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Local rolling contact fatigue and indentations on high-speed railway wheels: Observations and numerical simulations

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ABSTRACT

Local rolling contact fatigue (LRCF) has occasionally been observed on wheels of high-speed electrical multiple units (EMUs) in recent years in China. It typically propagates to 2.5–8.5 mm deep along shallow angles to the tread surface, leading to large material removal during lathe turning. To reveal the initiation and propagation mechanisms of LRCF, a thorough investigation has been conducted by means of field observations, statistical analyses, and numerical simulations. It is found that 69% of LRCF occurred on the leading axles of leading coaches, and its occurrence rate on the 380 km/h class EMU was 2.87 times that on the 250 km/h class. Records of a 380 km/h class EMU train have shown that LRCF initiated with an occurrence rate of 14.3% from indentations of 2.3–3.0 mm deep and 4 mm in diameter, and the crack depth increased by 0.011–0.031 mm every 1000 km. All these phenomena, among others, suggest that indentations are the main causes of LRCF. The cracks, according to 3D transient and 2D static simulations of wheel–rail rolling contact, probably initiate at the bottom of deep indentations with a characteristic dimension longer than 2–4 mm. Preventive measures against LRCF are recommended at the end.

1. Introduction

A rolling contact fatigue (RCF) problem on high-speed wheels (one-piece forged wheels), as shown in Fig. 1(a), has drawn great attention in China since 2012 owing to its potential threat to running safety. Because of its isolated occurrence on the tread, the problem is referred to as local rolling contact fatigue (LRCF) hereinafter to distinguish it from the classical RCF occurring continuously along the circumference of wheels (see Fig. 1(b)). Cracks of LRCF are observed during wheel reprofiling to be typically 2.5–8.5 mm deep, and their extent on the tread enlarges with the cutting depth owing to their shallow angles to the surface, as indicated in Fig. 2. Furthermore, many LRCF defects are not instantly recognizable from the tread surface (see Fig. 1(a)). To better understand its initiation, propagation, and consequences, intensive studies have been conducted in the past years. This paper presents some field observations and statistical results on LRCF, followed by numerical studies to reveal its initiation mechanism. A study on the classical RCF of high-speed wheels in China was recently published in [1]. Before showing the results, the research background is further elaborated in the following subsections.

1.1. Laboratory tests

Metallurgical and mechanical analyses of LRCF samples have shown that the chemical composition, microstructure, grain size, inclusions, hardness, and mechanical properties of the wheel material all meet the requirements of EN13262-2008 [2]. This suggests that LRCF does not originate from material defects. Presently, it is still unclear whether LRCF initiates on the surface or in the subsurface (very shallow), because the possible origins may have been modified or destroyed after initiation by wear and plastic flow.

The risk of LRCF was evaluated by a test of BU300 roller rig in Lucchini RS laboratory at speeds of up to 300 km/h, for which a high-speed trailer wheelset with an LRCF defect detected by ultrasonic inspectors in a Chinese depot was used [3]. After an equivalent service mileage of 150,000 km, it was observed that the LRCF cracks did not propagate into the bulk, but upward to the surface, which would later detach and lead to shelling. Its surface appearance, originally unrecognizable, gradually became very similar to mature squats (LRCF defects on rails), i.e., a two-part or lung-like depression (see [4–8]).

It should be noted that wheel and rail LRCF defects are very different: the cracks of squats may propagate downward, driven by rail bending, to form transverse cracks and result in rail breaks at the end, while this seldom occurs to the wheel LRCF, as tested in [3], due to the absence of a driving force and the existence of com-

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(a) LRCF damage

(b) Classical RCF damage

Fig. 1. RCF of high-speed wheels in China.

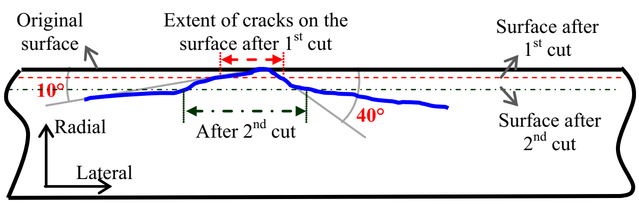

Fig. 2. Cracks (in blue) traced from a lateral-radial section of an LRCF sample. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

pressive residual stress in the rim. Valuable data on the service state and laboratory analyses of railway wheels can be found in [9–13].

1.2. Classification, initiation, and reproduction of LRCF

LRCF (referring to wheel LRCF hereinafter) was reported as early as the 1970s in Japan [14] and recently in Australia [15]. The existing models of RCF proposed by Ekberg and others [12], including the quantitative $T\gamma$ approach [16], seem not applicable because LRCF is a more stochastic phenomenon than classical RCF. According to the classification by Deuce [17], LRCF are close to the type of RCF clusters. Deuce believed that if maintenance measures were not timely, RCF clusters might lead to localized shelling, which is consistent with the test results in [3]. Deuce also believed that their immediate cause was plastic flow or ratcheting similar to that of classical RCF, but locally, and the root causes could be localized hollow tread or local radial run-out effect. These suggest that an original geometric defect is required to trigger LRCF, being in agreement with the common understanding that fatigue cracks always start at stress risers.

In addition to geometric defects, the stress risers may also be non-metallic inclusions, microstructural inhomogeneity, and asperities for bearings and gears manufactured from hard steels and working in lubricated conditions [18–25]. For relatively softer wheels and rails, however, asperities become insignificant due to much higher wear rates under un-lubricated conditions. Moreover, the advanced manufacturing technologies for steel, wheels, and rails have greatly reduced the inclusions, inhomogeneity, etc., leaving only geometric defects as the main stress riser for railway wheels and rails nowadays. Wheel RCF initiated from geometric defects such as hollow tread, out-of-roundness, flats, and indentations, and rail RCF from welds, corrugation, wheel burns, and indentations have been reported in [1,7,8,17,26–28]. Curving is another important cause of classical RCF [1,12,17,29,30]. After initiation, the propagation of cracks becomes highly affected by the third-body layer existing between the wheel and rail [24,29,31,32].

In laboratory studies, LRCF of bearings has been observed to originate from indentations by many researchers [31,33,34]. Using a scaled twin-disc rolling rig, Kaneta et al. [35] observed the LRCF of a rail disc originating from a tiny pit, for which a sequence of dry and wet running was set. Cantini and Cervello [3] in their full-scale rolling test observed that cracks initiated at the bottom of almost all artificial cracks (1–3 mm deep) applied along the radial direction using an electric discharge technique, and on the edges (in the tread surface) of a ϕ4 mm spherical indentation.

This research intends to clarify the relationship between LRCF and indentations based on field observations, statistical analyses and numerical simulations, and an initiation mechanism of LRCF is proposed therefrom. Note that LRCF throughout this work refers to its early stages, i.e., noticeable depressions or those that are not instantly recognizable on the tread.

2. Field observations and statistics

2.1. LRCF and indentations

2.1.1. Initiation of LRCF from indentations

During daily inspections, nine LRCF defects were detected successively on a 380 km/h class electric multiple unit (EMU) train (16 coaches) in a depot located in central China. The recorded data are as follows.

- Day 1: a series of indentations, approximately 4 mm in diameter and 2.3–3.0 mm in depth, were found on the left side wheels of the trainset; eight indented wheels of the two leading coaches (trailer ones at two ends) were reprofiled, while the other 56 wheels remained untreated (Wheels A and B mentioned later are among these).
- Day 113: periodic reprofiling (every 200,000–250,000 km) was performed on all wheels of the trainset with a radial cut of 0.5 mm (less than the depth of the indentations); the radial cuts of Wheels A and B were 0.54 and 0.5 mm, respectively.
- Day 158: Wheel A (in coach 2) was scheduled for turning in order to treat an excessive indentation (the limit is 30 mm long or 0.25 mm deep), and after a radial cut of 0.375 mm no cracks were reported.
- Day 161: plastic deformation and a two-part depression were observed around the indentation of Wheel A with dimensions of 100 mm length (circumferential) and 50 mm width (lateral) (see Fig. 3, i.e., an LRCF defect); to remove the cracks below the surface, a radial cut of 5.755 mm was performed.