Wear 372-373 (2017) 158–168

Contents lists available at ScienceDirect

Wear

journal homepage: www.elsevier.com/locate/wear

Influence of solid solution strengthening on spalling behavior of railway wheel steel

Dongfang Zeng [a], Liantao Lu [a,*], Yanhua Gong [b], Yuanbin Zhang [a], Jiwang Zhang [a]

[a] State Key Laboratory of Traction Power, Southwest Jiaotong University, Chengdu 610031, China
[b] Technology Center Ma'anshan Iron and Steel Co., Ltd., Ma'anshan 243000, China

ARTICLE INFO

Article history:
Received 31 July 2016
Received in revised form
13 December 2016
Accepted 16 December 2016
Available online 21 December 2016

Keywords:
Rolling contact fatigue
Steel
Rail-wheel tribology
Finite element modelling

ABSTRACT

The object of this paper is to investigate the influence of solid solution strengthening on the spalling behavior of railway wheel steel. White etching layer (WEL) was reproduced by twin-disc test and analyzed by phase transformation kinetic. Spalling of WEL was then evaluated by rolling contact fatigue (RCF) test and finite element analysis. The results show that solid solution strengthening improves the resistance to WEL formation for wheel steel through increasing the austenitization temperature. WEL remarkably reduces the RCF life of wheel steel. Whether containing WEL or not, solid solution strengthened steel exhibits a better rolling contact fatigue strength than the traditional wheel steel.

1. Introduction

Spalling is a well-known rolling contact fatigue (RCF) damage for the railway wheel. During a wheel-rail slide caused by excessive braking or acceleration, the friction heat is sufficient enough to austenitize the material near the contact surface. Then the material is rapidly cooled by heat conduct into the adjacent material and thus the white etching layer (WEL) forms on the wheel tread [1–4]. Besides, impact loading would be generated since the wheel tread is disrupted during the wheel-rail slide. Cracks often initiate in the WEL and then propagate into the wheel due to cyclic rolling contact. The cracked material may break away from the railway wheel, leaving voids known as spalling.

The spalling of railway wheel includes two stages, WEL formation occurring above austenitization temperature and rolling contact fatigue cracking within the material containing WEL. As a consequence, two methods seem effective to improve the spalling resistance of railway wheel steel: (i) increasing the resistance to WEL formation and (ii) delaying the RCF failure for the wheel steel containing WEL. Since the phase transformation kinetic of the steel is influenced by chemical compositions, it has been reported that the resistance to WEL formation can be improved by alloy design [2,5]. Besides, since WEL formation on the surface of railway wheel is inevitable because of the complicated service condition, several works have been focused on the RCF behavior of railway wheel steel containing WEL [6–10]. Kato et al. have shown that the crack initiations are less in the smaller white etching layers than in the larger ones [9]. Makino et al. have shown that RCF life of WEL increases with an increase in the strength of the bulk material below the WEL [6]. Works conducted by Carroll et al. have shown that the crack growth is dependent on the subsurface deformation of the pearlite below the WEL [7,8], which also indicates that the RCF behavior of WEL can be associated with the strength of the bulk material.

The strength of railway wheel steel is usually increased by increasing carbon content. However, carbon addition would increase the thermal sensitivity since it reduces the austenitization temperature. This may decreases the spalling resistance of wheel steel. Silicon and manganese can be used to improve the strength of wheel steel through solid solution strengthening [11–15]. Besides, it has been reported that the addition of silicon and manganese can stabilize the steel at elevated temperatures [14]. Works conducted by Cvetkovski et al. have shown that the high Si-Mn wheel steel is more resistant to thermal degradation below austenitization temperature [11,13]. Therefore, it is expected that the spalling resistance of wheel steel can be improved by solid solution strengthening. However, the influence of solid solution strengthening on spalling behavior of railway wheel steel, which includes WEL formation occurring above austenitization temperature and RCF behavior of the steel containing WEL, has not been conducted so far.

Several test methods have been proposed to study the spalling behavior of railway wheel [6–10,16–19]. Jergeus et al. conducted the full-scale railway wheel flat experiment to investigate the

---

* Corresponding author.
E-mail address: luliantao@swjtu.cn (L. Lu).

http://dx.doi.org/10.1016/j.wear.2016.12.025
0043-1648/

spalling behavior from the view of WEL formation [16,17]. Since the full-scale experiment is costly, WEL formation was also simulated in the laboratory [6–10,18]. Spot weld and laser heating have been used to quench the test sample, which reproduces martensite on the surface of test sample [7,9,18]. Besides, WEL has also been simulated by twin-disc test [6,7,10,19]. As compared with spot weld and laser heating, the actual wheel-rail sliding can be better simulated by twin-disc test. Since the microstructure of WEL is too complicated to be reproduced by spot weld and laser heating [3,18], the white etching layer was reproduced by twin-disc test in this study.

The object of this paper is to investigate the influence of solid solution strengthening on the spalling behavior of railway wheel steel. WEL was reproduced by twin-disc test and analyzed by phase transformation kinetic. Spalling of WEL was then evaluated by rolling contact fatigue test and finite element analysis. Results obtained from a solid solution strengthened steel and a traditional steel were compared and analyzed.

2. Materials

Test materials were machined from the wheel rims that were never used in service. Chemical compositions of the test materials are given in Table 1. The investigated steel is a railway wheel steel with high contents of Si and Mn, which is denoted as HiSi steel in this study. Spalling behavior of ER8 steel is also investigated as a reference. ER8 is a commercial wheel steel, which is defined by EN 13262 and widely used in Europe and China. HiSi is a recently developed steel, which has a more than threefold increase in silicon content as compared with ER8 steel. Chemical compositions of both steel types are similar to those of AAR-Class A steel. Compared with ER8 steel, HiSi steel is hardened by solid solution strengthening. The wheel rim was heat treated using the following procedure: austenitizing at 860 °C for 2 h followed by quenching in a spray of water and tempering at 500 °C for 2 h followed by cooling to room temperature under normal heat exchange conditions. U71Mn steel was selected as the test rail material.

3. WEL reproduction

3.1. Test method

In this study, the white etching layer was reproduced using a twin-disc machine. Fig. 1 shows the schematic illustration of the test method. Microstructures and mechanical properties of the material vary with the depth in the wheel rim due to the heat treatment. To ensure the uniformity of material properties, wheel discs were machined from wheel rims at a depth of about 15 mm with their top surfaces parallel to the wheel tread. Test discs were machined into the shape shown in Fig. 1 and then the contact surface was polished. The roughness of the contact surface was measured using a profilometer (MarSurf PS1) along the axial direction of test disc. The result shows that the contact surface of test discs has an average roughness of about 0.2 µm. Optical micrographs of wheel steels shown in Fig. 2 prove a typical ferrite-pearlite structure. Mechanical properties and microstructural characterizations of test wheel steels are summarized in Table 2. It can be seen that HiSi steel exhibits a higher strength than ER8 steel.

Table 1
Chemical compositions of wheel steels *w*/%.

Steels	C	Si	Mn	P	S	Cr
ER8	0.52	0.26	0.73	0.016	0.002	0.25
HiSi	0.52	0.93	0.93	0.009	0.001	0.04
U71Mn	0.72–0.82	0.65–0.90	0.75–1.05	≤ 0.04	≤ 0.035	≤ 0.035

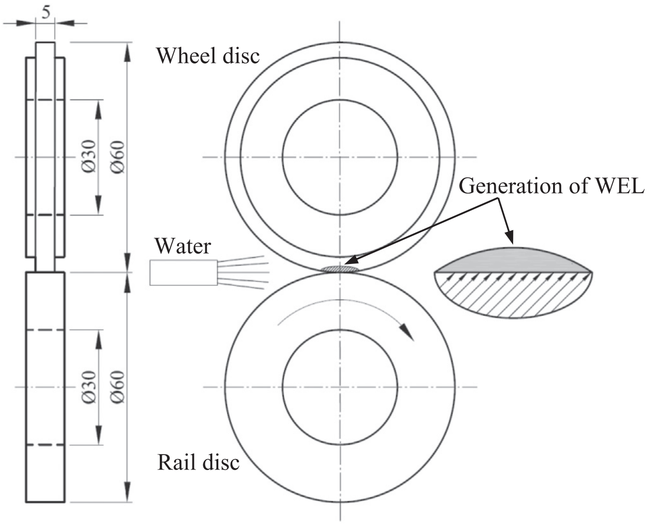

Fig. 1. Schematic illustration of test method.

During the test of WEL reproduction, the contact stress between wheel disc and rail disc was set as 1100 MPa. Then, the rail disc which was driven by an AC motor began rotating and sliding against the fixed wheel disc, as shown in Fig. 1. Fig. 3 shows the variation of rotational speed of rail disc. The contact area was continuously lubricated and cooled by water when the sliding occurs. The materials in the vicinity of the contact area of wheel disc were rapidly austenitized due to the friction heat and then they were rapidly cooled by water and heat conduction into the cold wheel material. The rapid temperature increase followed by rapid cooling causes the formation of white etching layer on the surface of wheel disc. White etching layer covers a small section of the perimeter of the wheel disc, which has a length of about 12 mm. In order to obtain reliable results, six different wheel discs were used to produce WEL for each test material.

After the test, wheel discs were sectioned along the track center and prepared for metallographic observation by an Olympus OLS4100 confocal laser scanning microscope. WEL sizes were measured from the metallographic images. The hardness of WEL was measured with a microhardness tester.

3.2. Results and discussions

3.2.1. Microstructure and hardness of WEL

Figs. 4 and 5 show typical micrographs of WEL observed in this study. Three regions can be observed, i.e. a dark etching layer, a martensite zone and a transition zone. The microstructural feature of the WEL is consistent with that observed from the full-scale railway wheel [3,16]. Microhardness as a function of the depth from the disc surface towards the center was measured from the corresponding wheel discs, as shown in Fig. 6. A dark etching layer was found to form on the topmost surface of WEL as previous reported [3]. This layer has an average hardness of around 500 $HV_{0.1}$. It can be identified as fine-grained pearlite by microstructural observation (Figs. 4b and 5b) and hardness measurement. The austenite grains in the surface region were heavily strained during the sliding; this increases the cooling rate for pearlite formation. Therefore, although the cooling rate reached the maximum in the surface region, the pearlite regenerated during the cooling. The maximum hardness is found to be up to