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A novel microstructure of carbide-free bainitic medium carbon steel observed during rolling contact fatigue

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ABSTRACT

A novel microstructure caused by rolling contact fatigue has been observed in a carbide-free bainitic medium carbon steel. The microstructure is associated with localized non-uniform deformation, and is in the form of vortices of plastic deformation centred on non-metallic inclusions in the vicinity of the contact surface. The resulting severe plastic deformation led to the formation of nanocrystalline material, where fatigue cracks initiated and propagated along the upper edge of the nanocrystalline area.

Carbide-free bainitic steels (CFBS) are excellent structural material and have been widely applied in industry, such as railway frogs, rails and bearings [1,2]. In the service of railway frogs, rails and bearings, rolling contact fatigue (RCF) is the main failure mode, which leads to microstructural change and mechanical property decay in the surface or subsurface of the steels. Bhadeshia [3,4], Evans et al. [5–8] and Lund [9] determined that the RCF performance of steels is affected by many factors, such as slip, lubrication state, especially non-metallic inclusions. Evans et al. [5–8] and other researchers [9–11] indicated that non-metallic inclusions can be initiators of butterflies and white etching cracks (WECs) that have associated microstructural changes to nanocrystalline area, these typically leading to fatigue failures in high-carbon bearing steels. Some researchers revealed that butterfly exists around the non-metallic inclusions at a depth typically 1 mm below the contact surface in high-carbon bearing steels [5–8,12,13]. The formation of nanocrystalline in butterfly is the combination of shear reversal stresses from rolling contact with hydrostatic stress, or carbide dissolution, or low temperature recrystallisation [3–11,14–16]. Generally, butterflies and WECs can be formed both under pure rolling and rolling–sliding conditions in high-carbon bearing steels. But in high carbon pearlitic rail application, only hardened layer forms under pure rolling condition, whereas white etching area (WEA) is formed under rolling–sliding condition [16,17]. The WEA on the surface of high-carbon pearlitic rail steel is generated because of heavy plastic deformation, carbide dissolution or low temperature recrystallisation [3,14–16].

Compared with the probable existence of the nanocrystalline area or the WEA in high-carbon steel, a nanocrystalline area in low and medium carbon steels is rarely generated except under particular conditions, such as high strain rate and impact wear [18]. The formation mechanism of nanocrystalline in low- and medium-carbon steels differs from that of high-carbon steel. Some researchers believed that the generation of the nanocrystalline area in low- and medium-carbon steels may be the result of phase transition [18], rather than carbide dissolution or the local stress field in high-carbon steel. However, the effects of the non-metallic inclusions on the nanocrystalline microstructure in the CFBS during RCF test have been rarely reported. Therefore, the microstructure evolution caused by inclusions and the RCF mechanism in the CFBS should be further investigated.

The steel used in this study is a new type of CFBS with medium carbon content(C 0.30, Mn 2.17, Si 1.12, Cr 1.19, Ni 0.23, Mo 0.24, W 0.22, Al 0.98, S 0.002 and P 0.006 in wt.%). The steel ingot with 200 mm in diameter was melted by a 45 kg vacuum induction furnace and homogenized for 10 h at 1200 °C, then forged into round bars with 90 mm in diameter and treated as follows: heated at 920 °C for 40 min, followed by cooling in a salt bath at 350 °C for 100 min, and finally air cooled. The Ms temperature of the steel was measured to be 332 °C by the dilatometric experiments along diameter on the Gleeble-3500 thermo-mechanical simulator. The sample size for measuring Ms was 6 mm in diameter and 80 mm in length. The steel presented a tensile strength of 1320 MPa, a total elongation of 15.1% and a hardness of 42.7 HRC and contains bainitic ferrite and retained austenite (γ_r). The volume fraction of γ_r was 11.8 vol.% measured using a D/max-2500/PC X-ray diffractometer [19]. The RCF testing was performed in dry atmosphere condition with a three-roller line contact RCF testing machine with one drive

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shaft and two driven shafts, for details refer to Ref. [19]. A nominal rotating speed of 800 rpm of the wheel sample was used, with a normal applied load of 12 kN. The radiuses of the test specimens were 40 mm, 35 mm and 40 mm, respectively, contact length of the specimen was 8 mm, the roughness of the sample surface was 0.4 μm and maximum Hertzian contact stress was 1.7 GPa, for detailed calculation method refers to Ref. [19]. The microstructural changes in the surface of the steel after the RCF test were characterized in detail through SEM and TEM.

After different rolling cycles, the microstructure of longitudinal section parallel to the rolling direction is shown in Fig. 1. A deformation area formed at the sample surface and the microstructure changed after different rolling cycles. After 3.2×10^4 rolling cycles, a structureless area with a thickness of a few microns, formed at a depth typically 10 μm below the contact surface of the RCF sample after etching with 3% Nital, is called WEA or white etching matter [3,5]. The structureless area is a nanocrystalline area, as shown in Fig. 2b and c. This observation is in agreement with the results presented in previous works [3–8]. The matrix of the steel contains bainitic ferrite lath and retained austenite film, as shown in Fig. 2a. A severe plastic deformation area in the form of vortices exists at the front of the nanocrystalline area, as shown by the surrounding area of the white dash–dot line and white solid line in Fig. 1. After 1.1×10^5 rolling cycles, the cracks are formed along the nanocrystalline area, as shown by the white arrow in Fig. 1b. A vortical microstructure and a nanocrystalline area are formed. As the rolling cycle is increased to 1.1×10^6 and 7.6×10^6, cracks, as well as the nanocrystalline area, expand downwards at an acute angle to the surface, as shown in Fig. 1c and d.

A similar nanocrystalline area was reported in Fig. 14b of Ref. [17] and Fig. 4e of Ref. [19]. This microstructure was referenced to AISI 15B30 bainitic steel (carbon content of 0.35 wt.%) during the rolling–sliding process, but not during pure RCF test nor in high carbon pearlitic steel during rolling–sliding process [17]. Moreover, previous studies [17,19] did not analyse factors influencing nanocrystalline area formation. According to Carroll et al. [20], the WEA was broken with two or more cracks existed at the same time. Evans et al. and Grabulov et al. [5–8,14] mentioned that WEA was initiated from non-metallic inclusions (size of more than 5 μm) at a depth typically 1 mm below the contact surface in high-carbon bearing steels. The microstructure morphology in the present work (Fig. 1) differs from that reported in Ref. [16,20], which did not contain the vortical microstructures. Therefore, in the present study, the local nanocrystalline area and the vortical microstructures caused by local inhomogeneous plastic deformation are considered as the novel microstructure morphologies of the steel, which is distinct from those in high-carbon rail steel.

The microstructure on the surface of the steel after a long period of the RCF test is shown in Fig. 3. Similar to the longitudinal–sectional microstructure, the nanocrystalline area is surrounded by the vortical microstructure formed near the sample surface with the depth of about 10 μm, as shown in Fig. 3a (the surrounding area of white dash-dot line) and Fig. 1. One can see that there is a non-metallic inclusion in each vortical microstructure, and the non-metallic inclusion composition (Fig. 3) measured by SEM with an energy dispersive spectrometer (EDS, beam energy is 20 keV, working distance is 15 mm) contains Al, O or N. Thus, they should be Al-containing inclusions, i.e. Al_2O_3 (Fig. 3b) or AlN (Fig. 3d). However, around the larger AlN inclusion (approximately 3 μm in Fig. 3d), the vortical microstructure is not obvious.

As is known, the elastic modulus and the thermal expansion coefficient of Al_2O_3 are about 375 GPa and $7.6 \times 10^{-6}\ K^{-1}$, while that of AlN are 300 GPa and $4.9 \times 10^{-6}\ K^{-1}$ [8,21], respectively. However, the elastic modulus and the thermal expansion coefficient of the steel in this study are about 200 GPa and $12.3 \times 10^{-6}\ K^{-1}$, respectively. The difference in physical properties between the Al-containing inclusions (especially Al_2O_3 inclusion) and the steel is very large, which may cause obvious difference in the elastic and plastic deformation behaviours in the area containing the non-metallic inclusions with the matrix of the steel. During the RCF testing, under the shear stress of the rolling contact the inclusions can obviously enhance the surrounding stress field [8,22], which can result in an obviously non-uniform deformation. The plastic deformation of the inclusions is very little, whereas the deformation of the steel around the inclusions is very large. The differences in the elastic modulus value and thermal expansion coefficient are larger, and then the degree of the non-uniform plastic deformation is worse [8]. So in the area with different types of inclusions, the degree of the non-uniform deformation is obviously different. The deformation degree of the area around Al_2O_3 inclusion is much severe than that of around AlN inclusion, as shown in Fig. 3.

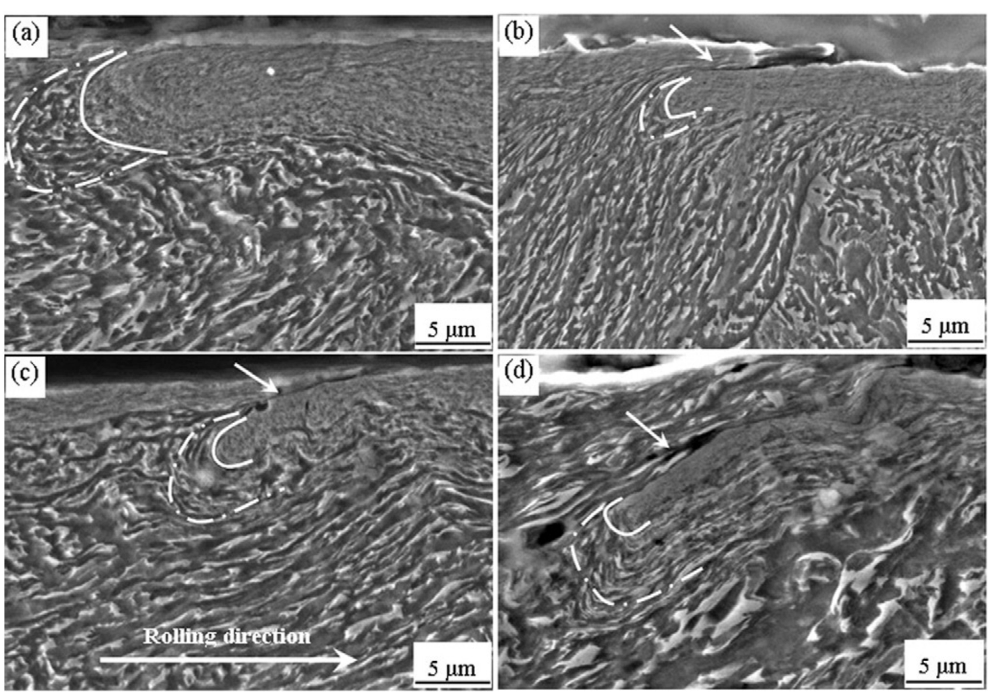

Fig. 1. Longitudinal–sectional microstructure of the sample after different cycles. (a) 3.2×10^4, (b) 1.1×10^5, (c) 1.1×10^6, (d) 7.6×10^6.