Wear ■ (■■■■) ■■■–■■■

Contents lists available at ScienceDirect

Wear

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

Modeling wear and rolling contact fatigue: Parametric study and experimental results

G. Trummer [a,*], C. Marte [a], S. Scheriau [b], P. Dietmaier [c], C. Sommitsch [d], K. Six [a]

[a] *Virtual Vehicle Research Center, Inffeldgasse 21a, 8010 Graz, Austria*
[b] *Voestalpine Schienen GmbH, Kerpelystraße 199, 8700 Leoben, Austria*
[c] *Graz University of Technology, Institute of Applied Mechanics, Technikerstraße 4, 8010 Graz, Austria*
[d] *Graz University of Technology, Institute for Material Science and Welding, Kopernikusgasse 24, 8010 Graz, Austria*

ARTICLE INFO

Article history:
Received 2 October 2015
Received in revised form
18 April 2016
Accepted 19 April 2016

Keywords:
Wheel–rail contact
Rolling contact fatigue
Plastic shear deformation
Crack initiation
Wear

ABSTRACT

A recently developed simulation model is used to study wear and rolling contact fatigue crack initiation. The model is capable of predicting the damage pattern observed in a full-scale test-rig experiment with respect to crack initiation and wear under conformal contact conditions. The crack initiation model assesses the propensity for rolling contact fatigue crack initiation at the surface of rails based on the combined assessment of the rolling contact stresses and the plastic shear strain distribution in a near-surface layer. Crack initiation is not necessarily linked to low wear rates. If favorable microstructural crack paths away from the surface exist, crack initiation can also take place in parts of the rail where high wear rates are observed. The parametric study shows that an increasing angle of attack of the wheel and an increasing coefficient of friction lead to an increase in the profile height change at the gauge corner of the rail. Likewise, the effective stress for crack initiation at the gauge corner of the rail increases with both an increasing angle of attack and an increasing coefficient of friction, but it is insensitive with respect to small changes in the rail inclination under test rig conditions.

1. Introduction

Contacts between railway wheels and rails put the surfaces of wheels and rails under severe stress in practice. This results in rolling contact fatigue and wear which cause considerable maintenance cost for railway operators. Improved simulation tools to predict wear and rolling contact fatigue crack initiation are therefore of widespread interest. These prediction tools may aid in maintenance as well as in material and vehicle development directed towards minimizing the impact of rolling contact fatigue and wear in railway operation.

Full-scale wheel-rail test rig experiments aid in developing reliable simulation models, because rolling contact fatigue and wear can be studied under well-controlled conditions. Such a test rig experiment has been used to study rolling contact fatigue crack initiation and wear with a recently developed simulation model [1]. This model takes plastic shear deformation in estimating the local profile height change and in predicting crack initiation into account.

* Corresponding author.
E-mail address: gerald.trummer@v2c2.at (G. Trummer).

http://dx.doi.org/10.1016/j.wear.2016.04.024
0043-1648/© 2016 Published by Elsevier B.V.

2. Simulation model

2.1. Contact modeling

The contact calculation is done with the contact model, developed by Marte et al. [2,3]. This contact model divides the contact patch into strips, whose long sides are oriented parallel to the longitudinal direction of the rail. For each strip in the contact patch, the normal contact problem is solved according to the Hertzian solution for line contact. The tangential contact problem is solved by means of a strip-wise brush model. Extra creepage terms in the individual strips, which result from the curved three-dimensional shape of the contact patch, are taken into account in the simulation. This approach allows the efficient approximation of non-elliptic, curved, conformal contacts.

The ability of the contact model to deal with non-elliptic, curved, conformal contact conditions is important for the simulation of the test rig experiment investigated here. In this experiment the rail profile adapts to the wheel profile because the same wheel rolls repeatedly over the same short piece of rail. At the end of the experiment, the conformal contact patch may extend from the gauge face to the top of the rail.

2.2. Modeling of plastic shear deformation

The plastic shear strain near the surface of the contacting bodies is calculated with an approximate model [4]. This model determines the angular plastic shear strain α based on the local creepages and the linear-elastic bulk contact stresses. The influence of surface roughness and the influence of thermal softening of the material due to frictional heating are empirically taken into account by amplifying the contact stresses near the surface.

2.3. Change of profile geometry

The geometric change of railway wheels and rails is the result of both wear and plastic deformation. The local height change n perpendicular to the surface in the simulation is the sum of the height change due to wear n_w and the height change as a result of plastic shear deformation n_p.

$$n = n_w + n_p \tag{1}$$

The height change due to wear n_w is calculated according to the model of Krause and Poll [5]. This model distinguishes between mild and severe wear depending on the frictional power per contact area p_A in the contact. The transition between mild and severe wear takes place at $p_A = 4\,\text{W mm}^{-2}$. For a strip in the model, n_w is calculated as

$$n_w = I_w(p_A) \cdot \frac{W_r}{sb} \tag{2}$$

I_w is the wear volume per frictional work, W_r is the frictional work, s is the sliding distance and b is the width of the strip.

n_p results from plastic shear deformation in lateral direction (y-direction) parallel to the surface. The (laterally) sheared material volume per (longitudinal) unit length Δv for a strip is calculated from the lateral displacement increment $\Delta u_y = u_y - u_{y,0}$ below the strip as

$$\Delta v = \int_{z=0}^{\infty} \Delta u_y \, dz \tag{3}$$

The local height change $n_p{}^i$ of strip i is estimated as

$$n_p^i = \frac{1}{b} \cdot \left(|\Delta v^i| - f(+\Delta v^{i-1}) - f(-\Delta v^{i+1}) \right) \tag{4}$$

with

$$f(\Delta v) = \frac{1}{2}(\Delta v + |\Delta v|) \tag{5}$$

Δv^i is the sheared volume below strip i. This volume is lost from strip i. Δv^{i-1} is the sheared volume below the adjacent strip $i-1$ in the negative y-direction and Δv^{i+1} is the sheared volume below the adjacent strip $i+1$ in the positive y-direction (see Fig. 1). Function f determines whether the sheared material volume in adjacent strips contributes to a height change in strip i or not. n_p is positive if material is removed. n_p is negative if material is deposited.

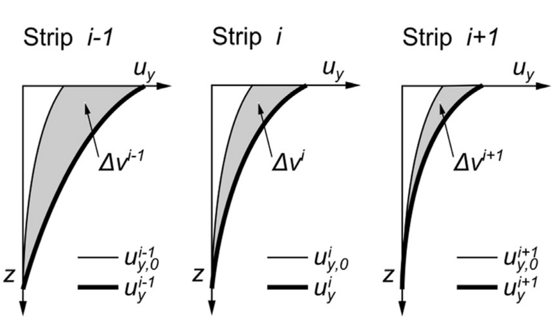

Fig. 1. Lateral displacement u_y as a function of depth z below three adjacent strips $i-1$, i and $i+1$. The sheared material volume Δv in each strip is calculated from the initial displacement $u_{y,0}$ and the displacement u_y after the load cycle.

2.4. Assessment of crack initiation

Severe plastic shear deformation is frequently observed near the surface of railway wheels and rails in practice. It causes an anisotropy in the fatigue and crack growth properties of the material. The crack initiation model [1] used here accounts for the important role of severe plastic shear deformation near the surface with respect to surface crack initiation. Depending on the distribution of plastic shear strain near the surface in depth direction, (microscopic) cracks lead to the formation of either flakes or wedge-like structures. Flakes break off the surface easily because of their small cross-sectional area perpendicular to the surface. They form wear particles with a high aspect ratio. Wedge-like structures do break off the surface and contribute to wear as well, but they remain attached to the surface with a higher probability compared to flakes. This can be attributed to the fast increase in the cross-sectional area with wedge length parallel to the surface, which makes breaking off more difficult. Microscopic cracks in a wedge-like configuration may grow further without being removed to ultimately form macroscopic fatigue cracks.

To assess the propensity for crack initiation in the simulation, the angular plastic shear strain $\alpha(z)$ is compared to a reference angular plastic shear strain condition $\alpha_R(z)$. This assessment is done within a "crack initiation layer" near the surface, which is a layer of finite thickness z_c, where the physical processes leading to crack initiation and wear take place. In the model, the actual shear strain $\alpha(z)$ is compared to the reference condition $\alpha_R(z)$ in terms of a similarity parameter A_α, which is calculated as [1]

$$\alpha_D = \int_{z=0}^{z_c} |\alpha(z) - \alpha_R(z)| \, dz \tag{6}$$

$$A_\alpha = 1 - 2 \cdot \frac{\alpha_D}{(\alpha_2 - \alpha_1) \cdot z_c} \tag{7}$$

with

$$\alpha_1 \le \alpha(z) \le \alpha_2, \quad \alpha_1 \le \alpha_R(z) \le \alpha_2 \tag{8}$$

This similarity parameter A_α is based on the area α_D between $\alpha(z)$ and $\alpha_R(z)$ in an angular plastic shear strain–depth diagram, as shown in Fig. 2. z_c is the thickness of the crack initiation layer, measured from the surface (z=0). α_1 and α_2 are the limiting values of the angular plastic shear strain range, which is relevant for the assessment towards fatigue crack initiation in the severely shear-deformed crack initiation layer. The values of z_c, α_1 and α_2 are preferably determined by experiments. This can be done by fitting a linear function defined by the points $\alpha_1 = \alpha_R(z_c)$ and $\alpha_2 = \alpha_R(0)$ to the experimentally observed angular plastic shear strain $\alpha(z)$ by the method of least squares at positions on the rail where fatigue cracks are observed [1]. The average value of angular plastic shear strain α as a function of depth z can be determined experimentally from the visible predominant orientation of the shear-deformed microstructure in etched metallographic sections [6].

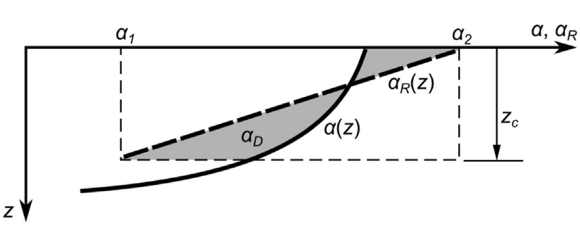

Fig. 2. Interpretation of α_D as the area between the angular plastic shear strain $\alpha(z)$ and the reference angular plastic shear strain $\alpha_R(z)$ within the crack initiation layer of thickness z_c.

Please cite this article as: G. Trummer, et al., Modeling wear and rolling contact fatigue: Parametric study and experimental results, Wear (2016), http://dx.doi.org/10.1016/j.wear.2016.04.024