Wear 344-345 (2015) 46–57

Contents lists available at ScienceDirect

Wear

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

Calculation of minimum crack size for growth under rolling contact between wheel and rail

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ARTICLE INFO

Article history:
Received 3 July 2015
Received in revised form
16 September 2015
Accepted 24 October 2015
Available online 9 November 2015

Keywords:
Rolling contact fatigue
Rail–wheel contact
Contact mechanics
Fatigue

ABSTRACT

The minimum crack size for growth a_{min}, which is defined as the smallest sized crack that grows fast enough to stay ahead of removal by wear and periodic grinding, was studied by employing Archard's wear model and Fletcher and Kapoor's "2.5D" fatigue crack growth model. For this purpose, a numerical analysis process was proposed by modeling the real railway operation conditions: typical crack driving forces, including bending, contact, thermal and residual stresses, and crack truncation, including contact wear and periodic grinding. A series of parametric studies was then conducted to predict a_{min} by varying the dominant crack growth contributors, such as the tractive coefficient (t_c=0.1, 0.2, 0.3 and 0.4), creepage coefficient (γ=0.1%, 0.2%, 0.3%, 0.4% and 0.5%) and temperature difference (ΔT=−20, 0 and 20 °C). From the analysis results, we found that the tractive coefficient is the most influencing parameter in the determination of a_{min}, while the creepage coefficient has a large effect on a_{min} under a low tractive coefficient, but the effect is diminished as the tractive coefficient is increased. The sizes of a_{min} vary from 0.106 (t_c=0.4, γ=0.1%) to 5.730 mm (t_c=0.1, γ=0.5%) without the application of a periodic grinding condition, but they are increased by approximately 24% on average with the application of periodic grinding. This means that even though a larger crack can be worn out with the implementation of grinding, once a crack grows over a certain size, the periodic grinding does not stop its growth.

1. Introduction

Rolling contact fatigue (RCF) [1,2] is a damage phenomenon that appears on the surface of a rail. This phenomenon is mainly the result of the repeated overstressing of the surface of a material by the millions of intensive wheel–rail contact cycles. A surface-breaking crack, observed on the running band of a tangent rail, occurs due to unidirectional plastic flow caused by repeated wheel sliding under high tractive force. Once a crack initiates and grows over a certain size, it will continue to grow until finally bringing about the whole rail breakage. Therefore, the periodic removal of the damaged surface layer has been adopted as a maintenance method in the railway industry. Removal of the surface material eliminates the damaged layer responsible for the crack initiation of a surface while also truncating the existing cracks. The continuous removal of just the right amount of metal to control the surface crack initiation and propagation when the growth rate is still low is called the "Magic Wear Rate" (MWR) [3]. Finding the optimum combination of wear and grinding to prevent cracks from growing is the key to running a safe and cost-effective railway.

A series of studies [4–19] has examined the prediction of wear and crack growth during the rolling of wheels over a rail, and great advances have been achieved. Several have focused on the interaction between wear and RCF [4–8]. Donzella et al. [4,5] studied the competitive role of wear and short surface RCF cracks by implementing finite element (FE) analysis and small-scale rolling and sliding tests. They calculated the depths of the RCF cracks and wear rates under different lubricating conditions. Franklin et al. [6] studied the modeling of wear and crack initiation, proposing the 'brick' model. In this model, the wear mechanism was simulated by removing the failed element as wear debris. Tunna et al. [7] reviewed the available wear and RCF mechanisms and models, along with the effects of variable parameters such as lubrication, metallurgy and the direction of rolling. Brouzoulis [8] performed a parametric study on the impact of wear on RCF crack growth. The effects of surface friction, the wear coefficient, normal pressure and fluid pressurization were investigated on cracks with a depth of 1.0 mm. Ringsberg [9] examined the growth of cracks in twin disc test specimens and concluded that sliding mode crack growth dominated and that a net crack growth greater than zero could lead to spalling failures on the surface of the specimen. However, there have been few studies on the interaction between the wear

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http://dx.doi.org/10.1016/j.wear.2015.10.013
0043-1648/

Nomenclature

a_0	initial crack depth
a_c	critical crack depth
a_i	crack depth at *i*th iteration
a_{min}	minimum crack size (depth) for growth
b_0	initial half crack width
c_x, c_y	Hertzian elliptical contact patch long and short axis half-lengths
da	crack growth rate
da_{net}	net crack growth rate
dw_{wear}	crack truncation rate by wear
dw_{grind}	crack truncation rate by periodic grinding
e	center point of Hertzian contact ellipse relative to the crack mouth
$g_N^f(X)$	crack line Green's functions
k	wear coefficient
k_L	elastic foundation of support
p_0	maximum Hertzian contact pressure
p_N	Hertzian contact patch normal pressure distribution
p_T	Hertzian contact patch tangential traction distribution
s	slip distance in the center plane where $y=0$
s_d, s_w, s_l	distance between two supports, support width and length, respectively
t_c	tractive coefficient
w_h	wear depth at the center plane
x	coordinate in the contact plane along the direction of motion
y	coordinate in the contact plane across the direction of motion
z	coordinate normal to the contact plane
C	foundation modulus of discrete support
E	elastic modulus
H	hardness of the softer of the two contacting materials
K_I	crack opening mode stress intensity factor
K_{II}	crack sliding mode stress intensity factor
K_σ	crack opening mode stress intensity factor along the crack face
K_τ	crack sliding mode stress intensity factor along the crack face
F_N	normal wheel load
F_T	tangential traction force
T_N	neutral rail temperature
T_o	operating rail temperature
V	wear volume
α	thermal expansion coefficient
γ	creepage coefficient
γ^{fs}	creepage coefficient in a full slip condition
θ	inclined angle from normal to rail surface to the crack face
θ_e	crack growth angle
ζ	local coordinate normal to the crack plane
η	local coordinate tangential to the crack plane
μ_c	crack face friction coefficient
μ_s	surface friction coefficient
$\sigma_{b,c,r,T}$	bending, contact, residual and thermal stresses in a rail, respectively
$\sigma_{x,y,z}$	stress components along the global coordinate
$\sigma_\zeta(\eta,\theta,e)$	stress component normal to the crack
$\tau_{\eta\zeta}(\eta,\theta,e)$	stress component parallel to the crack
ΔK_{eq}	equivalent stress intensity factor range
ΔK_I	crack opening mode stress intensity factor range
ΔK_{II}	crack sliding mode stress intensity factor range
ΔK_{th}	threshold stress intensity factor range

and crack growth mechanisms of large RCF cracks in consideration of realistic railway operating conditions, which is an urgent question in the industry.

In the current study, we proposed a numerical analysis model for the calculation of the minimum crack size for growth a_{min}, which was defined as the smallest-sized crack that will grow fast enough to keep ahead of their removal by contact wear and periodic grinding. This was accomplished through employment of Archard's wear model [20] and Fletcher and Kapoor's "2.5D" fatigue crack growth model [13–15]. The main purpose of this study was to calculate the sizes of a_{min} under realistic railway operating conditions, and to provide the results to railway operating companies to help them set up cost-effective rail maintenance strategies.

2. Fatigue and wear interaction

The passage of a wheel over a crack drives crack growth, but it also leads to contact wear of the rail surface, which shortens the existing crack. If the wear rate exceeds the crack growth rate, then the surface will be worn out faster than the crack tip can advance, thus resulting in a net shortening of the crack. In contrast, if the wear rate is slower than the crack tip advancing, then the crack will continue to grow. Fig. 1 [16] shows an illustration of the crack growth mechanism into a railhead. The net crack growth is calculated as follows:

$$\frac{da_{net}}{dN}=\frac{da}{dN}-\frac{1}{\sin(90-\theta)}\times\frac{dw}{dN} \tag{1}$$

where da_{net}/dN is the net crack growth rate and da/dN is the crack growth rate in the crack advancing direction. dw/dN is the wear rate and θ is the inclined angle from the crack face to the normal to surface of the rail.

2.1. Fatigue crack growth due to loading in a rail

2.1.1. Loading in a rail

Fig. 2 shows the illustration of the applied loadings during railway operation. Four main loadings are critical to the acceleration of crack growth: the global bending stress due to the weight of the vehicle imposed when a wheel rolls over a rail; the local contact stress at the surface of the rail due to contact between the wheel and the rail; the thermal stress due to the temperature difference between the neutral and operating temperatures of the rail; and the residual stress resulting from plastic deformation in the rail during manufacture and train operation. Therefore, all of the stresses should be considered to determine the shape of the total stress by superposing each stress component in the

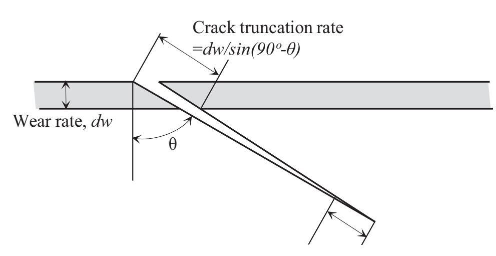

Fig. 1. Illustration of a wear–fatigue interaction model [16].