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# A model for predicting plastic strain and surface cracks at steady-state wear and ratcheting regime

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## ABSTRACT

Unidirectional plastic strain accumulation (ratcheting) is one of the main causes of surface crack nucleation in rails and wheels in dry condition. It is related to frictional forces which develop at the contact interface due to sliding, especially in curve and in braking. Surface cracks generated by ratcheting can subsequently lead to severe damage when environmental fluid contaminants (such as rain or snow) are added at the contact interface, due to the complex solid-fluid interaction, which can enhance crack growth.

In dry condition, wear and ratcheting can reach an equilibrium, such that the strain field and the crack depth are stationary. Understanding such steady-state deformation regime can be a key factor for predicting the expected crack depth and scheduling a correct maintenance programme.

In this paper a model for predicting the strain field at steady-state regime is proposed. Such model, based on an integral equation, allows predicting the strain field and crack morphology at high cycle number with no need of iterative numerical simulation. The potentiality of the model was proven both in characterizing the cyclic plasticity behaviour of materials and in predicting the maximum expected crack depth in full scale railway wheels.

## 1. Introduction

Rolling Contact Fatigue (RCF) is the main reason of severe damage in railway wheels and in rails. Usually it develops through the initiation and propagation of surface cracks. Surface crack nucleation was studied by several authors. Trummer et al. [1] considered unidirectional plastic strain (ratcheting) as the cause of crack initiation and elaborated a numerical model for predicting surface crack formation. Recently Athukorala et al. [2,3], considering ratcheting the main cause of fatigue in rails, proposed a new experimental methodology for characterizing the material cyclic plasticity. Grassie [4] studied the role of surface defects due to high plastic strain, such as studs and squats, in the RCF of rails. Fletcher and Sanusi [5], Ekberg and Kabo [6], and Kwon et al. [7] studied the role of thermal fatigue due to high frictional forces in the formation of surface cracks consequent to heat induced microstructural changes. Ren et al. [8] and Haidemenopoulos et al. [9] evidenced the role of corrosion in favoring the formation of surface cracks.

Among the possible causes of surface crack nucleation, ratcheting is one of the most frequent, as some follow-up reports on train wheels show [10,11]. Ratcheting can occur at the flange or at the tread of wheels, as well as at rail heads, especially near the side. Usually it is related to longitudinal wheel-rail sliding occurring in curve and in braking [12,13]. Wear interacts with ratcheting and crack propagation by removing layers of deteriorated material from the surface: this way, surface micro-cracks can be completely removed, and macro-cracks can be reduced in length [14–18].

Some studies evidenced the role of wear in dry contact by means of twin-disc rolling-sliding experiments, with various combinations of rail and wheel steels [15,16,19]. These experiments were characterised by high contact friction, significant wear and ratcheting. Cracks nucleated in the surface layer due to the accumulation of the plastic strain beyond the material ductility; however, under constant working condition such cracks did not propagate up to cause shelling. In particular, Donzella et al. [15] made some experiments on multiple specimens working in the same condition, varying only the number of cycles. They showed that after a determined number of cycles the strain field and the surface crack depth and morphology are unchanged, despite the specimens were subjected to very different test durations. This phenomenon was explained as a stationary regime which is set up by the equilibrium between wear and ratcheting. In other words, as far as ratcheting proceeds, wear removes the most strained layers from the surface, making deeper and less strained layers emerge, such that the plastic strain field under the contact surface is stabilized, as well as the surface crack length. Such phenomenon, sometimes identified as “magic wear”

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[14], was numerically simulated by Mazzù [20].

A deep understanding of this stationary regime can be a key issue for design and maintaining of wheels and rails. In fact, even though these cracks are not able to propagate up to cause severe damage, they can be the preferential site for severe fatigue initiation when liquid contaminants are added to the contact. Many researches, in fact, showed that surface crack propagation can be enhanced by the presence of fluid at the wheel-rail interface (rain, ice, soaked leaves, oil and grease). Propagation initially is towards the bulk, subsequently branches towards the surface causing severe damage such as shelling [21–25]. Several mechanisms can concur to crack growth in wet condition, including fluid sucking inside the crack, squeeze fluid film lubrication, crack face friction reduction, entrapped fluid pressurization [22,24–28]. Therefore, an optimized maintenance of both of rails and wheels should periodically remove (by grinding and reprofiling turning respectively) a layer as thick as the maximum expected surface crack depth. As RCF by solid-fluid interaction is a seasonal phenomenon [10,11,29,30], a correct maintenance carried out at the right time could improve the durability of wheels and rails.

In this paper a model for a fast prediction of the strain field at the stationary wear-ratcheting regime is proposed. Such result is obtained by an integral equation: this way, time consuming iterative numerical simulation are no more needed for predicting the strain regime at high cycle number. The strain field can be used for predicting the shape and size of surface cracks.

## 2. A model for ratcheting assessment in presence of wear

### 2.1. Model formulation

The basis for the assessment of wear and ratcheting in elastic-plastic regime is the simplified non-linear kinematic and isotropic hardening model proposed by Mazzù [20], applied to a half-space in plane strain condition, under a traveling Hertz pressure $p(x)$ with peak $P_0$ and proportional frictional stress $t(x) = f \cdot p(x)$ distributed over a contact area as long as $2b$ (see Fig. 1), where $f$ is the coefficient of friction. *t(x)* is supposed to be positive if the friction force is concordant with the direction of motion of the load (driver role), negative if discordant (follower role).

In that model, the orthogonal plastic shear strain $\gamma_{xz}$ is considered the only strain component which can accumulate indefinitely, and the shear stress component $\tau_{xz}$ the only responsible of shear strain. Such hypothesis is realistic in the subsurface region for high cycle number, as the normal strain components $\varepsilon_{xx}$, $\varepsilon_{yy}$ and $\varepsilon_{zz}$ are compressive and pulsating, therefore they have to saturate, otherwise the volume of the material would be reduced indefinitely. In the region close to the surface such hypothesis is not accurate, as $\varepsilon_{xx}$ and $\sigma_{xx}$ are alternate and contribute to the plastic strain accumulation [31]. However, as discussed below, in presence of wear the strain history of an elemental volume of material is scarcely affected by the events occurred in the surface region.

The stress field below the contact surface is calculated under the hypothesis of elastic material: in fact, as shown by Merwin and Johnson [32], Bhargava et al. [33,34] and Hearle and Johnson [35], this is a sufficiently accurate approximation even for the elastic-plastic domain.

The present model is addressed to predict the plastic strain field at high cycle, when it is stationary due the equilibrium between wear and ratcheting. For this reason, isotropic hardening is not considered, as it is a transient saturating phenomenon; however, its influence on the overall plastic strain field will be discussed below.

The present model is basically in agreement with the Koiter's theorem for a kinematic hardening material [36], which identifies the upper bound for the elastic shakedown limit (the lower bound being determined by the Melan's theorem for an elastic-perfectly plastic material [37]). As detailed in [31], the elastic shakedown limit predicted by the present model is accurate in the subsurface region, whereas it is overestimated in the surface region when the coefficient of friction exceeds 0.25, due to the inaccuracy in the surface region discussed above. In [31] a correction of the prediction in the surface layer was introduced in order to improve the accuracy and the consistency with the Koiter's model in the surface layer; however, in the present model this correction was not introduced, due to the low relevance of the very surface strain in the overall damage prediction.

Under the hypothesis of purely kinematic hardening, the yield function is expressed by Eq. (1):

$$F_Y = |\sqrt{3}\tau_{xz} - X_{xz}| - (\sigma_c) = 0 \tag{1}$$

where $\sigma_c$ is the cyclic tensile yield stress (i.e. after saturation of isotropic hardening) and $X_{xz}$ is the "backstress" component expressing kinematic hardening, i.e. the displacement of the elastic domain centre in the $\tau_{xz}$ - $\gamma_{xz}$ space. The backstress variation law is the following:

$$dX_{xz} = C\frac{d\gamma_{xz}}{\sqrt{3}} - \gamma X_{xz}\left|\frac{d\gamma_{xz}}{\sqrt{3}}\right| \tag{2}$$

where $C$ and $\gamma$ are the material parameters of the Chaboche-Lemaitre model [38,39].

Eq. (2) can be integrated analytically to give:

$$X_{xz} = \nu\frac{C}{\gamma} + \left(X_{xz}^0 - \nu\frac{C}{\gamma}\right)exp\left[-\nu\frac{\gamma}{\sqrt{3}}(\gamma_{xz} - \gamma_{xz}^0)\right] \tag{3}$$

where $\nu$ is 1 for a loading and $-1$ for an unloading process, whereas $X_{xz}^0$ and $\gamma_{xz}^0$ are the initial conditions, that can be referred to the previous flow. In event of plastic flow, Eq. (1) gives that at any moment the relationship between the shear stress and the backstress is:

$$\tau_{xz} = \frac{1}{\sqrt{3}}[X_{xz} + \nu\sigma_c] \tag{4}$$

and consequently the backstress variation between two load conditions can be calculated as:

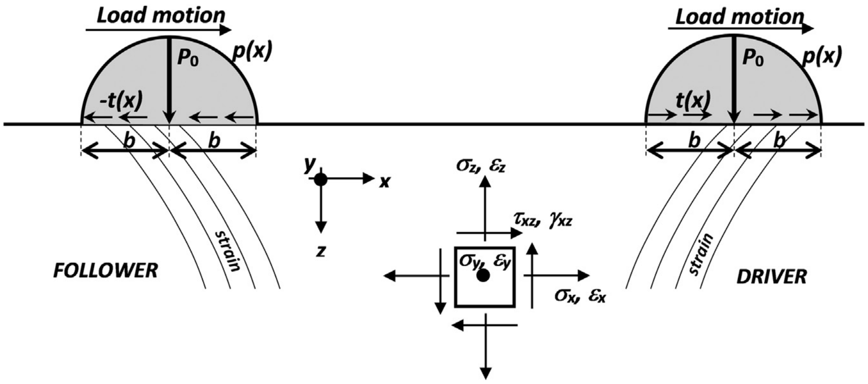

**Fig. 1.** Schematisation and conventions of the problem of contact with friction in plane strain.