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Effects of retained austenite and hydrogen on the rolling contact fatigue behaviours of carbide-free bainitic steel

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ABSTRACT

The effects of retained austenite and hydrogen on the rolling contact fatigue (RCF) behaviours of a new carbide-free bainitic steel (CFBS) were studied by means of the RCF testing, electrolytic hydrogen charging, transmission electron microscope (TEM), scanning electron microscope (SEM) and X-ray diffraction (XRD). The results showed that the new carbide-free bainitic steels (CFBSs) exhibited very good RCF performance under the high contact stress of 1.7 GPa, and pitting and spalling were the main mode of the RCF failure. The RCF performance of the new CFBS was improved by the retained austenite content increasing, while obviously decreased by hydrogen.

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1. Introduction

RCF is always a major puzzle for researchers in wheel–rail contact and bearings. Therefore, calculation, simulation and experimental studies in this research area have been developed by many researchers for many years. On the one hand, based on the previous studies [1–3], the effects of lubrication conditions, slip rate, roughness, residual stress, plastic deformation and tangential force on the rolling contact stress have been widely investigated and many important results have been obtained [1,3,4–7]. On the other hand, the crack initiation and spalling on the surface of the RCF samples, the relationship between the contact stress, the fatigue crack propagation rate, intensity factor of crack tip and the temperature on the rolling contact surface of the samples have also been studied [8–11].

Many researchers have focused on the RCF microstructures, the most important influence factor of the RCF performance, combined with the RCF model and mechanism, such as the pearlitic, martensitic and austenitic steels [7,12,13]. The properties of a new kind of bainitic steel have been studied and it has been found that the comprehensive mechanical properties of the bainitic steel are superior to those of traditional pearlitic, tempered martensitic and austenitic steels [14,15]. Green et al. have indicated that lower bainite exhibits slower fatigue crack propagation than the granular bainite [16]. In recent years, some research results indicated that CFBSs exhibited high strength and high toughness, and compared with other bainitic steels, CFBSs exhibited lower wear rate, which were considered to be the first substitute for railway systems (rails and crossings) and engineering parts (bearings and gears) with high carbon bainitic steel [17,18]. Most studies have paid much attention to the effect of the retained austenite in the martensitic steel [19,20] and the gas content (such as oxygen, nitrogen and hydrogen) on the RCF performance in steels [21–23]. Refs. [24,25] have shown that, compared with other bainitic steels, CFBSs exhibit lower wear rate and retained austenite is an important factor in improving wear resistance and the fatigue crack propagation. However, there are less reports on the effects of the gas content in the CFBSs on the RCF performance, as well as the effect of retained austenite on the RCF performance, which need thorough and meticulous investigation. The RCF damage, such as premature brittle fracture and block spalling, often occurrs during service in railway system. Meanwhile, in our previous work, the CFBSs have been found to be sensitive to hydrogen, and over hydrogen could make the CFBS brittle [26,27]. Then, over hydrogen content could reduce the RCF life of the CFBS. These problems may be very interesting for scientists and engineers.

In this paper, the effects of hydrogen and retained austenite on the RCF performance of CFBS were studied to provide some bases for the wide use of the CFBSs, especially in railway systems.

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Table 1
Chemical compositions (wt%) of CFBS.

C	Mn	Si	Al	Cr	Ni	Mo	W	S	P
0.30	2.17	1.12	0.98	1.19	0.23	0.24	0.22	0.0015	0.006

Table 2
Mechanical properties of CFBS subjected to different heat treatments.

Sample	Tensile strength σ_b (MPa)	Yield strength $\sigma_{0.2}$ (MPa)	Elongation η (%)	Reduction of area Φ (%)	Impact toughness A_{ku} (J/cm^2)	Hardness HRC	Retained austenite content (%)
S1	1320	1055	15.1	59.0	114	42	11.8
S2	1365	1074	17.8	60.5	121	44	18.9

2. Experimental procedures

The chemical compositions of the new CFBS are listed in Table 1. The steel ingot produced by vacuum melting was forged into round bars of 90 mm in diameter. The round bars were heated to 920 °C for 40 min for austenization and then quenched in a salt bath at 350 °C for 100 min (named as S1) and 30 min (named as S2), respectively, and then cooled to room temperature in air. Thus, the samples with different retained austenite contents were obtained. The microstructures of the samples consist of bainitic ferrite and retained austenite. The mechanical properties of the samples subjected to different heat treatments are listed in Table 2.

Cathodic electrolytic charged hydrogen (H) testing, using a stabilized power supply (YJ83/2 type DC), was carried out in 0.5 mol/L H_2SO_4+200 mg/L Na_3AsO_3 electrolytes. The current density for hydrogen charging was 10 mA cm^{-2} [27]. The charging time was 180 min in this study. Protective bright cadmium plating was applied to prevent hydrogen to escape from the samples. The sample and the cadmium were used as the anode and cathode, respectively. The plating solution was aqueous solution (1 L) of 98% oil of vitriol (50 g/L), dried $CdSO_4$ powder (50 g/L), anhydrous Na_2SO_4 (45 g/L), gluten (6 g/L) and phenol (3 g/L). The current density for plating was 25 mA cm^{-2}. 5 min was sufficient for cadmium plating to prevent hydrogen from diffusing and dissipating. Homogenisation treatment at 200 °C for 10 h was carried out for the uniform distribution of hydrogen and resulted in the diffusion of hydrogen into the centre of about 3 mm. The hydrogen content in the sample was analysed with a hydrogen content analyser (CQY-2), which is 0.6 ppm for the sample without hydrogen charging and 2.4 ppm for the sample with hydrogen charging for 180 min, respectively. The coating layer was polished clean by a fine sandpaper before RCF testing.

The RFC testing was carried out with a TLP-3 model RCF testing machine. The rotating speed of the sample was 800 rpm. The testing load was 12 kN. The RCF equipment was as shown in Fig. 1.

The maximum Hertzian contact stress can be calculated by Eq. (1) [28,29]:

$$\sigma_{\max} = \sqrt{\frac{P}{\pi L}\frac{(1/R_1)+(1/R_2)}{(1-v_1^2/E_1)+(1-v_2^2/E_2)}} \tag{1}$$

where P is the load, R_1 is the radius of the sample, R_1=40 mm; R_2 is the radius of another sample, R_2=35 mm; L is the contact length, L=8 mm; E is elastic modulus, E_1=E_2=206 GPa; ν is Poisson's ratio, assuming that ν_1=ν_2=0.3, as is typical for steels. When P=12 kN, $\sigma_{\max}$=1.7 GPa. The testing parameters for the different samples are listed in Table 3.

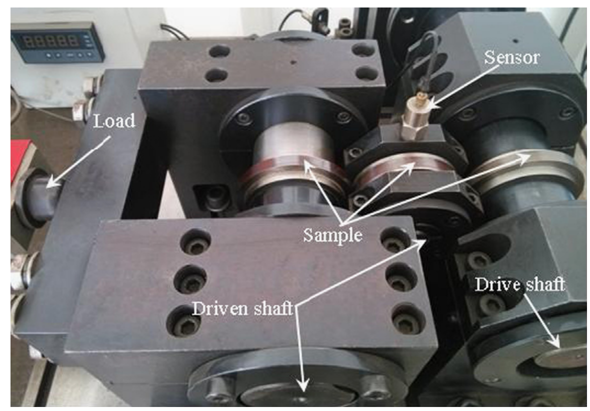

Fig. 1. TLP-3 line contact RCF testing machine.

Table 3
RCF testing conditions for CFBS.

Sample	Hydrogen content (ppm)	Rolling cycles
S1	0.6	1.0×10^5
		1.0×10^6
		5.0×10^6
S1 charged H	2.4	1.0×10^6
S2	0.6	1.0×10^5
		1.0×10^6
		5.0×10^6

The microstructures of longitudinal-section of the samples after the RCF testing were observed by field emission scanning electron microscope (FESEM, HITACHI-S4800). The microhardness distribution of the RCF sample from the surface to the matrix was measured by Vickers tester (HVS-1000) with a load of 300 g. The phase composition was analysed by X-ray diffractometer (D/max-2500/PC) with Cu K_α radiation operated at 40 kV and 200 mA. The relative content of retained austenite was calculated based on the integrated intensity of $(200)_\alpha$, $(211)_\alpha$, $(200)_\gamma$, $(220)_\gamma$ and $(311)_\gamma$ peaks. The carbon content in the retained austenite (x_γ, wt%) was calculated by: a_γ=3.556+0.0453 x_γ, where a_γ is the lattice parameter of the austenite [30]. The results, listed in Table 4, show that the retained austenite content in the S1 is less than that in the S2.

The sample for in-situ tension by transmission electron microscope (TEM, H-800) was cut to 3 mm × 6 mm × 35 μm by the use of electric spark cutting and mechanical polishing. Then, the sample was prepared by a twin-jet electro-polishing device and a hole about Φ=0.1–0.3 mm in the centre of the sample was

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