields and provides the plastic deformations of the rail on the scale of the asperities. This calculation is necessary for the determination of a critical shear strain at which cracks will initiate. As it is assumed that this deformation process near the surface is also connected to wear, the model can be used to describe the physical process of wear. It is intended to find a simple criterion of a critical shear strain at which the material becomes so brittle that it is removed from the surface. This criterion can be used later to develop a physically based wear law. The critical shear strain can be measured or at least estimated in metallographic pictures of loaded rail surfaces. The maximum shear deformation can be found in most sliding contact cases very close to the surface and will reach its critical value there, first.

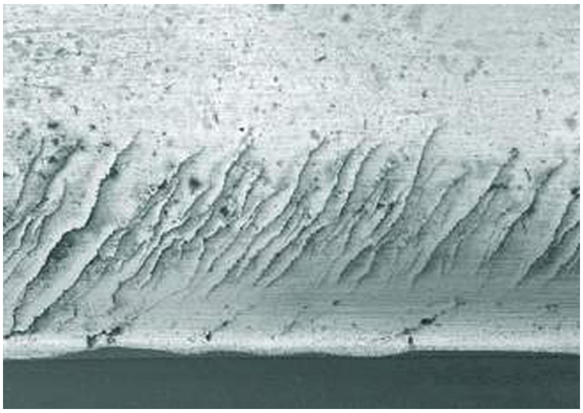

Fig. 1. Headchecks (typical RCF cracks) on the surface of a rail.

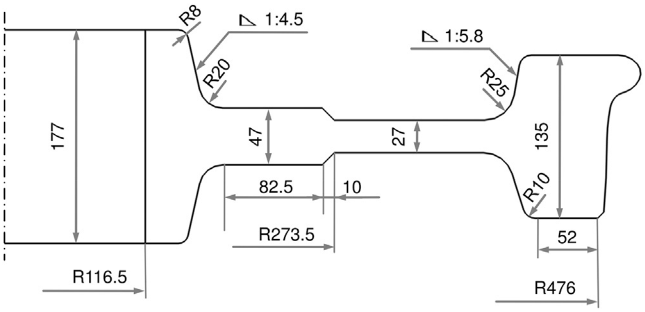

Fig. 2. The dimensions of the wheel rim in mm.

2. Modelling

2.1. The 3-D test-rig model

In a three-dimensional finite element model the contact patch between the wheel and the rail in the test rig is calculated. One wheel and a 1.6 m part of the rail are modeled. The wheel profile is of the type S 1002 with a radius of 0.46 m and the used rim profile is defined in Fig. 2. The modeled wheel has a rigid axle with a radius of 116.5 mm. The rail has an unworn UIC 60 E1 profile. The rail is mounted in the test rig and modeled with an inclination of 1/40, corresponding to an angle of 1.432°. The mesh is shown in Fig. 3. There is no angle of attack of the wheel for the modeled load case in the test rig because this case produces similar damage as in the track. As the wheel is not of primary interest in this work, it is modeled with elastic material behavior (Young's modulus of 210 GPa and a Poisson's ratio of 0.3).

The rail grade was chosen as R260 (UIC900A) [3]. The rail is modeled with an elastic–plastic material description that uses a combination of isotropic and kinematic hardening (or softening) as introduced by Chaboche [7]. The material data has been fitted to a monotonic tensile test and uniaxial low cycle fatigue tests with three strain amplitudes (0.5%, 1.1% and 1.9%) and a strain ratio of -1. The Young's modulus and the Poisson's ratio of the rail were measured as 205 GPa and 0.3, respectively. The initial yield stress σ_{y0} was measured as 320 MPa. The isotropic hardening is

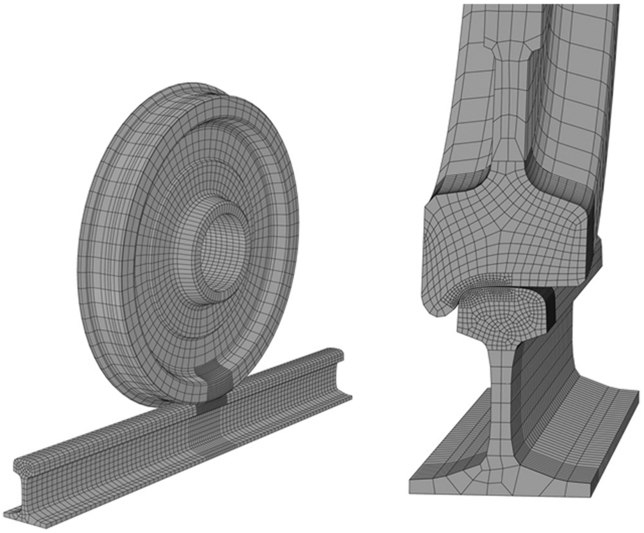

Fig. 3. The whole mesh of the test rig (left) and a lateral cut (right). The transition between the different mesh sizes can be seen in both wheel and rail.