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An efficient computational approach to evaluate the ratcheting performance of rail steels under cyclic rolling contact in service

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ABSTRACT

A comprehensive study was carried out to numerically evaluate the ratcheting performance of three high strength pearlitic rail steels under different wheel–rail cyclic rolling contact conditions, i.e. free rolling, partial slip, and full slip conditions, different friction coefficients and different axle loads. The wheel–rail cyclic rolling contact was simulated by repeatedly passing a distributed contact pressure and a distributed tangential traction on the rail surface. This study combined the non-Hertzian contact pressure from finite element analysis with the longitudinal tangential traction from Carter's theory to simulate the wheel–rail cyclic rolling contact problems. A cyclic plasticity material model considering the non-proportionally loading effect developed recently by the authors was applied to simulate the ratcheting behaviour of rail steels. The ratcheting performance of the rail steels was evaluated by the crack initiation life which was determined from the stabilized ratcheting strain rate and the ductility limit of the rail materials. The numerical results indicate that the crack initiation life decreases with the increase of the normalized tangential traction, the friction coefficient and the axle load for all three rail steels. Among the three rail steels, the hypereutectoid rail steel grade with a lower carbon content provides the best ratcheting performance under higher axle loads such as those used railway transport of mineral products in Australia. Furthermore, the numerical results obtained in this study are in reasonable agreement with the in-service performance of the three rail steels. This indicates that the developed approach has the capacity to evaluate the ratcheting performance of other rail steels under service loading conditions. The outcomes can provide useful information to the development and application of rail steels and the development of effective rail maintenance strategies in order to mitigate rail degradation.

1. Introduction

In an actual wheel–rail rolling contact process, the rail is subjected to cyclic loading and the rail surface is subjected to rolling and sliding loading with high contact stresses. It has been found that the cyclic stresses and the plastic deformation are the major factors influencing the rail degradation processes [1,2]. The stresses endured by the rail are always multiaxial, non-proportional and randomly fluctuating in magnitude and direction [3]. If the wheel–rail cyclic rolling contact conditions result in a stress level above the plastic shakedown limit or ratcheting threshold, new plastic deformation will occur and accumulate, i.e. ratcheting occurs, under each loading cycle. Although the plastic deformation in the rail in each cycle may be very small, the plastic deformation accumulates to large values over many cycles of loading [4]. When the ratcheting strain reaches the limiting ductility of the rail, the rail will fail at the local material point, which corresponds to the initiation of wear or rolling contact fatigue [5–7], e.g., in the form of head checks in the rail head. This states that the ratcheting behaviour plays a key role in causing the rolling contact failure of the rail, i.e. wear and rolling contact fatigue damage. Additionally, the demanding conditions imposed by rail transport of mineral products with higher axle loads and increasing annual haulage rates give rise to rail degradation and the requirement for ongoing grinding to maintain operational safety of the rail. Selection of the most appropriate

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rail material grades becomes important, and for this reason, evaluation of the ratcheting performance of the available rail steel grade under service loading is necessary. Such information can be used to assess the consequences of changes to the service conditions, i.e. increasing axle load.

Due to the relatively high costs in conducting field tests, the finite element method has been widely applied to numerically simulate wheel–rail cyclic rolling contact problems [8–17]. Kulkarni et al. [8–10] conducted several numerical studies on the ratcheting behaviour in elastic–plastic with the kinematic-hardening, elastic-perfectly plastic materials, and actual rail material under cyclic frictionless pure rolling contact. A two-dimensional finite element model was also developed by Xu and Jiang [11] to simulate steady-state line rolling contact on a 1070 steel under partial slip conditions. Jiang et al. [12] generated a three-dimensional numerical model to investigate the partial slip conditions and the contact stresses under three-dimensional rolling contact. However, all these studies applied the Hertzian contact pressure distribution, which is originated from the Hertz contact theory [13] and is limited to elastic material properties and half-space assumptions. The study by Yan and Fischer [14] indicated that the assumptions employed in Hertz contact theory impose limitations of its applicability in wheel–rail rolling contact problems. Plastic deformation frequently takes place on both wheel and rail as the maximum contact pressure exceeds the elastic limit of both wheel and rail materials [15]. Some discrepancies in the contact pressure distribution between the analytical solutions and real situations may be found if the plastic deformation in contact zone is high [14–16]. These problems were also highlighted in the studies by Ringsberg [17] and his colleagues [18] who compared the numerical results obtained from Hertzian contact pressure and those obtained from non-Hertzian contact pressure. Their numerical results indicated that the use of non-Hertzian contact pressure in the finite element simulations can provide a more realistic simulation for wheel–rail cyclic rolling contact problems. Similar discussion was also given by Wen et al. [2]. According to this, a non-Hertzian contact pressure distribution, which was obtained from a separate three-dimensional wheel–rail contact simulation, was applied in current study.

Beside using accurate loading conditions, to accurately evaluate the ratcheting performance of rail steels under different service loading conditions in numerical studies, an appropriate cyclic plasticity material model, which can satisfactorily describe both uniaxial and multiaxial ratcheting behaviour of the rail materials, is of paramount importance for simulating wheel–rail cyclic rolling contact problems [19]. Although many cyclic plasticity constitutive models, i.e. Chaboche model [20–22] and Ohno–Wang model [23], for ratcheting simulation have been developed, it is still challenging to find a generic and precise constitutive model due to the complexity of ratcheting behaviour. For instance, some common models for nonlinear hardening cannot simultaneously simulate and predict ratcheting with acceptable accuracy [24]. Additionally, extensive studies of ratcheting have demonstrated that different materials exhibit different ratcheting behaviour and varying cyclic characteristics. This indicates that the existing models may not be reasonably and simultaneously capture the ratcheting behaviour of the rail materials, for instance, the isotropic softening behaviour of heat treated rail steels [25]. According to this, a cyclic plasticity material model, which was recently developed by the authors [25] based on the experimental results by coupling a non-proportional multi-axial parameter into isotropic softening and kinematic hardening rules, was applied to simulate the wheel–rail cyclic rolling contact problems in current study. The capability of this material model to simulate both uniaxial and biaxial ratcheting behaviour of the studied rail steels has been verified in [25]. Application of this material model can provide a more realistic quantification of plastic ratcheting in the rail head to evaluate the ratcheting performance of the rail steels under different loading conditions in service.

The performance of the rail steels can be evaluated based on the predicted crack initiation life of the rail steels under cyclic rolling contact conditions. In recent years, several models for rolling contact fatigue crack initiation have been developed, such as the equivalent strain approaches, energy-density based models and the empirical model [26]. One of the well-known models of the equivalent strain approaches is the Coffin–Manson relation, which is expressed in the total shear strain range, and the crack initiation life is determined based on the material plane with maximum total shear strain range [27]. However, it has been found that the equivalent strain approaches do not take into account the influence of multi-axial non-proportional loadings on the crack initiation life [28]. Another well-known model for rolling contact fatigue crack initiation is the energy-density based model, which was proposed by Smith et al. [29]. This model, which belongs to the strain-life phenomenological approach for multi-axial loading, takes into account mean stress effect and both elastic strain range and plastic strain range in multiaxial loading. Although it has been widely used for determining mode I fatigue crack initiation and growth, its application is mostly limited to tensile mean stresses, which cannot reflect the actual wheel/rail rolling contact situations. An empirical model proposed by Kapoor [5] has been applied to predict the fatigue crack initiation life due to ratcheting only. The crack initiation life from the empirical model is determined based on the equivalent ratcheting strain rate and the material ductility. Tyfour and Beynon [30] have found that ratcheting rather than low-cycle fatigue was the dominant damage mechanism under typical wheel/rail cyclic rolling contact conditions. Study from Kapoor [4] and Bandula-Heva and Dhanasekar [31] further confirmed that ratcheting plays a key role in causing rolling contact failure of rail steels. According to this, the empirical model was used to predict the crack initiation life for the purpose to evaluate the performance of the rail steels in the current study.

In this paper, three high strength pearlitic rail steels, a low alloy heat treated rail steel (LAHT) and two hypereutectoid rail steels (HE1 for higher carbon content and HE2 for lower carbon content) with similar nominal hardness, were considered as an example of applying the developed approach for evaluating ratcheting performance of the rail steels. The influence of different cyclic rolling contact conditions, i.e. free rolling, full slip and partial slip, different friction coefficient and different axle load on the ratcheting performance of the three rail steels were investigated. The results can then provide useful information applicable to the selection of rail steels and the development of effective rail maintenance strategies for mitigating rail degradation.

The structure of this paper is as follows: the approach, which includes the significant findings of the experimental results, the developed ratcheting model for rail steels and the method of determining the crack initiation life, for evaluating the ratcheting performance of rail steels is given in Section 2. The finite element model and the methodology to determine the non-Hertzian normal pressure and the longitudinal tangential traction distributions are presented in Section 3. The numerical results of the ratcheting performance of the three rail steels under different service loading conditions are presented and discussed in Section 4. Conclusions are given in Section 5.

2. The comprehensive approach to evaluate ratcheting performance of rail steels

For the purpose of evaluating the ratcheting performance of rail steels under different loading conditions in service, a comprehensive