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Low cycle fatigue behavior in a medium-carbon carbide-free bainitic steel

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ABSTRACT

In the paper, different morphologies of bainite were obtained through isothermal quenching at 320 °C and 395 °C in a medium-carbon carbide-free bainitic steel. The cyclic deformation mechanism was explored by using low cycle fatigue testing. The volume fraction of retained austenite was measured by X-ray diffraction and the space partitioning of the solute atoms was constructed by three-dimensional atom probe. Results showed that the fatigue life at 320 °C was always higher than that at 395 °C under low and high total strain amplitude. The cyclic softening at the early fatigue stage increased the plastic strain of the sample which was responsible for the reduction of the fatigue life at 395 °C. Strain-induced retained austenite to martensite contributed to initial cyclic hardening, but almost having no effect on the subsequent cyclic stable/softening behaviors. The finer bainitic ferrite sheaves obtained at 320 °C changed the small fatigue crack propagation direction and delayed the crack propagation rate, which was beneficial for the fatigue properties. In addition, the substitutional atoms did not redistribute between the retained austenite and bainitic ferrite before and after cyclic deformation.

1. Introduction

In the early work, carbide-free bainite is obtained through adding sufficient amounts of Si and Al to steel [1–3], which is considered as an ideal microstructure [4,5]. The microstructure consists of bainitic ferrite plate with high density dislocation and film-like retained austenite with carbon enriched [6–8]. Based on its microstructure feature, high strength and suitable toughness can be achieved in the carbide-free bainitic steel [9–11]. Since Bhadeshia has fabricated the nano-structured bainite microstructure with high ultimate tensile strength of 2500 MPa and toughness in excess of 30–40 MPa m$^{1/2}$ [6,12], reducing the thickness of bainitic ferrite plate to nanometer level to obtain better mechanical properties becomes the hotspot research in the recent years [13–17]. However, limited researches have been reported on the fatigue behavior of the carbide-free bainitic steel.

Peet tested the fatigue behavior at high stresses with the maximum values ranging from 1200 to 1600 MPa in a nanostructured steel containing slender plates of bainitic ferrite and retained austenite with high carbon [18]. Our group made research into the high-cycle bending fatigue behavior of high-carbon Si-Al-rich steel and found that the retained austenite and second cracks had positive effects for the fatigue properties [19]. Rementeria et al. reported that higher amounts of stable retained austenite in a carbide-free bainitic steel alloyed with higher carbon increased the fatigue crack nucleation site; perhaps increasing ferrite-austenite interphases (stress concentration) [20]. The literatures mentioned above are all concentrated in the high cycle fatigue behavior of the carbide-free bainitic steel due to its high strength. However, the carbide-free bainitic steel may also suffer a large cyclic plastic deformation in some practical application or operating conditions, such as railway crossing. Work studied by Georgiyev showed that the carbide-free bainite microstructure had the highest cyclical crack resistance resulting from its stable retained austenite compared to other structural states of the same strength obtained in medium-carbon steel [21]. In the cyclic straining deformation testing of the TRIP-aided steels, cyclic softening/hardening behavior was not necessarily due to strain induced austenite to martensite transformation. It was mainly related to the substructure evolution and the size of the retained austenite as well as the strain distribution of the surrounding phase [22,23]. Qian et al. thought that the initial high density of dislocations, which were pre-existent and mobile in the starting microstructure, was responsible for the initial cyclic hardening followed by softening behavior in a low-carbon carbide-free bainitic steel [24].

Therefore, in this paper different morphologies of carbide-free bainitic microstructure were obtained in a medium-carbon steel through varying the isothermal temperatures. The low-cycle

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fatigue test controlled by the total strain amplitude has been carried out and the role of microstructures on the fatigue behavior has been studied.

2. Experimental material and procedures

The chemical composition of the studied medium-carbon bainitic steel is listed in Table 1. The design principle of the composition is based on Si+Al=2 wt% in order to suppress the carbide precipitation and shorten the time of bainite transformation. Specimens were all austenized at 930 °C for 45 min. Then the specimens were treated at 320 °C for 1 h and 395 °C for 2 h isothermal quenching to obtain carbide-free lower and upper bainite, respectively, in the salt bath furnace. The different holding time is for purpose of obtaining similar volume fraction of retained austenite according to our previous work [23].

Tensile testing and low-cycle fatigue testing were carried out on a MTS hydraulic universal testing machine. The tensile sample was fabricated to round bar of Φ 5 mm × 25 mm according to the China Standard GBT228-2002. The testing strain rate was $6\times10^{-3}\ \mathrm{s}^{-1}$. The round bar sample of Φ 5 mm × 10 mm was adopted in the low cycle fatigue testing according to the China Standard GBT15248-2008. The cyclic deformation testing was controlled by the total strain amplitudes ($\Delta\varepsilon_t/2$) 0.52% and 0.8% at room temperature. The strain ratio was −1 at a strain rate of 6.0×10^{-3} with a sine wave.

The microstructure and sub-structure were characterized and analyzed by S-4800 type high resolution field emission scanning electron microscope (FE-SEM) and JOEL-2010 type transmission electron microscope (TEM). The TEM samples were prepared on a TenuPol-5 type twin jet electro polishing instrument with working voltage of 28 V at room temperature. The twin jet polisher was 8% HClO4 and 92% acetic acid solution. The phase components and relative volumes were tested using a Rigaku D/max-2500/PC X-ray diffractometer with the radiation target of $Cu\text{-}K_\alpha$ in step scanning method, with 0.2°/step, and each step for 2 s. The volume fraction of the retained austenite (Vγ) calculation is determined according to Eq. (1) [25]. The carbon concentration in the retained austenite (C_γ) calculation is determined according to is Eq. (2) [26] using the lattice parameters of the retained austenite.

$$V_\gamma=\frac{(1/n)\sum_{j=1}^{n}I_\gamma^j/R_\gamma^j}{(1/n)\sum_{j=1}^{n}(I_\gamma^j/R_\gamma^j)+(1/n)\sum_{j=1}^{n}(I_\alpha^j/R_\alpha^j)} \quad (1)$$

$$\alpha(\dot{A})=3.578+0.033C_\gamma \quad (2)$$

where n is the number of peaks examined, and I is the integrated intensity of the diffraction peak. R is a material scattering factor, $R=(1/v^2)[|F|^2P((1+\cos^2 2\theta)/\sin\theta\sin 2\theta)]\cdot e^{-2M}$ v is volume of unit cell, F is structure factor, P is multiplicity factor, e^{-2M} is temperature factor, θ is diffraction angle, $\alpha(\dot{A})$ is austenite lattice parameter.

To explore the composition distribution and three-dimensional space condition of the dissolved solute atoms in different bainite morphologies, the partitioning of carbon and other substitutional atoms in bainitic ferrite and retained austenite was analyzed by three-dimensional atom probe technology (APT). Samples from the central region were cut after heat treatment via wire electrical discharge machining to obtain thin rods of 0.5 mm × 0.5 mm × 15 mm. The surfaces were then polished using sandpapers followed by chemical polishing [27]. First, 75% acetic acid and 25% perchloric acid were used to induce corrosion, and ethylene glycol monobutyl ether solution ($C_6H_{14}O_2$) with 2% high chlorine acid was applied to further induce corrosion. Finally, the blunt needles of the experiments were obtained. The tip samples were analyzed using a ImagoScientific Instrument LEAP 3000 h via a local electrode method. The samples were cooled to 50 K with a pulse frequency of 5 kHz and 20% pulse fraction. The collected data were processed and analyzed using IVAS software by reconstructing the three-dimensional spatial distribution of atoms of different elements.

Table 1
Chemical composition of the studied carbide-free bainitic steel (wt% and at%).

	C	Mn	Si	Cr	Al	Ni	Mo
wt%	0.34	1.52	1.48	1.15	0.71	0.93	0.40
at%	1.51	1.48	2.82	1.18	1.41	0.85	0.22

3. Experimental results and analysis

3.1. Microstructure and mechanical properties

Fig. 1 shows the SEM and TEM microstructures obtained through 320 °C and 395 °C isothermal treatments in the studied medium-carbon bainitic steel. As can be seen, the lower bainitic ferrite sheaves obtained at 320 °C isothermal are slender needle-like shape. Most of the retained austenite is film-like and parallel distributed between the bainitic ferrite plates. There also exists small blocky retained austenite. The upper bainitic ferrite sheaves obtained at 395 °C are feature-like and coarser. The area of blocky retained austenite is relatively larger.

The different features of the microstructure lead to the variation of the mechanical properties. Table 2 shows the conventional mechanical properties and the fundamental parameters of the microstructure characterization of the studied carbide-free bainitic steel. It can be seen that most of the properties obtained after 320 °C and 395 °C isothermal treatment differ little including the ultimate tensile strength, yield strength, elongation and work hardening exponent. Only the toughness of the sample at 320 °C is much higher than that at 395 °C. According to the parameters of the microstructure characterization, the volume fraction of each phase is almost the same. Hence, it appears that the variation of the properties mainly depends on the morphology and size of the retained austenite and bainitic ferrite. The coarse size of the bainitic ferrite sheaves and the more amounts of the blocky retained austenite obtained at 395 °C isothermal are detrimental to the toughness. From TEM observations in Fig. 1c and d, the dislocation density in bianitic ferrite at 395 °C isothermal is less than that at 320 °C and the bianitic ferrite plate is coarser. The sample at 395 °C isothermal should have a much lower yield strength based on its features. However, the yield strength at 395 °C is just slightly lower. The improved yield strength at 395 °C cannot be anything but the larger blocky retained austenite transforming to hard martensite at the early stage of the tensile testing. The finer bainitic ferrite plate matches with film-like retained austenite in the carbide-free lower bainite obtained at 320 °C, which is responsible for a better balance of strength and toughness.

3.2. Cyclic hardening/softening behavior

Fig. 2 shows the evolution of stress amplitude with the number of cycles (N) of the studied carbide-free bainitic steel. The fatigue life at 320 °C was always higher than that at 395 °C under low and high total strain amplitude. The sample at 320 °C always processed higher stress amplitude along the cyclic straining. Under low total strain amplitude, the cyclic hardening followed by cyclic stable occurred at 320 °C while the cyclic softening occurred after initial cyclic hardening at N > 200 at 395 °C. Under high total strain