Experimental study on the surface microstructural evolution and fatigue wear resistance of pearlite wheel steels during rolling-sliding condition

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Abstract
In present paper, the relationship between fatigue and wear of three kinds of pearlite wheel steel samples is investigated by using rolling wear tester under 0.2% slip ratio condition. The results show that the weight loss, the surface hardness and the thickness of plastic deformation layer of three kinds of wheel samples are increased as the increase of cycles during rolling wear process. The weight loss of the G1 wheel sample is the highest owing to the existence of a large amount of proeutectoid ferrite (PF) grains. The correlation between weight loss and fatigue is competitive. High weight loss of the G1 wheel sample can hinder the formation of fatigue wear cracks. As a result, the G1 wheel sample surface changes to smooth after wear. The low weight loss of the G2 wheel sample and the G3 wheel sample cannot hinder the production of fatigue wear cracks during wear process. At the late wear stage, the wheel sample surface produces many fatigue wear cracks, and the wear mechanism becomes fatigue wear. Fatigue wear cracks, which are the rolling contact fatigue (RCF) crack source, can accelerate the RCF failure of wheel samples.

1. Introduction
In recent years, as the axle load of trains is increased, the problem of wear failure is more serious. The serious wear can cause the formation of wheel polygonization wear, the vibration of trains and influence the safety of trains operation, and the wear mechanism of crest and trough of polygonization wear, the wear mechanism of trough is fatigue wear, other is adhesive wear [1]. During the operation of trains, some factors can affect the wear property and change wear mechanism of wheel steels, such as contact stress [2], slip ratio [3, 4], rolling speed [5], etc. The study of Liu et al [6] and Zhou et al [7] indicated that the surface hardness, the thickness of plastic deformation layer and weight loss were gradually increased according to the increasing of contact stress and slip ratio, and the wear mechanism changed from adhesive wear to the fatigue wear. Bolton et al [8] proposed that there were three wear regimes of wheel materials during wear process, which were the mild wear regime, severe wear regime and catastrophic wear regime. In catastrophic wear regime, the wheel sample surface formed a large amount of fatigue wear cracks. Therefore, the fatigue wear is a more dangerous factor to cause the wear failure of wheel steels.

The original microstructure also has great influence on the wear property of wheel steels. The investigation of Liu et al [9] found that tempered sorbite could improve the microstructural homogeneity and fatigue wear resistance during wear process. The microstructures of bainite and martensite have great effect on wear property of wheel materials [10–12]. During wear process, the bainite microstructure can inhibit the formation of white etching layer (WEL) [13]. WEL is formed at wheel surface, it can result in the production of fatigue cracks [14]. The reason is that the dissolve of cementite particles in bainite is difficult. The wear resistance of lamellar
Cementite is better than the spheroidized cementite [15]. The result of Wang et al. [16] proposed that high content of Vanadium in wheel materials could enhance the precipitation strengthening. In most pervious researches, the improvement of wear property of wheel materials is based on the increase of carbon content. The increase of carbon content can reduce weight loss, but it can not reflect the fatigue wear resistance of wheel materials. The production of fatigue wear cracks is more dangerous to trains operation than the variation of weight loss. The fatigue wear of wheel materials can accelerate the rolling contact fatigue failure of wheel materials [17]. The study of fatigue wear resistance of different carbon content of wheel materials is not found. In this paper, the fatigue wear resistance of three kinds of wheel steels with different carbon content (G1, G2 and G3) is studied by rolling wear tester under 0.2% slip ratio condition. The surface worn morphology and the evolution of surface microstructure of wheel samples is investigated by an optical microscope (OM), a scanning electron microscope (SEM) and a transmission electron microscope (TEM). During wear process, the wear mechanism of three kinds of wheel samples is analyzed. The relationship between weight loss and fatigue wear resistance of wheel samples also is systematic discussed.

2. Experimental materials and methods

The test wheel samples were G1, G2 and G3 wheel steel. The wheel samples were cut from the wheel tread, as displayed in figure 1. The chemical components of three kinds of wheel samples were displayed in table 1. Figure 2 displays the optical microscope (OM) micrographs of the original microstructure of three kinds of wheel steel samples. The original microstructures of three kinds of three kinds of wheel samples were composed of pearlite and proeutectoid ferrite (PF), as presented in figures 2(a)–(c). However, the fraction of PF grains of three kinds of wheel samples is different. The increase of carbon content in wheel samples can reduce the fraction of PF grains. The fraction of PF grains of G1 wheel sample was highest, which was about 7%. With the increase of carbon content, the fraction of PF grains was reduced. The fraction of PF grain of G2 wheel sample and G3 wheel sample was 5% and 4.8%, respectively. The rail sample was U75V wheel steel. The original hardness of G1, G2 and G3 wheel steel was 230 HV, 250 HV and 300 HV, respectively.

Wear tests were carried out by using GPM-30 wear tester, as shown in figure 1(b). During wear test, the contact stress was 1227 MPa, the rolling speed was 500 r min⁻¹. The slip ratio was 0.2% and contact condition was dry wear. The wear cycles were 2 × 10⁵ cycles, 3 × 10⁵ cycles and 4 × 10⁵ cycles. Each wear parameter was repeated three times. After wear test, the surface worn morphology and microstructural evolution of three kinds of sample were analyzed by a Leica optical microscope (OM, Leica, Germany), a Zeiss Supra 55 field-emission scanning electron microscope (SEM, Zeiss, Germany) and a Tecnai G2 F30 S-TWIN transmission electron microscope.
The preparation process of the EBSD samples was as follows: firstly, the small samples were ground with sandpapers. Next, the wheel samples were polished by a silica sol suspension. Finally, mechanical vibration polishing was conducted. For EBSD characterization, the acceleration voltage was 20 kV, the working distance was \( \sim 15 \) mm, the inclination angle of the sample was 70°, and the step length was 50 nm. The surface hardness was measured by using a FM-700 hardness tester (Future-Tech, Japan) with a load of 2.45 N and dwell time of 15 s. The weight loss of three kinds of wheel samples after wear was measured by an AX523ZH/E electronic scales (measurement accuracy: 0.001 g).

3. Results

3.1. Weight loss and surface worn morphology

Figure 3 shows the variation of weight loss of three kinds of wheel samples with different cycles. The weight loss of three kinds of wheel samples is increased as the cycle increasing. At different cycles, the weight loss of the G1 wheel sample is the highest, and the weight loss of the G3 wheel sample is the lowest.

After wear, the change of surface morphology of three kind of sample is obvious (figure 4). The surface morphology of the G1 wheel sample is significant smooth at \( 2 \times 10^5 \) cycles. As for G2 wheel sample, the sample surface generates a lot of fatigue wear cracks at \( 2 \times 10^5 \) cycles. However, the G3 wheel sample surface forms a small amount of fatigue wear cracks at \( 2 \times 10^5 \) cycles. When the cycle increases to \( 3 \times 10^5 \) cycles, the fatigue wear cracks are produced at G1 wheel sample surface. The fatigue wear cracks of G2 wheel sample are more serious at \( 3 \times 10^5 \) cycles, and the sample surface produces spalling pits. The fatigue wear cracks of G3 wheel sample also are more serious at \( 3 \times 10^5 \) cycles. As the cycle increases to \( 4 \times 10^5 \) cycles, the fatigue cracks of G2 wheel sample and G3 wheel sample are most serious. However, the length of fatigue wear cracks of G2 wheel sample is largest.

3.2. Surface hardness

After wear, the variation of surface hardness of three kinds of wheel samples is measured (figure 5). The original hardness of the G1 wheel sample is lowest, which is about 230 HV. The original hardness of the G2 wheel sample is around 250 HV. The original hardness of the G3 wheel sample is highest. It is about 300 HV. At \( 0 \sim 4 \times 10^4 \) cycles, the surface hardness of the G2 wheel sample and the G3 wheel sample is increased as the cycle increasing. After \( 4 \times 10^5 \) cycles, the surface hardness of two kinds of wheel sample is in steady state. The hardness of the G2 wheel sample and the G3 wheel sample in steady state is 520 HV and 560 HV, respectively. However, the variation of hardness of the G1 wheel sample is different. Before \( 6 \times 10^4 \) cycles, the hardness of the G1 wheel sample
sample continues to increase as the cycle increasing. After $6 \times 10^4$ cycles, the hardness of the G1 wheel sample is in steady state, which is about 500 HV. The hardening rate of three kinds of wheel samples at different cycles is shown in figure 5(b). During hardness increasing stage, the hardening rate of the G1 wheel sample is lowest, the hardening rate of the G2 wheel sample is highest. During hardening steady state, the hardening rate of the G3 wheel sample is lowest, the hardening rate of G2 wheel sample is highest.
3.3. Surface microstructure

After wear, the microstructural evolution of three kinds of wheel samples is shown in figure 6. The change rule of microstructure of three kinds of wheel is the same, the thickness of plastic deformation layer is increased according to the increase of cycles. At \(2 \times 10^5\) cycles, the thickness of plastic deformation layer of G1 wheel sample, G2 wheel sample and G3 wheel sample is 110 \(\mu\)m, 42 \(\mu\)m and 35 \(\mu\)m, respectively. When the cycle increases to \(3 \times 10^5\) cycles, the thickness of plastic deformation layer of three kinds of wheel becomes obvious thicker. The plastic deformation layer thickness of G1 wheel sample, G2 wheel sample and G3 wheel sample increases to 128 \(\mu\)m, 92 \(\mu\)m and 80 \(\mu\)m. As the cycle increases to \(4 \times 10^5\) cycles, the plastic deformation layer thickness of G1 wheel sample, G2 wheel sample and G3 wheel sample becomes 152 \(\mu\)m, 123 \(\mu\)m and 108 \(\mu\)m. During wear process, the plastic deformation layer thickness of G1 wheel sample is highest. The plastic deformation layer thickness of G3 wheel sample is lowest. It can be seen from table 1 that the carbon content of G1 wheel sample is about 0.55%. However, the carbon content of G3 wheel sample is higher, which is about 0.63%. Therefore, the
content of proeutectoid ferrite of G1 wheel sample is high. The proeutectoid ferrite, as the soft phase, can accelerate the plastic deformation \[18\]. The lamellar cementite can resist the plastic deformation of ferrite grains in pearlite. Therefore, the plastic deformation of G1 wheel sample is obvious during wear process.

In order to further analyze the microstructural evolution of three kinds of wheel samples, SEM with EBSD and TEM are used to observe the microstructural evolution of G2 wheel sample at different depth from surface after wear with \(4 \times 10^5\) cycles, as shown in figures 7–9. Figure 7 displays the SEM micrographs of G1 wheel sample at different depth from surface. At depth of 140 \(\sim\) 150 \(\mu\)m below the surface, the plastic deformation of pearlite and PF grains is not obvious. The cementite and ferrite grains are still lamellar and there is no significant plastic deformation in PF grains. As the reduction of distance from surface, the degree of plastic deformation become gradually serious. At depth of 80 \(\sim\) 90 \(\mu\)m from the surface, the fine grains are formed in PF grains and the PF grains become lamellar. In pearlite, a part of lamellar cementite is broken up into particles. At depth of 30 \(\sim\) 40 \(\mu\)m from the surface, the PF grains are further refined and all lamellar cementite are fragmented into cementite particles. At the depth of 0 \(\sim\) 10 \(\mu\)m from surface, the degree of plastic deformation is most serious. The PF grains are obvious refined and they cannot be distinguished by SEM and a part of cementite is dissolved, which is similar with the result of Liu et al \[4\].
Figure 8 shows the EBSD micrograph of G1 wheel sample at different depth from surface after wear with $4 \times 10^5$ cycles. Lamellar cementite phases are at interface of both lamellar ferrite grains in pearlite. The lamellar cementite can not be resolved by EBSD. Therefore, it is difficult to distinguish that the misorientation is lamellar ferrite phase or the misorientation is the lamellar cementite and lamellar ferrite grains. In fact, the misorientation distribution of lamellar ferrite in pearlite is the sum of two parts. It can be considered the misorientation distribution is the orientation between lamellar ferrite.

At depth of $80 \sim 90 \mu m$ below the surface, the ferrite grains are mainly low angle grain boundaries. As the reduction of distance from surface, the fraction of high angle grain boundaries is increased, as shown in figure 9(b). At depth of $30 \sim 40 \mu m$ below the surface, the ferrite grains are changed into high angle grain boundaries. According to the result of Izotov et al [19] and Tao [20] that the refinement process of ferrite grains is divided into four stages. In first stage, during cyclic stress, a large amount of dislocation is formed in ferrite grains. Then the large amount of dislocation changes into dislocation cells and dislocation walls. In third stage, the dislocation cells and dislocation walls transform into low angle grain boundaries. Lastly, the low angle grain boundaries changes into high angle grain boundaries in ferrite grains and ferrite grains are refined. The change of PF grains and ferrite grains in pearlite is observed by TEM. It can be seen from figure 9 that the size of PF grains at surface is about $100 nm$ and the spacing of ferrite grains are obviously refined. After wear, the formation of diffraction ring indicates that the surface ferrite grains are high angle grain boundaries, as shown in figure 9(b).

3.4. Fatigue wear cracks

Figure 10 shows the fatigue wear cracks of three kinds of wheel samples after wear with $4 \times 10^5$ cycles. The fatigue wear cracks of G1 wheel sample are thin, the length and depth are $10 \mu m$ and $2 \mu m$. The length and depth of fatigue wear cracks of G2 wheel sample are about $20 \mu m$ and $5 \mu m$. As for G3 wheel sample, the length and depth of fatigue wear cracks are large, which are $30 \mu m$ and $8 \mu m$. The relationship between microstructure and fatigue wear cracks initiation and propagation is studied by SEM, as shown in figure 11. The fatigue wear cracks mainly initiate and propagate at the interface between pearlite and PF and in PF, as drawn in figure 11(b). The reason is that during wear the plastic deformation of PF grains is quick and serious. The plastic deformation between pearlite and PF grains is not harmonious [21]. Therefore, the interface between pearlite and PF grains is the main path of fatigue wear cracks formation.

4. Discussion

After wear with $4 \times 10^5$ cycles, the shear strain of three kinds of wheel samples is calculated [22]. Figure 12 shows the variation of shear strain of wheel samples. The shear strain of G1 wheel sample is highest, which is about 2.74. The shear strain of G2 wheel sample is about 1.2. The shear strain of G3 wheel sample is lowest, which is about 0.57. High content of PF grain causes the serious of plastic deformation and increase surface plastic strain. Therefore, the shear strain of G1 wheel sample is high. The high fraction of PF grains of G1 wheel sample lead to low surface hardnes during wear process. High shear strain and a large amount of PF grains of G1 wheel sample result in the high weight loss during wear process. Therefore, the weight loss of G1 wheel sample is high during wear process, as displayed in figure 3. The relationship between fatigue and wear is competitive (figure 13). The influence of wear on the formation of fatigue cracks is calculated according to the result of Zhou.
Figure 10. The fatigue wear cracks of three kinds of wheel samples after wear with $4 \times 10^5$ cycles. (a) G1 (b) G2 (c) G3.

Figure 11. The relationship between microstructure and the formation of fatigue wear crack. (a) Low magnification (b) high magnification.
When the wheel sample is in steady wear, the surface wear depth is \( d \), the angle between contact surface and fatigue wear cracks is \( \alpha \), the crack propagation rate is \( da \). The rate that wear reduce the fatigue crack propagation is \( dw \), and the rate of fatigue wear crack increasing \( Dr \) is calculated by equation (1):

\[
\frac{dr}{da} = \frac{dw}{\sin \alpha}
\]

Therefore, during wear process, the high weight loss reduces the formation of fatigue wear cracks of G1 wheel sample. As a result, the surface worn morphology of the G1 wheel sample is smooth. As for G2 wheel sample, the weight loss is low. Therefore, during wear process, the G2 wheel sample produces a large amount of fatigue wear cracks. As for G3 wheel sample, during wear with \( 2 \times 10^5 \) cycles \(-3 \times 10^5 \) cycles, the surface hardness is high. Therefore, the degree of plastic deformation of G3 wheel sample is light. As a result, the worn morphology of G1 wheel sample is smooth. After wear with \( 4 \times 10^5 \) cycles, the degree of plastic deformation of G3 wheel sample is high. Therefore, the worn morphology of G3 wheel sample produces a lot of fatigue wear cracks.

5. Conclusions

In present paper, we study the fatigue wear resistance of three kinds of wheel samples with different carbon content (G1, G2 and G3) by rolling wear tester under 0.2% slip ratio condition. The SEM, EBSD and TEM are conducted on analyzed the surface worn morphology and the evolution of surface microstructure of three kinds of wheel samples during wear process. The following conclusions are drawn as:
(1) During rolling wear process, as the increasing of cycles, the weight loss of three kinds of wheel samples is increased. The carbon content can change the weight loss of wheel materials. Low carbon content wheel sample (G1 wheel sample) exhibit high weight loss. With the increase of carbon content, the weight loss is reduced. The weight loss of G3 wheel sample is the lowest.

(2) During rolling wear process, the surface hardness and the plastic deformation thickness of three kinds of wheel samples are increased according to cycles. However, the degree of surface hardening and the thickness of plastic deformation layer of G1 wheel sample is largest owing to high fraction of PF grains. After wear, the wheel samples form a gradient plastic deformation layer. As the reduction of distance from surface, the fraction of high angle grain boundaries of ferrite grains is increased and the ferrite grains are gradually refined. At the sample surface, the PF grains refine to about 100 nm, the spacing of ferrite grains in pearlite is reduced and a part of cementite is dissolved.

(3) During rolling wear process, the correlation between weight loss and fatigue is competitive. High weight loss of the G1 wheel sample can hinder the formation of fatigue wear cracks. The G1 wheel sample surface is smooth. The low weight loss of the G2 wheel sample and the G3 wheel sample can not inhibit the formation of fatigue wear cracks. After wear, many fatigue wear cracks are produced at the wheel sample surface, which accelerate the RCF failure.

Data availability statement

All data that support the findings of this study are included within the article (and any supplementary files).

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Conflicts of interest

The authors declare no conflict of interest.

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