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The influence of microstructure on the rolling contact fatigue of steel for high-speed-train wheel

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ABSTRACT

Rolling contact fatigue (RCF) is an important concern for the durability of railroad wheels and rails, especially when considering high-speed trains. In this work, the effect of microstructures on the RCF of high-speed-railway was studied under a simulated train speed of 500 km/h. Two different carbon steel microstructures: spheroidized pearlite and lamellar pearlite, were achieved by different heat treatment. Results of rolling contact fatigue test demonstrated that the fatigue resistance of lamellar steel considerably exceeds that of spheroidized steel. The lamellar steel presented a more fragmentary surface but lower weight loss during the entire fatigue tests. Analysis of cross-section profiles of worn specimens suggests that cracks propagated near the surface of lamellar steel and may strengthen the fatigue resistance of the steel. Based on micro-indentation hardness data, it is suggested that greater energy dissipation induced by larger plastic deformation may also improve RCF resistance.

1. Introduction

Taken a variety of aspects such as capacity, cost, speed and safety into account, railway, especially high-speed-railway, is an outstanding means of transportation. A considerable amount of money and time have been devoted into projects focusing on improving the speed and safety of high-speed-railway all over the world. The service life of wheel and rail plays a critical role in operation of high-speed-railway and naturally catches researchers' eyes in different disciplines.

Wear and rolling contact fatigue (RCF) are considered to be two of the main failure mechanisms for wheel and rail. A lot of investigations have been made in those two fields. Many researches have been done in diverse aspects of wheel materials. Jha [1] focused on the effect of microstructure on the abrasion resistance of steels and proposed that combining of soft ferrite and hard martensite leads to a better abrasion resistance. Deters [2] investigated the wear behavior of the wheel and rail and discussed the influence of load, creepage and speed, found that the wear volume decreased as the running speed increased but presented opposite behaviors as the load and creepage rose. Garnham [3,4] focused on the RCF of rail and wheel and studied the influence of different operating conditions (like creepage and load) and microstructures of materials on RCF of the rails. Ekberg [5] fully described the fatigue of wheel and rail and discussed the influence factor of the fatigue. Furthermore, Benuzzi [6] noticed the competitive relationship between wear and RCF and investigated the propagation of the surface cracks. In 1980s, RCF had drawn the attention of European Rail Research Institute; thus experiments of distinct scale and numerical simulations had been used to explore this problem [7]. Nelias [8] studied the RCF performance of bearing steels with artificial dents under different working condition on a high-speed twin-disk machine and found that sliding creepage had a great influence on the durability of the materials. Fletcher [9] conducted full-scale experiment and numerical simulation to investigate the fluid penetration of cracks under walk pace and suggested that the growth rate of fatigue crack was around 10 times the rail wear rate. Ringsberg [10] proposed a strategy combining elastic–plastic finite element (FE) analyses, multiaxial fatigue crack initiation models used together with the critical plane concept, fatigue damage summation calculations to predict the fatigue life of rolling contact fatigue crack initiation.

In those previous researches, pearlitic steel is commonly used for manufacturing wheel and rail due to its great wear resistance and appropriate ductility [11–13]. Among the pearlitic steels with different microstructures (metallographic structure), spheroidized pearlitic steel is the most popular material for wheel due to the low cost and easy fabrication. Some researchers [14] found that the wear resistance of lamellar pearlitic steel is better than spheroidized pearlitic steel because of the more effective work hardening of cementite lamellar. However, the influence of different microstructure on the rolling contact fatigue, and eventually

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the service life, of wheel under high speed is still unknown even though the problem of rolling contact fatigue is fully developed. This work intends to achieve two kinds of pearlitic steels with same hardness and components but different microstructures and explore the influence of microstructures on the rolling contact fatigue performance.

Furthermore, most of existing researches were performed at a relatively lower speed. Since the high-speed-rail in China has already been running above 300 km/h, the operation of rail/wheel under even higher speed should be appropriate for the purpose of safety. Thus the study of wear and fatigue behavior of materials under a high speed is needed, which is not mentioned in the previous paper. Besides, though the wear of the wheel and rail decreased with the increase of running speed [2], the RCF of railway increased a lot with the rise of speed. Thus, serving life of wheel at extremely high speed is unclear. In the present research, a series of twin-disc experiments were conducted to simulate the speed of the wheel at 500 km/h. Through this research, the author expects to find the fatigue behavior of materials under extremely high speed and the influence of microstructure on the service life of wheel.

2. Material and methods

2.1. Materials

The components of the steel are listed in Table 1. The steel was fabricated through vacuum induction melting. Then the steel ingot was held at 1523 K for 90 min and rolled to a plate of 15 mm between 1223 and 1398 K. Next, two groups of specimens with a diameter of 59.5 mm were cut from the plate. Specimen A was held at 1113 K for 20 min and water quenched to 813 K and then insulated for 120 min and finally cooled down in air. Specimen B was held at 1113 K for 20 min and water quenched to 923 K and spray cooled to room temperature.

Another kind of pearlitic steel was used to simulate the rail in this experiment. The components of the rail are also listed in Table 1.

2.2. Tensile tests

Tensile experiments were conducted in accordance with GB/T 228-2002 on MTS809 tensile test machine (MTS, America) with the tensile rate of 2 mm/min. The tensile specimens were cut into $\Phi 5 \times 25\ mm^2$.

2.3. Rolling contact fatigue experiments

The fatigue experiment of wheel and rail was undertaken in accordance with YB/T 5345-2006 on a twin-disc MJP-20 RCF test machine (China). The as-treated sample was located at the top simulating the wheel, while the sample of a diameter of 60.5 mm was located at the bottom simulating the rail in the test. The geometry of the specimen is listed in Fig. 1. In order to accelerate the propagation of the cracks [5] and maintain a suitable temperature during the test, HL32 hydraulic liquid was introduced in this test. The kinematic coefficient of viscosity, flash point and density of this liquid were 32 mm^2/s, 493 K and 0.875 g/cm^3 respectively. In order to ensure the reliability of the experiment results, rolling contact fatigue tests under three distinct conditions were conducted. The creepage, rotation speed and normal pressure of these tests are set as follows: 1) 1.6%, 2200 rpm, 1000 MPa; 2) 1.6%, 2200 rpm, 1200 MPa; 3) 1.6%, 2800 rpm, 1000 MPa. The frequency of 2200 rpm during the test is the same with that of the realistic running speed of 400 km/h, while the frequency of 2800 rpm equals that of the realistic running speed of 500 km/h. Meanwhile, the normal pressure of 1000 MPa is the same with the realistic pressure under the wheel/rail contact and the performance of the materials under higher pressure (1200 MPa) was also investigated. The specimen was cleaned, dried, weighed and carefully examined after each 500 thousands of rotations. According to YB/T 5345-2006, a vibration transducer was assembled to detect the vibration over 0.03 mm, which is induced by the fatigue pit of the steel surface. Once the vibration occurred, the test machine would stop immediately.

Table 1
Component of wheel and rail steel.

	C	Si	Mn	P	S	Cr	Fe
Wheel	0.4	0.35	0.75	<0.02	<0.02	0.25	Bal.
Rail	0.7	0.26	1.13	<0.02	<0.02	\	Bal.

2.4. Microstructure examinations

The profiles of original and worn specimen are first ground and polished through the same procedure and then eroded by the alcoholic solution containing 3% of nitric acid (volume fraction). Then, the microstructure of the specimen is examined with a scanning electron microscope (SEM). The worn surface of the wheel was also examined under SEM (FEI Quanta 450, America).

2.5. Microhardness tests

The microhardness test was conducted in accordance with GB/T 4340.1-2009 on microhardness tester. The cross-section profiles of specimens were ground and polished through the same procedure either. The data of different distances below the surface were repetitively tested 3 times and an average value was calculated.

3. Results

3.1. Microstructure and mechanical properties of steels

The images of original and heat-treated steels (spheroidized and lamellar) are presented in Fig. 2. It can be seen from the Fig. 2 (b) that tiny spheroidized carbide in specimen A, the tempered pearlitic steel, uniformly distributed on ferrite matrix. The microstructure of pearlite in specimen B, the water sprayed pearlitic steel, presented a totally different morphology. Typical lamellar pearlite with lamellar spacing of around 0.3 μm and little pre-eutectoid ferrite are demonstrated in Fig. 2(c). Through the comparison of the original microstructure in Fig. 2(a) with the following two microstructures, it can be concluded that both two heat treatments have avoided the eutectoid of large ferrite at the boundary of austenite.

The mechanical properties of original and heat treated steels are listed in Table 2. The tensile strength, both ultimate tensile strength and yield tensile strength, of two different steels had risen greatly after the heat treatment. The ultimate tensile strength of both two steels was elevated to above 900 MPa, while the yield tensile strength of spheroidized steel and lamellar steel had risen by 326.4 and 121.9 MPa respectively. Meanwhile, the elongation of steel, the symbol of ductility, had not decreased much. Those improvements of mechanical properties of steels attribute to the little pre-eutectoid ferrite and thin lamellar spacing, which avoid the weak zone at the boundary of austenite and improve the ductility. Besides, the surface hardness of both two