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Field and laboratory investigation of the relationship between rail head check and wear in a heavy-haul railway

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ABSTRACT

Head checks (HCs) are widespread in railway tracks. They can cause rail fracture. In theory, and under some laboratory conditions, a proper amount of natural wear exists which is just enough to suppress HC initiation and growth and is called magic wear rate. It will minimize the costs of rail maintenance. In practice, such magic wear rate still seems elusive. This paper is an attempt to investigate the feasibility of magic wear rate under operational conditions. To such an end, the growth of and competition between HCs and wear in the high rail of a curve of a heavy-haul railway is analyzed. The length and depth of the HCs were measured by laboratory examination and image recognition from rail specimens sampled at different traffic gross tonnages. Rail wear was calculated from the measured rail profile. Three phases of HCs and wear evolution and competition were identified. It was found that the wear rate was almost constant for a broad range of traffic tonnages, even though the rail hardness varied significantly. With such a wear rate the initially severe HCs were reduced in size, indicating the feasibility of engineering magic wear rate to avoid HCs by the proper design or selection of the materials and profiles of the rails.

1. Introduction

Rolling contact fatigue (RCF) can cause spalling and even rail fracture which will endanger the operational safety of the trains, reduce the lifetime of the rail and increase maintenance costs [1,2]. Head check (HC) is now one of the major types of RCF. It is well known that the initiation and propagation of HC cracks are influenced by rail wear [2–5]. This competition mechanism between wear and RCF cracks was widely applied in rail maintenance [6–10]. Kalousek and Magel [6] presented the concept of magic wear rate based on the mechanism that RCF cracks can be suppressed by the natural wear of the rail together with artificial wear, like rail grinding with an appropriate interval. Magel et al. [7] introduced this concept to the process of rail grinding and presented the parameters of preventive rail grinding, such as the grinding interval and amount of metal removal. Burstow [10] considered the wear number $T\gamma$ (the so called T-gamma) in defining the RCF damage index to forecast the risk of RCF crack initiation.

The wear and RCF of rails have been investigated with a wide range of methods, such as computer simulation [11,12], scaled experimental testing [13,14], as well as with a full-scale test rig and track testing [15,16]. Their purposes were to identify the characteristics of wear and RCF, to simulate the development mechanism of wear and RCF or to choose the rail grade for different loading conditions.

To explain how wear and RCF interact, Fletcher and Beynon [17] observed a balance between crack growth and wear rates from tests on a twin-disc machine, which showed that equilibrium was established after approximately 10,000 cycles, leading to a steady state of shallow crack depth. Donzella et al. [18] presented a numerical model considering the material properties and loading conditions to study the competitive role of wear and surface originated RCF. Then, a twin-disc machine was employed to examine the competition between wear and RCF under dry and wet rolling–sliding contacts [19] and to calibrate a ratcheting model for predicting the shear strain accumulation during rolling contact loading and wear [20]. Work on the competition between wear and RCF cracks under field operation conditions still seems to be missing.

In this paper, the relationship between rail HCs and wear is investigated for the high rail of a curve in a heavy-haul railway. Rails were sampled from the track at different traffic gross tonnages. The depth and length of the HCs in the gauge shoulder of the samples were measured in the laboratory by sectioning and image recognition (IR). Rail transverse profiles were measured for rail wear calculations. The different phases in which the wear and the HCs competed with each other were analyzed.

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Table 1
Major chemical composition and surface hardness requirement of U75V rail [22].

Chemical composition (%)						Surface hardness (HB)	
C	Si	Mn	P	S	V	Crown, shoulder and gauge corner	Gauge face
0.71–0.80	0.50–0.80	0.70–1.05	≤ 0.030	≤ 0.030	0.04–0.12	340–390	≥ 330

Table 2
Traffic tonnage and time of sampling.

Sampling number	Accumulated Traffic Tonnage(MGT)	Time from beginning of test (month)
	New rail*	0
1st	10	1
2nd	30	2
3rd	62	4
4th	100	7
5th	150	10
6th	210	14
7th	275	17
8th	320	20

* The new rails were not ground after installation or anytime during this study.

2. Experimental procedure

2.1. Field tests

A field investigation in a dedicated coal heavy-haul railway in China, the Shuohuang line, showed that the most serious HCs and wear occurred in the rails of the curve track with a radius of 500–600 m in the loaded train direction, which is consistent with the findings of Tunna and Urban [21]. Therefore, a curve of 500 m radius in the loaded train direction of this line was chosen for the field monitoring of crack development and rail transverse profile evolution, as well as for rail sampling.

The test curve is a ballasted track with continuously welded rail (CWR), 75 kg/m rail, concrete ties and elastic fasteners. The curve has a cant of 90 mm, a gradient of 7° and a rail inclination of 1:40. During the test period, the high rail was constantly lubricated. It experienced both dry and wet (rain and snow) environment, but it was in a dry climate in general. The gauge was also corrected to the standard periodically as the high rail wore. The train speed on the test curve was 60–70 km/h with balanced running through the curve. The vehicle axle load was 21 t or 23 t (two types of vehicles).

At the beginning of the monitoring, both the high and low rails were replaced with new 75 kg/m U75V heat-treated rail. The major chemical composition and the surface hardness of the rail in the specification [22] are listed in Table 1. The new rails were not ground after installation or anytime during this study.

Rail samples of 1 m were cut from the high rail for laboratory examination of the HCs. The tonnage and time of the samplings are given in Table 2. The positions of the samplings were in the middle of the curve to avoid the transient effects that the trains usually experience when entering and exiting curves (Fig. 1). The replacement rails were made to have the same profile as their neighboring rails and the same length as the replaced rails and were connected to their neighboring rails with bolts and fishplates for convenience with regard to the next sampling. Fig. 1 also shows that the samples were taken in the sequence opposite to the direction of the traffic so that any disturbance caused by the replacing rails would have no effect on subsequent samples. After about 320 million gross tonnages (MGTs), the high rail had to be completely replaced due to excessive side wear.

It can be seen from Fig. 1 that, at the time of each sampling, transverse profiles of the high rail were measured over a length of 100 m on both sides of the sampling position. The measurement positions are indicated by × in Fig. 1, with distance of 5 m between each, thus a total of 19 profiles were measured during a sampling. The profiles were compared in Section 3.3 with that of a new rail for wear calculation.

2.2. Laboratory examination

Since the samples were taken from the same curve at adjacent positions in the middle of the curve where steady state curve negotiation had been achieved, the loading conditions of the samples can be considered to be the same for all the positions. The initiation and propagation of the HCs were, therefore, influenced by the same factors and can be put together for comparison and further analysis.

The specimens of 100 mm length for examination were cut from the center of the samples in the way shown in Fig. 2. The length and depth of the HCs in the specimen were measured at 12 mm away from the gauge face because HCs were first observed at this location.

Fig. 3(a) shows the micrograph images of the vertical–longitudinal cross-section of the specimen (gray side of the specimen in Fig. 2) obtained with an optical microscope. The IR method was applied according to the gray image [23] to identify the length and depth of the HCs. After IR processing, the HC image was converted to pixel points with coordinates (Fig. 3(b)).

To calculate the length and depth of the HCs in Fig. 3(e), the horizontal line of the top surface of the specimen (reference line) and the HCs lines were first identified. Then the straight-line distance between two adjacent pixel points in one HC was calculated from the coordinates of the points. The length of an HC crack is the sum of all the straight-line distances between adjacent pixel points along the same crack. The depth of an HC crack is the vertical distance between the lowest pixel of the HC and the reference line. Finally, the real length and depth of the HC can be obtained by applying the scale factor which were the 5 mm-line shown in Fig. 3(a–c), the 10 mm-line shown in Fig. 3(d).

3. Analysis

3.1. Observations of the HCs on the rail surface

The contact between the profiles of a new 75 kg/m rail and the commonly used wheels (new and typically worn) of freight wagons in the heavy-haul railway is shown in Fig. 4. The radii of the curvature of the rail profile are 500, 80 and 15 mm at the crown, the gauge shoulder and the gauge corner, respectively. The distribution of the wheel–rail contact points is obtained when the wheel set is transversely displaced between −10 mm and 10 mm with respect to its position, ideally aligned with the track center. The contact at the gauge corner was minor and the major contact took place on the gauge shoulder and the crown in the range 11–26 mm away from the gauge face for the former case (Fig. 4(a)),