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Tribo-chemical behavior of eutectoid steel during rolling contact friction

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ABSTRACT

The tribo-chemical behavior of the eutectoid steel during rolling contact friction is investigated via scanning electron microscopy, X-ray diffraction, X-ray photoelectron spectroscopy (XPS) and electron probe X-ray microanalysis. The worn surface is divided into three zones: matrix zone (without friction), tribo-film zone (formed during friction) and delamination zone (tribo-film spalling). The different chemical states of atoms between those three zones and the air were investigated using the XPS analysis. The results showed that the matrix zone is composed of Fe_2O_3, FeO and metallic Fe, while the tribo-film and delamination zones only contain Fe_2O_3 and FeO. Where the tribo-film is formed, the absorptive ability of O and C atoms on the top 2–3 atomic layers is probably weakened, while the exposed fresh metal in the delamination zone tends to be continuously oxidized and form tribo-film. The tribo-chemical reaction in the delamination zone is more activated than that in the other two zones. The protective nature of the tribo-film probably maintains a low friction coefficient under rolling contact friction condition.

1. Introduction

Eutectoid steel has been widely used in the railway industry over several hundred years because of its proper mechanical properties and excellent wear resistance [1–3]. The problem induced by the friction in wheel-rail system is as significant as other serious problems, such as the dynamics problem. It is known that the typical friction mode to simulate the wheel-rail contact is the rolling or rolling-sliding contact. Wheel-rail rolling contact friction has great influence on the wear, rolling contact fatigue and other related maintenance issues that are, associated with the eutectoid steel materials [4,5]. From the design point of view, some studies of wheel/rail rolling contact have focused on the rolling contact fatigue [6–9], the wear behavior associated with the crack initiation/propagation problem [5,10], and the gradual structure changes [11] which is considered as an important factor to the corrugation, squat and other fatigue-related system deteriorations [4,7,12–14]. While these types of contact fatigue phenomenas have attracted adequate attention when they are associated with severe wear, they did not receive enough consideration when the wear is mild. This is actually a false perception, since the slight surface damage is connected to the tribo-chemical behavior of surface, especially the variation of surface compositions, microstructure and the formation of transfer films during the friction process. The effect of surface coatings on increasing the wear resistance has always been an interesting aspect in the tribological system, and its tribo-chemical behavior during the friction process [15–18]. The tribo-chemical reaction usually contributes to the formation of tribo-film layer during the friction process which can result in a lower friction coefficient and further reduction in the material wear loss, especially in a lubrication environment. However, in non-lubrication friction system, the tribo-chemical reaction also plays an important role during the friction process, since the third body layer acts as a solid interfacial layer; e.g., the oxidation layer in the case of railway system [19]. In this sense, the definition of third body can be extended beyond the media between the rubbing interfaces such as wear particles or the lubricating oil to include the tribo-film layer. In this case, it is known as a third body layer. There are various definitions for the surface-layer with structure or chemical composition changes.

Therefore, this paper is aimed to highlight the forming condition for tribo-film, the variation of tribo-film compositions and its microstructure during rolling contact friction process. The surface analysis method of XPS is used to investigate the chemical states of the atoms between friction contact interfaces and the air.

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Table 1
The chemical composition and the main mechanical property.

Materials	Chemical composition (wt.%)							Main mechanical property		
	C	Si	Mn	P	S	V	Cr	Tensile Strength R_m (MPa)	Hardness HB	Elongation (%)
Rail	0.65	0.15–0.3	1.00–1.5	≤0.03	≤0.03	/	/	860–980	260–300	≥12
Wheel	0.56	0.82	0.79	0.013	0.012	0.01	0.1	860–980	≥245	≥13

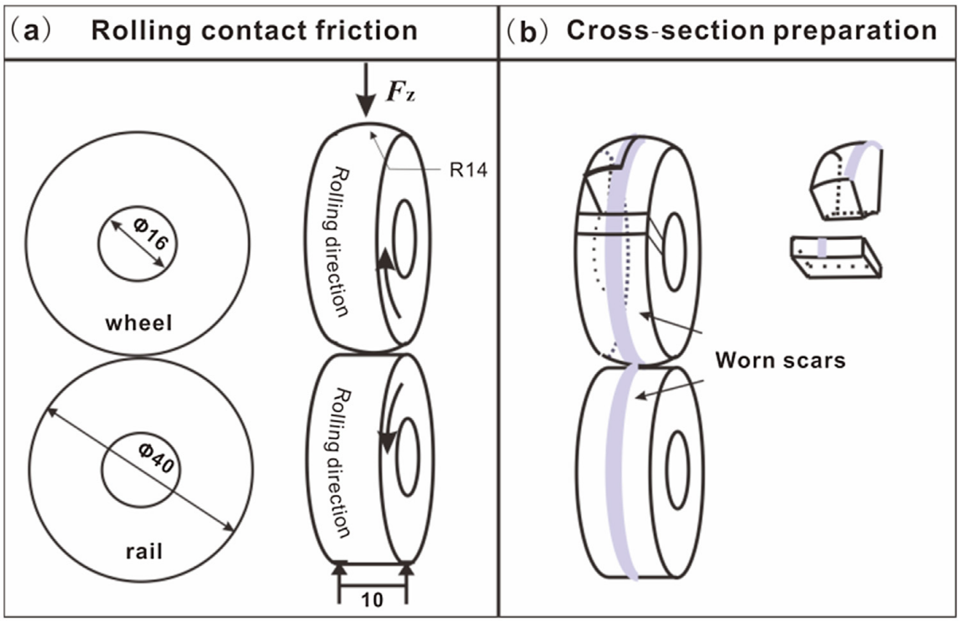

Fig. 1. A schematic of the experimental configurations: (a) rolling contact friction tests; (b) cross-section preparation.

2. Experimental method

2.1. Sample preparation

Rail material, TB/T 3276-2011 U71MnK, is usually used for the high-speed railway in China. Wheel material is produced by LUCCGINI corporation. The chemical composition and the main mechanical properties are shown in Table 1.

The rail specimens are machined to form a disc with a contact width of 10 mm and a diameter of 40 mm, meanwhile the wheel specimens are shaped into ellipsoid-surface, with a contact width of 14 mm and a diameter of 40 mm (see in Fig. 1).

The tests were conducted on the rolling contact friction tester that allows two discs with different velocities to roll against each other, with normal and tangential forces. In all tests, a normal load of 120 N and the rail rotation speed of 500 rpm (rotation per minute) were applied. The friction between two discs with the same rotation speed is defined as the rolling contact friction condition. When the rotation speeds are different, it is defined as the rolling-sliding friction condition. For comparison, the wheel rotation speed was set as 500 and 490 rpm to form these two types of friction condition, respectively. Rotation cycles were in the range of 5×10^3–2×10^5. All tests were conducted at temperature of 25 °C and atmosphere humidity of 60 ± 5%.

After the friction tests, the characteristics of the tribo-chemical interface were investigated. The morphologies of the worn surface were observed by optical microscope (OM, BX60MF5, OLYMPUS), scanning electron microscope (SEM, JSM-6610, JOEL) and the roughness was measured by 3D optical microscope (3D-OM, NPFLEX, BRUKER). The chemical composition was analyzed using energy dispersive spectroscopy (EDS, EDAX-7760/68 ME), While an electron probe microanalyzer (EPMA, JOEL-8230x) was utilized to detect trace elements and the distribution of the chemical elements. The latter has the capability of qualitatively detecting light elements, such as carbon and oxygen. The phase structure of the tribo-film was indirectly confirmed by the spalling debris, which was recorded by X-ray diffraction study (XRD, Phlips X'Pert PRO), using Cu radiation generated at 45 kV and 35 mA. The scanning parameters were performed with a 2θ ranges of 20–90° with 0.0331 step at a scan speed 300 s/step.

The chemical states of iron and oxygen atoms from top 5 nm tribo-film surface, were analyzed by the X-ray photoelectron spectroscopy (XPS, thermo-250Xi), using a monochromatic Al Ka X-ray source (1486.6 eV) operated at 12 kV with 15 mA emission current. The electron energy analyser was operated with a pass energy of 20 eV, enabling high resolution of the spectra that were obtained. The step size of 0.02 eV was employed and each peak was scanned twice. It is worth noting that Ar^+ etching was not used during the XPS analysis process to avoid artificial iron chemical state change. The binding energy scale was initially calibrated, using the Cu $2p_{3/2}$ (932.7 eV), Ag $3d_{5/2}$ (368.2 eV) and Au $4f_{7/2}$ (84 eV) peak positions and internal calibration was referenced to the C1s energy at 284.6 eV for metals. Quantification of outer layers atomic composition and spectral simulation of the experimental peaks were achieved via using the software provided by VG Scientific.

3. Results & discussion

3.1. Tribological behavior and morphology

Friction coefficient curves and corresponding optical micrographs of worn surfaces under the rolling and rolling-sliding friction with different cycles, are shown in Fig. 2. It can be seen