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Slippage effect on rolling contact wear and damage behavior of pearlitic steels

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ABSTRACT

The effects of slippage on rolling contact of pearlitic wheel–rail steels (rail-U71Mnk/wheel-ER8 steels for China high-speed railway) have been investigated in the laboratory on a twin disc tester under different slippages (varying from 0.17%, 0.91%, 2.38%, 4.55%, to 9.43%). The morphology of the worn surface and the cross-sections have been detected by scanning electron microscopy (SEM), and the variation of chemical composition on worn surface and the phase structure of debris were detected by the electron energy dispersive spectrometer (EDS) and X-ray diffraction (XRD), respectively. The results indicate that, as the slippage increased, the friction coefficient raised up at steady state of the rolling contact friction as well as the wear volume. With the increasing slippage, the damage of wear zone was transformed from mild to severe, which presented the typical fatigue features: delamination and sub-cracks. The worn surface was covered with a thin tribo-film under a small slippage condition. With the increase of slippage, the oxidation wear behavior weakened and the size of the debris particles became larger. As the slippage increased, the mainly wear mechanism transformed from the oxidation wear to the fatigue wear (delamination mechanism) and then into the abrasive wear accompanying delamination.

1. Introduction

The friction and wear behavior of the wheel–rail system is a complex phenomenon involving tribological behavior of materials and the structural modification. Previous research focused on the study of the crack initiation of wheel RCF, i.e. ratcheting, using various experimental and numerical approaches [1–4]. Moreover, the development of high-speed trains imposes a considerable material challenge concerning the microstructure stability of the surfaces of rails and wheels [5–7], and many studies have focused on the materials with different microstructures, such as pearlite, bainite, martensite and so on. For the bainite or martensite steel, wear resistance and fatigue behavior of the rail/wheel materials have been investigated under rolling contact friction in laboratory, while they have not been wildly used in the railway industry. Pearlitic steel, due to its good mechanical properties and good wear resistance, has been regarded as an important industrial steel and it was also the most widely used material in the railway system several hundred years ago.

From the aspect of tribology, many studies mainly focused on rolling contact fatigue during the wheel/rail rolling contact friction [8,9], and wear behavior before the initiation of crack was not emphasized. Clayton [10–12] conducted rolling contact friction tests with different parameters to analyze the fatigue behavior, and the results pointed out that the parameters of slippage would affect the crack behavior significantly while the effects of cycles on wear and damage behavior did not show. In tribological system, the friction conditions and parameters had a great influence on the wear behavior and the running condition friction map [13] and it is said that the specified mixed zone usually was accompanied with cracks which could result in fatigue of materials [14], so the parameter, which was related to the wear behavior running in the mixed zone, should be avoided.

From the aspect of metallurgical phase, many studies focused on the gradual structure changes near the rail–wheel contact surface, which was usually considered as an important factor to the corrugation, squat and other fatigue [9,15]. The microstructure of the white etching layer was controversial and it was considered as martensite [16], nanocrystalline Fe–C alloy [17] and deformed pearlite lamellae as well as nanocrystalline martensite, austenite and cementite [18]. Stuart L. Grassie [19] indicated that the slippage significantly influenced the rolling contact conditions when the slippage was up to 15%. The study of Pal et al. [20,21] inferred that slippage was also related to the transformation of a thin layer

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on the rail surface which was usually considered as martensite. From the summary of above studies, obviously, the slippage is an important parameter which can influence the wear behavior and the cracks behavior in different wear zones relating to different wear mechanisms. Furthermore, according to different wear mechanisms, by plotting wear maps of wear rate against contact pressure and cycles, the various territories associated and the transitions from mild to severe can be identified, which is provided by Lim and Ashby [22]. Another different approach for considering wheel/rail wear data has been used by Bolton and Clayton [10], three wear regimes were identified during twin disc testing of rail/wheel materials, mild, severe and catastrophic. Lewis [23] and Ding [24] performed the related research of wear maps.

In the present paper, we provide a further experimental investigation to understand how the slippage affects the wear behavior and reveals the wear mechanism of pearlitic steels under rolling contact friction with different slippages.

2. Materials and methods

Rail material, TB/T 3276-2011 U71MnK, is usually used in the high-speed railway in China. Wheel material, ER8, is produced by LUCCGINI corporation. And the chemical composition and the main mechanical properties are presented in Tables 1 and 2.

In the experiment, the rail specimens were machined to give a disc with a width of 10 mm and a diameter of 40 mm, and the wheel specimens were shaped with a ellipsoid-surface, a contact diameter of 14 mm and a diameter of 40 mm (Fig. 1).

The tests were conducted on the rolling contact friction tester which allowed two disks with different velocities to roll against each other with normal and tangential forces. The value of contact stress was calculated based on Hertzian theory, and the geometry of samples were designed according to the ratio of major and minor axes of ellipse as well as the maximum contact stress in lab, which were equal to that in field [4,25]. Therefore, the test conditions with a Hertzian contact pressure of 1200 MPa (calculated from the axle weight 16 t) and the wheel disc speed of 500 rpm were used for all tests under different slippages including 0.17%, 0.91%, 2.38%, 4.55% and 9.43%, and the number of cycles was 10^3–2^*10^5. All tests were conducted under the temperature of 25 °C, and the atmosphere humidity of 60 ± 5%. The different slippage is defined as $\delta\% = \frac{2(v_1 - v_2)}{v_1 + v_2}$, where v_1, v_2 are the rolling speed of two disks, respectively.

Before and after the tests, the hardness and the mass of the disc specimens (which were cleaned with the acetone/alcohol by a ultrasonic cleaner) were tested by the Vickers Hardness Tester (MVK-H21, Akashi) and the analytical balance (measurement accuracy: 0.001 g). The average hardness was obtained by measuring 10 points in the contact zone along the circle of disc specimens, meanwhile, in order to eliminate the system error, the wear loss of the disc was acquired by the difference in value between tested specimens and the standard sample. The worn surfaces and the cross-section morphologies were detected by an optical microscope (BX60MF5, OLYMPUS) and a scanning electron microscope (JSM-6610, JOEL), and the chemical compositions of the worn surface and the phase structure of debris were detected by the EDS (X-MAX50 INCA-250, OXFORD) and the X-ray diffractometer (X'Pert PRO, PANalytical), respectively.

Table 1
Composition properties of materials used in tests.

Materials	Chemical composition (wt%)						
	C (**%**)	Si (%)	Mn (%)	P (%)	S (%)	V (%)	Cr (%)
U71Mnk	**0.65**	**0.15–0.3**	**1.00–1.5**	**≤ 0.03**	**≤ 0.03**	/	/
ER8	**0.56**	**0.82**	**0.79**	**0.013**	**0.012**	**0.01**	**0.1**

Table 2
Main mechanical properties of materials used in tests.

Materials	Tensile strength R_m (MPa)	Hardness (HB)	Elongation (%)
U71Mnk	**860–980**	**260–300**	≥ **12**
ER8	**860–980**	≥ **245**	≥ **13**

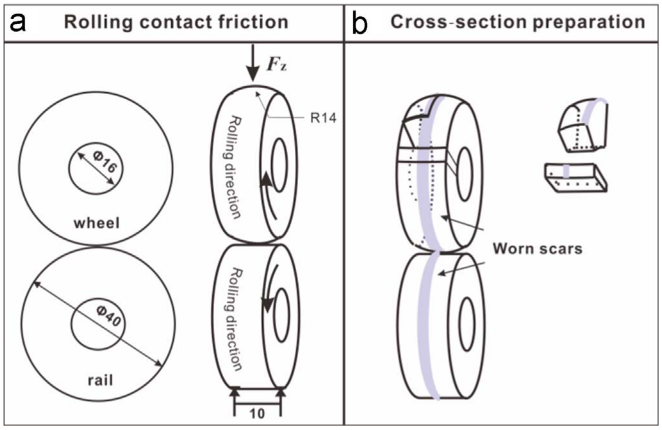

Fig. 1. Experimental method: (a) rolling contact friction tests and (b) cross-section preparation.

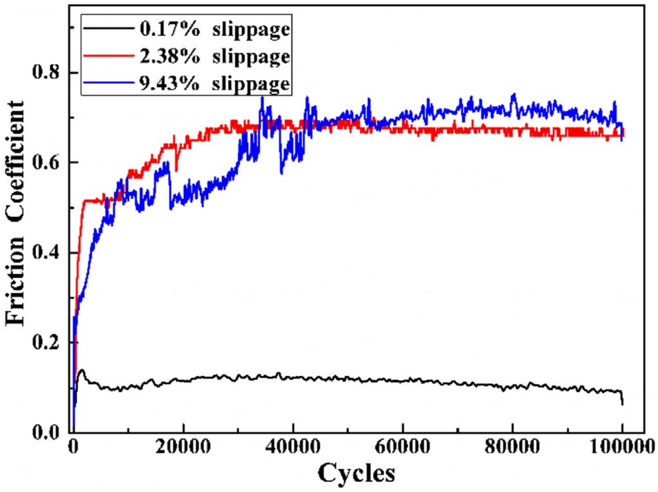

Fig. 2. Friction coefficient curves under different slippages of 10^5 cycles.

3. Result and discussion

3.1. Wear behavior

3.1.1. Friction coefficient

The friction coefficient curve is an important dynamic output information for the rolling contact friction system. Fig. 2 shows the variation of friction coefficient curves under three typical slippages.

As the slippage increased, the friction coefficient reached a stable value and the number of cycles increased with gradual strong fluctuation of the friction coefficient, especially when the slippage was 9.43%. Under the smallest slippage of 0.17%, it was