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Phase and microstructural evolution in white etching layer of a pearlitic steel during rolling–sliding friction

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ABSTRACT

To understand the microstructural evolution of a pearlitic rail steel during rolling–sliding contact friction, phase structure and mechanical properties of deformed layers, from top surface to inner matrix, were investigated gradually by scanning electron microscopy, electron probe microanalysis (EPMA), X-ray diffraction, transmission electron microscopy (TEM) and nano-hardness indentation. Focused ion beam method was used to prepare site-specific TEM specimens to study the thickness-dependent deformed microstructure. After the deformation, a white etching layer (WEL), was formed on the top surface, which appeared in white color under an optical microscope. Quantitative EPMA analysis revealed slightly lower carbon concentration, inhomogeneously distributed within the WEL. According to high-resolution TEM observation and quantitative electron diffraction analysis, it was found that the WEL was indeed composed of uniform nano-grains of martensite and ferrite, where no cementite and austenite were found. All the results supported that the WEL was formed by severe plastic deformation, and the hardness value of WEL reached 12 GPa by nano-hardness indentation.

1. Introduction

In the modern railway system, rails are subjected to intense use under large axle loads at high speed conditions. Due to the high contact pressure at the rail–wheel interfaces exceeding 1 GPa, severe plastic deformation of rail materials would be induced during the rail–wheel rolling contact friction, and thus the original structures were dramatically changed to form new structures [1,2] or new phases [3]. The gradual surface structural modifications of rail materials at rolling contact interfaces are related to surface corrugations and micro-cracks, which ultimately results in damage or failure of machine parts, even possibly lead to a traffic accident [4–6]. The rolling–sliding contact friction problem [4,7–10] in the wheel–rail system has been a significant topic for many researchers, which has been investigated from many aspects, such as contact load [11], relative slip [2,12–14], chemical composition and microstructure [14–16]. Specifically, the degradation of surface microstructure is thought to be an essential cause to the failure of materials, and thus the investigation on microstructural evolution will help to understand the damage and to improve the material design.

In the field railway lines, white etching layer (WEL) is a typical degradation form of microstructure defect on the surface of rail tracks, which is named for its white featureless appearance under an optical microscope after etching with nital solution. It has drawn great interests of many researchers in the past decades. However, research on the phase structure of WEL is controversial, which has been thought as martensite [17], nanocrystalline Fe–C alloy [18], deformed pearlite lamellae, nanocrystalline martensite, austenite and cementite [19]. Besides to the different results on the microstructure of WEL, there exist some arguments on the origin and formation mechanism of WEL.

The early work by Newcomb and Stobbs reported that WEL was fully martensite, and the rail–wheel contact was unlikely to be heated to austenization temperature, so the formation mechanism of WEL had been considered as cementite decomposition without austenization due to repeated shear fatigue [20]. However, some studies pointed out that WEL contained retained austenite, which indicated that martensite was formed by a considerable raise in temperature [21–24]. Whether austenite exists or not has been considered as a rule to distinguish if the friction was thermal type with effect on the formation of martensite in WEL. In addition, Baumann et al. showed that the XRD pattern of WEL on the UIC60 rail was different from that of the S54 rail [25]. The former one contained retained austenite while the later one did not, indicating that the formation mechanism of these WELs might be different.

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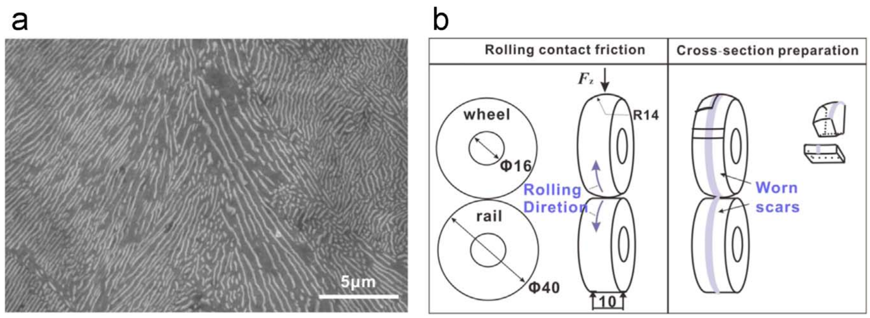

Fig. 1. (a) Microstructure of the pearlitic rail steel and (b) the wheel/rail specimens for rolling-contact friction.

As mentioned previously, the nanocrystalline structure was a specific characteristic of WEL formed on rails [1,17,19,20,23,25–28]. Based on the results of XRD patterns by Baumann et al. [25,26], both WELs formed on the S54 and UIC60 rails were nanocrystalline structures, which could be simulated by mechanical ball milling. Lojkowski et al. [18,29,30] also provided further evidences showing that the formation mechanism of nanocrystalline structure resulted from the heavy plastic deformation at wheel-rail contact zone, which was similar to the mechanical alloying. It seemed that the mechanical alloying was a way to produce nanocrystalline structures, while it was uncertain if it was the mechanism of the formation of WEL in previous studies.

Under the condition of sliding friction, the formation of nanostructured tribolayer was always reported in sliding of metals [31]. Sliding contact friction for ductile metals can induce typical structural changes underneath the worn surface, including recrystallization of deformed structures [32], grain refinement [33], transfers [34,35], plastic deformation and mechanical mixing [36,37]. In addition, the plastic deformation happened in the subsurface may result in substantial changes of the microstructure and properties of subsurface metal, which can generate local micro-cracks or even lead to the failure of materials. According to the studies by Carroll et al. [38,39], the microstructural evolution of the subsurface played an important role in rolling contact fatigue, confirming that crack behavior was depended on the plastic deformation of the pearlite microstructure below WEL. It is essential to investigate the microstructural evolution of rail–wheel materials under the rolling contact friction.

In this work, in order to understand the subsurface structural degradation during rolling-sliding contact friction and to control the wear and the fatigue problems in the railway system, we carried out a thorough experimental investigation on the rail/wheel materials to understand the microstructural evolution underneath the worn surface after rolling-sliding contact friction. The rail–wheel rolling contact friction was simulated by a twin-disc rolling contact tester. The detailed microstructure features, the composition and the phase transformation mechanism of WEL were discussed based on the microstructural observation results.

2. Experimental

2.1. Samples preparation

The experimental materials was a rail of the U71Mnk pearlitic steel containing 0.83 wt% Fe, 0.6 – 0.8 wt% C, 0.8 – 1.3 wt% Mn, 0.1 – 0.5 wt% Si, 0.04 wt% P (max), and 0.04 wt% S (max). It had a hardness of about 260 HB on the rail head surface. The tensile and yield strengths of the rail were 1340 MPa and 890 MPa, respectively. A typical microstructure morphology image of the U71Mnk pearlitic steel, taken by a scanning electron microscope (SEM), is shown in Fig. 1(a).

A custom-made twin disc testing rig is depicted in Fig. 1(b), which allows two discs to roll against each other with normal and tangential force simulate the depth dependent microstructure. The test was done under conditions of a Hertzian contact pressure of 1500 MPa, a wheel disc speed of 500 rpm, and a slippage ($\delta\% = \frac{2(v_1 - v_2)}{v_1 + v_2}$) of 10% ($v_1$ is the speed of wheel disc, and v_2 is the speed of rail disc), and a period of time *i* about 30 s for the rolling–sliding friction tests.

2.2. Microstructure characterization

The highly stressed wear scars on the rail samples, as identified by optical inspection, were prepared for cross-sectional investigation by gluing them face to face together. The cross-sectional samples for optical and SEM observations were prepared by standard metallographic procedures. The cross-sectional morphologies were observed on a JEOL JSM-6500F field-emission SEM using secondary electron imaging (SEI) mode. The distribution of chemical elements in the microstructure as a function of depth was characterized by using a JEOL JXA-8230 field-emission electron probe microanalyzer (EPMA), and the content of the trace element (<1 wt%) was detected with calibration curve method. In this work, it is expected to get high-accuracy data for trace element carbon by a series of low-carbon steel standard specimens to obtain a linear calibration curve to confirm the background intensity, and then an interpolation method was used to calculate the carbon content of the specimen.

The micro-indentation hardness depth profile was obtained from a metallographic sample at an interval of 5 μm by a Mitutoyo Mvk-H2 model micro-indentation hardness testing machine, with a load of 500 gf for 10 s. The nano-indentation hardness distribution as a function of the depth was examined by a nano-indentation using Hysitron TI 900 Nano Indenter. The phase constitutions in the surface layer were detected by X-ray diffraction (XRD) using a PANalytical X'Pert PRO diffractometer with Cu Kα radiation (40 kW) with angular step of 0.02° in a step-scanning mode. The cross-sectional foils for TEM were prepared by focused ion beam (FIB) technique using a FEI Helios PFIB, which were cut off parallel to the rolling-direction from the discs. Detailed microstructural features of the surface layer after rolling–sliding contact were characterized by TEM using a JEOL 2100F field-emission TEM operated at 200 kV, working with selected-area electron diffraction (SAED), conventional bright-field (BF), dark-field (DF), and high-resolution TEM (HRTEM) imaging. For quantitative electron diffraction studies, the camera constant was carefully calibrated using a piece of standard foil composed of polycrystalline pure Al grains.

3. Experimental results

3.1. Optical metallography and hardness

Fig. 2(a) shows an optical micrograph of the rail material after rolling–sliding friction, and the corresponding hardness as a function