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Effect of different strengthening methods on rolling/sliding wear of ferrite–pearlite steel

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ABSTRACT

The object of this paper is to study the influence of different strengthening methods on wear resistance of ferrite–pearlite steel. Rolling/sliding wear tests were conducted for five railway wheel steels which were hardened by carbon addition, solid solution strengthening and precipitation strengthening, respectively. Wear rate, subsurface plastic deformation and strain-hardening of tested steels were examined. The test results show that wear resistance of ferrite–pearlite steel is improved by both carbon addition and solid solution strengthening, whereas it is deteriorated by precipitation strengthening. Wear resistance of ferrite–pearlite steel depends on the worn surface hardness that is influenced by bulk hardness and strain-hardening. Strengthening methods increase the bulk hardness to different extents, where the highest and lowest bulk hardness increments are obtained by the solid solution strengthening and precipitation strengthening, respectively. The strain-hardening is promoted by carbon addition, while it is reduced by solid solution strengthening and precipitation strengthening where precipitation strengthening makes a greater reduction in strain-hardening. Strain hardening of ferrite–pearlite steel is reduced by a high content of proeutectoid ferrite with a low ductility, which is caused by solid solution strengthening and precipitation strengthening.

1. Introduction

Wear and rolling contact fatigue of rails and railway wheels are costly problems for the railway system. They cost about 1.2 billion US dollars annually in China [1]. ER8 steel defined by EN13262 is a widely used wheel material for Chinese high-speed train. Wear is the principal reason for replacing railway wheels made of ER8 steel. Consequently, it is necessary to develop a wheel steel with a higher wear resistance.

Almost all railway wheels are made of ferrite-pearlitic steels. Wear resistance of these steels is most generally characterized by the bulk hardness, which is highly influenced by the microstructure and thereby can be improved by optimizing chemical compositions. Besides, increasing the worn surface hardness through strain-hardening has been proved to improve the wear resistance of the ferrite–pearlite steel [2–7]. Softer ferrite-pearlitic steels have better wear resistance than the initially harder bainite steel since ferrite-pearlitic steels develop greater strain-hardening during the wear process [8–11].

In the past years, many strengthening methods, including carbon addition, solid solution strengthening and precipitation strengthening, have been proposed to improve the wear resistance of the ferrite–pearlite steel.

1.1. Carbon addition

Considerable effort has gone into understanding the role of carbon addition on the wear behavior of the ferrite–pearlite steel [3,4,12–19]. One clear conclusion is that carbon addition enhances the wear resistance of the ferrite–pearlite steel through increasing the bulk hardness of the steel [3,4,12–17]. Investigations conducted by Ueda and Naka et al. have shown that the ferrite–pearlite steel with higher carbon content has greater strain-hardening rate since carbon addition promotes the grain refinement in the vicinity of the worn surface; this further improves the wear resistance of the steel [3,4].

1.2. Solution strengthening

Silicon and manganese can be used to increase the wear resistance of the ferrite–pearlite steel through solid solution strengthening [12,20–25]. In recent years, a ferrite–pearlite steel containing high contents of silicon and manganese was developed

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and applied for the railway wheel [20–22,25]. Silicon and manganese contents are increased to stabilize the material at elevated temperatures, which reduces the thermal sensitivity of the steel [20–22]. However, the wear resistance of this steel has not been reported.

1.3. Precipitation strengthening

The bulk hardness of the ferrite–pearlite steel can also be improved by additions of vanadium and niobium through the precipitation strengthening [26–30]. However, works conducted by Katsuki et al. have shown that although vanadium addition raises the bulk hardness of the steel, it reduces the strain-hardening rate of the worn surface [26,27]. And thus, the worn surface hardness, which depends on both the bulk hardness and the strain-hardening, is complicated for precipitation strengthening steels. Therefore, it is difficult to determine the effect of precipitation strengthening on the wear resistance of ferrite–pearlite steels; researches using different materials have led to different conclusions [26–29].

In order to improve the wear resistance of the railway wheel steel by optimizing the chemical compositions, it is necessary to study the effect of different strengthening methods on the wear behavior of the ferrite–pearlite steel. However, such a study has not been conducted so far. In this study, rolling/sliding wear tests were performed for five railway wheel steels which were hardened by carbon addition, solid solution strengthening and precipitation strengthening, respectively. Wear rate, plastic deformation and strain-hardening of the tested steels were examined. The effects different strengthening methods on the wear resistance were analyzed.

2. Materials and experiment

2.1. Materials

All tested materials were machined from the railway wheel and the rail that were never used in service. Table 1 gives the chemical compositions of the tested materials. In this study, wear tests were conducted for five railway wheel steels, which were denoted by ER7, ER8, ER9, HiSi and 0.07V, respectively. The main difference in compositions among ER7, ER8 and ER9 steels, which are defined by the EN 13262, is the carbon content. ER7, ER8 and ER9 steels have a carbon content of 0.48%, 0.52 and 0.57%, respectively. The contents of silicon and manganese of HiSi steel are increased compared with those of ER8 steel, where HiSi steel has a more than threefold increase in silicon content. The main difference in compositions between ER8 steel and 0.07V steel is the vanadium content. 0.07V steel has a vanadium content of 0.07%, while the vanadium content of ER8 steel is negligible. Compared with ER8 steel, HiSi steel and 0.07V steel are hardened by solid solution strengthening and precipitation strengthening, respectively. U71Mn steel was selected as the tested rail materials; it has a carbon content of more than 0.72%.

Table 1
Chemical compositions of test materials *w*/%.

Materials	Wheel steel					Rail steel
	ER7	ER8	ER9	HiSi	0.07V[a]	U71Mn
Carbon	0.48	0.52	0.57	0.52	0.53	0.72–0.82
Silicon	0.28	0.26	0.26	0.93	–	0.65–0.90
Manganese	0.75	0.73	0.73	0.93	–	0.75–1.05
Sulfur	0.016	0.006	0.007	0.009	–	≤ 0.04
Phosphorus	0.002	0.002	0.002	0.001	–	≤ 0.035
Chromium	0.22	0.25	0.26	0.21	–	≤ 0.035
Vanadium	0.003	0.002	0.003	0.003	0.07	/

[a] Chemical compositions of 0.07V steel are confidential.

2.2. Experiment

Rolling/sliding wear tests were carried out using a twin-disc machine. Fig. 1 shows the schematic illustration of wear testing. Microstructures and mechanical properties of the wheel steel vary with the depth below the wheel tread. In order to ensure the uniformity of material properties, wheel discs were removed from wheel rims at a depth of approximately 15 mm with their top surfaces parallel to the wheel tread. Rail discs were removed from the U71Mn rail with their top surfaces parallel and close to the top surface of railhead. Then the tested discs were machined into the shape and dimension as shown in Fig. 1. After that, the contact surface of test discs was polished to achieve an average roughness (Ra) of about 0.2 μm. A profilometer (MarSurf PS1) was used to measure the roughness of the contact surface before the testing. Five measurements were taken in the axial direction of the disc and an average value was calculated for each disc. The result shows that the values of Ra vary between 0.189 μm and 0.206 μm. All test discs can be considered to have a similar surface roughness.

The line contact between two cylindrical test discs was used to simulate the normal loading and slip present at rail/wheel contact. Wear tests were conducted under a maximum contact pressure of 800 MPa and a slip ratio of 5.4% to simulate the wearing condition in curved tracks. In order to prevent the change of the microstructure caused by friction heating and remove wear debris, the contact area was cooled with dry compressed air during the testing. A torque sensor, with a maximum torque capacity of 15 N m and relative error of ±1%, was used to measure the friction force during the testing, from which the friction coefficient was calculated. Previous work has shown that after a certain number of rolling cycles (running in stage), the accumulated plastic deformation within the subsurface of test discs reaches its maximum and thus a steady wear state is obtained for the remainder of the test [31]. Under the condition used in this study, the number of rolling cycles needed to establish a steady wear state is about 15,000 [32,33]. Therefore, all tests in this study were carried out by applying the discs 20,000 cycles to establish a steady wear state. Then, the discs were taken down and cleaned in

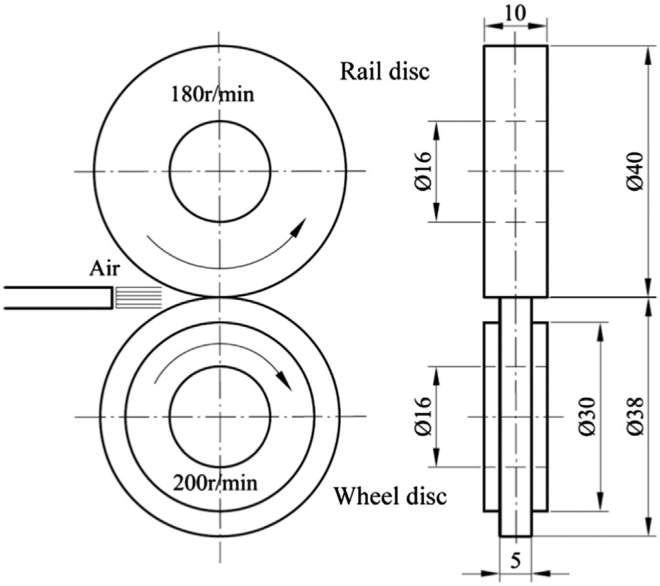

Fig. 1. Shapes of test discs and schematic illustration of wear tests.