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Progressive damage assessment in the near-surface layer of railway wheel–rail couple under cyclic contact

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ABSTRACT

The paper presents a ratchetting model, based on the non-linear kinematic-isotropic hardening law of Leimatre and Chaboche, able to predict the shear strain accumulation during rolling contact loading and including wear as a competitive phenomenon. A procedure was proposed to calibrate the model with the material constants suitable for rolling contact problems, obtaining them from bi-disk contact tests.

For this aim and to study the damage evolution at the wheel–rail interface, some twin disk rolling contact tests were carried out on a common wheel–rail material couple under a dry rolling–sliding condition typical of normal service. The tests were stopped at progressive cycles numbers for different couples of specimens, which were then cut and observed with optical and electron microscope in order to analyse the damage evolution in the zone near to the contact interface. A wear-rolling contact fatigue competition was observed with a progressive crack tip advance following a shear band cracking mechanism and crack tail removal due to wear.

The numerical model allowed predicting the experimental strain profile along the depth as a function of contact cycles number, also demonstrating through the critical strain approach that in the analysed conditions wear was able to prevent deep crack formation.

1. Introduction

Wheel–rail interface plays a fundamental role in determining the reliability of railway transportation, especially due to the continuously increasing performances on heavy haul and high speed railroads. The problem is very important and actual, as demonstrated by several accidents happened also in recent times, just related to damage and failure of these two elements in their contact zone [1].

As a consequence, a new impulse in the study of the damage and failure mechanisms and in the development of new materials and coatings, especially for rails [2–6] has been done in the last years.

The contact interface life is often determined by the relative importance of wear and RCF, depending on the working conditions and materials used for wheel and rail construction.

For example, wet service has been clearly recognised as a factor which reduces wear and significantly enhances RCF phenomena [7–9]; increasing material hardness in order to reduce wear, as in head hardened rails, makes more difficult for the rail and wheel profiles to became self-conformal, thus enhancing contact stresses: a correct grinding policy and defect management strategy (including the definition of inspection intervals) has therefore to be adopted in this case to avoid insurgence of RCF phenomena and to prevent catastrophic failures due to crack propagation [10,11].

Wear and RCF are also competitive [12,13], because wear continuously removes surface layers where cracks have been nucleated, limiting the possibility of severe damage occurrence and impeding at all, in same cases, the RCF insurgence. The concept of “magic wear rate” proposed by Kalousek and Magel [14] describes this mechanism, widely used in the preventive grinding as tool for rail maintenance [10,15,16], even though natural wear and grinding are not always sufficient to prevent deep crack propagation, as often happens in gauge corner region of the high rails in curves.

The study of the competition and interaction between wear and RCF is however very complex, involving several phenomena, like residual stresses formation, material hardening, ductility exhaustion and, especially for wet service, crack propagation driven by stress intensity factor.

As a consequence, only a few researches have been carried out to explain in detail how wear and RCF proceed and interact [17–19].

In particular, on BS11 rail steel under rolling plus sliding condition, Tyfour et al. [17] found that wear, ratchetting and material hardening are related phenomena which reach a steady state when material layers exposed to the surface have experienced the same prior plasticisation history.

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For the same material and test conditions, Fletcher and Beynon [18] observed an equilibrium between crack growth rate and wear rate, leading to a steady state constant crack depth of the order of 40 μm. Crack growth is here thought as a sequence of two mechanisms: crack initiation due to ratchetting (exhaustion of ductility), followed by propagation due to shear stresses.

The study of the wear–RCF interaction is however fundamental to comprehend and predict the damage evolution as a function of working conditions and material, thus allowing correctly scheduling the inspection intervals and optimising rail design.

Examining more deeply the mechanisms at origin of the damage, ratchetting has been recognised as one of the main cause of crack nucleation [7]. It can happens on the surface scale associated with the contact pressure peaks induced by asperities, or in the whole bulk layer interested by macro hertzian stress field [20]. Crack nucleation occurs when the material exhausts its ductility, i.e. a critical accumulated plastic strain is reached [21]. Once nucleated, cracks can growth only for a short length almost parallel to the surface, then determining the continuous de-attachment of flakes, with a mechanism named delamination wear [22], or they can growth towards the core, giving origin to RCF phenomena [12].

It is however not clear which are the causes for one or the other damage mechanism: it has been hypothesises that delamination wear converts to RCF (i.e. that cracks formed by ductility exhaustion proceed towards the core instead of determining debris deattachment) if the initially damaged points are surrounded by less damaged material, thus forming weakness zones which act as preferential crack growth paths [23].

Anyway, wear can be also concomitant with deep RCF cracks, as is a common evidence in rails [10,24].

Besides to the experimental studies carried out, mainly on twin disk machines, to describe the ratchetting evolution at the rail–wheel interface, several numerical models have been developed to simulate it [25–27].

In particular way, Merwin and Johnson [28] proposed a model considering an elastic-perfectly plastic material with a translating Hertz pressure distribution. They showed that only the orthogonal shear strain component γ_{xz} (where x is the parallel direction and z the orthogonal direction with respect to the contact surface; see Fig. 3) can be accumulated in a repeated contact process, and on this basis they neglected all the stress components except from the shear component τ_{xz}; this model was used to estimate the strain accumulation rate in specifical working conditions, corresponding to some experiments carried out by themselves. Hearle and Johnson [29] elaborated a method taking into account the stress field due to a dislocation distribution superposed to the one due to the applied load; again, they considered the τ_{xz} stress component only, developing a very efficient calculation method, but obtaining higher cyclic strain rates with respect to those experimentally measured by Merwin and Johnson. Bower [30] and Bower and Johnson [31] introduced a non-linear kinematic hardening model, obtaining good results in case of subsurface flow, but not so good in case of surface flow. They showed that this error was due to the fact that in the surface layer it is not sufficient to consider the shear stress τ_{xz} only, due to the importance of the tensile component σ_{xx}; thus, they proposed a method taking into account all the stress components in the surface layer, obtaining more correct results but a heavier computational cost. Kapoor and Franklin [22] elaborated a simplified shear band model introducing the critical strain concept, i.e. a critical accumulated plastic strain implying the ductility exhaustion of the material and consequent crack formation; by this model they simulated the wear process. This model hypothesised for each depth a shear strain rate proportional to the maximum applied shear stress. It is a quite empirical model that has the benefit of simplicity, but in its first formulation it resulted incompatible with experimental evidence, as in many rolling–sliding conditions the maximum applied stresses are in the subsurface region, whilst wear starts from the surface. Thus, they had to refine their model by the introduction of a statistical defect distribution, obtaining more reliable results, but losing the initial model simplicity. Mazzù [32] introduced a simplified kinematic hardening model, based on the Chaboche and Lemaitre model, taking into account the shear stress component τ_{xz} only; furthermore [33], he introduced a correction of his model for taking into account the effect of σ_{xx} in the surface layer, without increasing the computational effort. This model is more rigorous than the empirical model of Kapoor, because it simulates a well known plastic behaviour according to a consistent theory, but at the meantime is computationally much more efficient than other kinematic hardening models because it considers a single stress component. Moreover, it was introduced the possibility of simulating wear as a simultaneous phenomenon removing material layers form the surface: it was shown that presence of wear leads, after a transient phase, to a steady state where the wear rate is in equilibrium with the plasticisation rate, in agreement with the cited experimental results of Tyfour et al. [17]. A good agreement was found between the results obtained by this model and the results obtained by experiments and other numerical methods.

All these authors, however, pointed out the difficulty of calibrating the material plasticity constants on the basis of tension–compression tests, as they change for multiaxial stress state, as shown also by Fedele et al. [34] for tension and torsion, and particularly in contact, due to the hydrostatic compressive stress effect.

In this paper, the kinematic hardening model by Mazzù [32,33] was used to simulate the plasticisation process in rolling–sliding contact. A new procedure was introduced to calibrate the model with material constants based on rolling contact experiments rather than on uniaxial tension–compression tests. For this aim, bi-disk contact tests were carried out on a common wheel–rail material couple under dry rolling–sliding condition. These tests also permitted studying how RCF and wear proceed and interact. Their results were interpreted by the numerical model above described, considering wear as a concurrent phenomenon, which removes material layers from the surface and consequently affects ratchetting evolution.

2. Predictive model

The predictive model is based on the non-linear kinematic and isotropic hardening model of Lemaitre and Chaboche [35], as formulated by Mazzù for rolling contact [32,33]. In this formulation a uniaxial stress state is considered, based on the shear stress component τ_{xz} taken as responsible of plastic flow, and the computational cost is therefore reduced with respect to the original model. According to this model, the yield function is described by Eq. (1):

$$F = \left|\sqrt{3}\tau_{xz} - X_{xz}\right| - (R + \sigma_L) = 0 \qquad (1)$$

where σ_L is the initial tensile yield stress, X_{xz} the backstress expressing kinematic hardening, and R a variable expressing isotropic hardening.

The backstress variation law is the following:

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

where C and γ are material parameters.

As shown in [32,33,35] in uniaxial condition the backstress variation between two load conditions can be calculated as:

$$X_{xz} - X_{xz}^0 = \sqrt{3}(\tau_{xz} - \tau_{xz}^0) \qquad (3)$$

where X_{xz}^0 and τ_{xz}^0 are referred to the initial condition of the loading process.