Materials and Design 94 (2016) 1–8

Contents lists available at ScienceDirect

Materials and Design

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

Cyclic deformation behaviors of a high strength carbide-free bainitic steel

F.C. Zhang [a,b,*], X.Y. Long [a], J. Kang [a], D. Cao [c], B. Lv [d]

[a] State Key Laboratory of Metastable Materials Science and Technology, Yanshan University, Qinhuangdao 066004, China
[b] National Engineering Research Center for Equipment and Technology of Cold Strip Rolling, Yanshan University, Qinhuangdao 066004, China
[c] Department of Aeronautical Engineering, Xi'an Aeronautical University, Xi'an 710077, China
[d] School of Environmental and Chemical Engineering, Yanshan University, Qinhuangdao 066004, China

ARTICLE INFO

Article history:
Received 14 September 2015
Received in revised form 4 January 2016
Accepted 7 January 2016
Available online 8 January 2016

Keywords:
Carbide-free bainitic steel
Cyclic deformation
Fatigue
Microstructure

ABSTRACT

The cyclic deformation behaviors of low-temperature bainite, lower bainite and upper bainite obtained on a high-strength carbide-free bainitic steel were examined through low-cycle fatigue testing. The relationship between the bainitic microstructure and fatigue behavior was systematically studied using scanning electron microscopy, transmission electron microscopy, atom probe technology, and electron back-scattered diffraction analyses. The results show that low-cycle fatigue undergoes three stages, namely, cyclic hardening, saturation or cyclic softening, and fracturing. The low-temperature bainite exhibits a long fatigue life under the total strain amplitudes, because of its high strength and larger high-angle misorientation distribution of the packets of bainitic ferrite plates. The low-temperature bainite also presents bilinearity in the Coffin–Manson plots. Coordinate deformation and high-uniform elongation lead to prolonged fatigue life at low plastic strain amplitude, whereas phase component primarily affects the fatigue life at high plastic strain amplitude. Highly stable film-like retained austenite is beneficial to arresting fatigue crack propagation. Blocky type retained austenite easily transforms to martensite, resulting in high compatible deformation capability. The hardening ability of the low-temperature bainite is higher than that of the upper bainite, which is attributed to its high pre-existent density of dislocations transformed from movable to immovable during initial hardening stage.

1. Introduction

Carbide-free bainitic steels exhibit excellent mechanical properties and are widely applied in industry, such as automotive components, bearings, gears, or railway systems [1–4]. These parts are exposed to dynamic cyclic loading. Therefore, the cyclic deformation mechanism of carbide-free bainitic steels during low-cycle fatigue is worth investigating.

The cyclic hardening ability of the ferritic/martensitic dual-phase steel decreased with increasing martensite content during cyclic strain controlled deformation [5–7]. Lucas and Gerberich [8] researched the martensitic/austenitic steel with an acicular ferritic/bainitic microstructure, and found that the initial dislocation density decreased during the strain hardening in the fatigue process. The cyclic softening behaviors were related to the dislocation pinning and the dynamic recovery behaviors in the quenched and tempered steels and the ferrite/bainitic rotor steels [9–11]. Sankaran and Padmanabhan et al. [12–14] found that the retained austenite films between the bainitic ferrite laths prevented softening during low-cycle fatigue in a high strength ferritic/bainitic/martensitic steel. Branco et al. [15] reported that a high strength steel with martensitic and lower bainitic microstructures exhibited a subsequent strain-softening behavior until failure. Zhou et al. [16] studied the low-cycle fatigue performance of a low-carbon carbide-free bainitic steel with bainitic ferrite and retained austenite, and the results showed that the interactions among the higher density dislocations in the starting microstructure and the decreased density of mobile dislocations were responsible for the initial cyclic hardening. Moreover, the annihilation and the rearrangement of dislocations resulted in the followed cyclic softening.

The low-temperature bainite is a new type of bainite that consists of thin lath-like bainitic ferrite and film-like retained austenite. Bhadeshia and Solano-Alvarez et al. [17,18] studied the rolling contact fatigue behaviors of the low-temperature bainite and found that the fatigue microcracks were formed at the interface between the bainitic ferrite and the retained austenite, which were caused by the strain-induced transformation of the retained austenite to martensite. The retained austenite in the low-temperature bainite exhibited high stability because of its high carbon content and small scale [19,20]. Zhang et al. found that the low-temperature bainite steel exhibited relatively higher rolling contact fatigue resistance and its rolling contact fatigue life is twice higher than that of martensitic steel [21]. Rementeria et al. [22] performed tension–tension fatigue testing with notch on some nanostructured bainitic steels and identified the active slip systems in the bainitic ferrite and the crack deflection at grain boundaries. High-cycle

* Corresponding author at: State Key Laboratory of Metastable Materials Science and Technology, Yanshan University, Qinhuangdao 066004, China.
E-mail address: zfc@ysu.edu.cn (F.C. Zhang).

http://dx.doi.org/10.1016/j.matdes.2016.01.024
0264-1275/

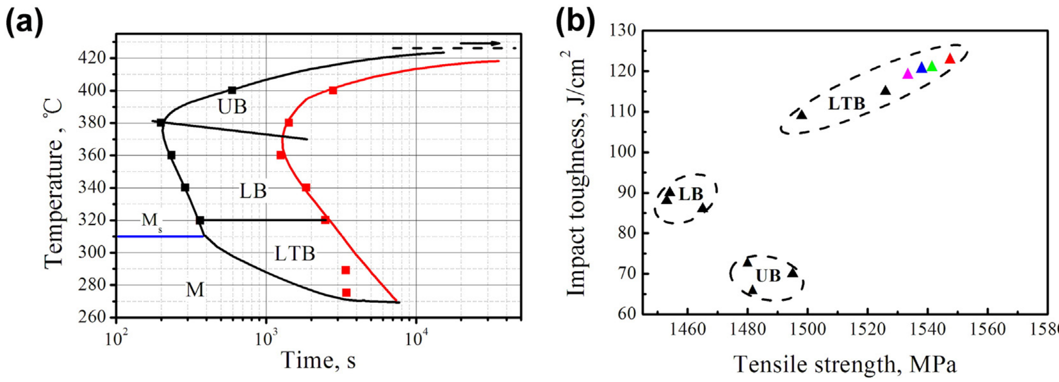

Fig. 1. TTT curve (a) and mechanical properties distributions (b) of the steel. Note: LTB: Low-temperature bainite; LB: Lower bainite; UB: Upper bainite; M: Martensite; Ms: Martensite starting temperature.

Table 1
Mechanical properties of samples subjected to different heat treatments.

Sample	δ %		φ %	σ_s MPa	σ_b MPa	a_{KU} J/cm^2	HRC	Strain-hardening exponent
	Total	UNI						
Low-temperature bainite	16.4	6.2	56.9	1230	1546	125	46.5	0.096
Lower bainite	17.9	9.8	45.6	921	1454	90	41.5	0.113
Upper bainite	17.3	13.1	45.5	1032	1495	70	44.4	0.119

Note: σ_s: Yield strength; σ_b: Ultimate tensile strength; δ: Elongation; UNI: Uniform elongation; φ: Reduction of area; a_{KU}: U-notch impact toughness.

bending fatigue testing on a nanostructured bainitic steel showed that the retained austenite and the secondary cracks had positive effect on the fatigue properties [23]. The factor of "soft- or coarsely soft structure-induced fatigue cracks" primarily affected the fatigue behaviors of the carbide-free bainitic/martensitic steel [24].

However, there are limited reports on the low-cycle cyclic deformation behaviors of the low-temperature bainite, the lower bainite and the upper bainite obtained in a high strength carbide-free bainitic steel in one study. In this paper, the low-temperature bainite, the lower bainite and the upper bainite were obtained in a high strength carbide-free bainitic steel. Their cyclic deformation behaviors were studied by means of low-cycle fatigue testing. The purpose of the present work is to comparative study the fatigue behaviors of the steel with three different bainitic morphologies, and analyze the effects of the bainitic ferrite, the retained austenite and their misorientations of the packets of the bainitic ferrite plates on the fatigue behaviors.

2. Material and experimental procedures

Steel with the chemical compositions of 0.34C, 1.52Mn, 1.48Si, 0.93Ni, 1.15Cr, 0.40Mo, 0.71Al (wt.%) was employed in this study. The steel was received in vacuum smelting condition and then hot forged with a ratio of approximately 6. All samples were austenitized at 930 °C for 45 min, followed by continuous cooling at 320–290 °C at a cooling rate of 0.5 °C/min for 60 min, isothermal transformation at 360 °C for 60 min, and isothermal transformation at 395 °C for 120 min. Then all samples were tempered at 320 °C for 60 min. Fig. 1 presents the TTT diagram and the mechanical properties distributions of the steel, as reported in our previous work [25]. Detailed informations on the low-temperature bainite, the lower bainite, and the upper bainite were presented in Ref. [25]. When the phase transformation temperature is higher than 385 °C, the bainite morphology is upper bainite, which consists of the catenary bainitic ferrite and the blocky retained austenite and exhibits high tensile strength but low impact toughness. When the phase transformation temperature range is between 385 °C to 320 °C, the lower bainite is obtained, which consists of the lath-like bainitic ferrite and the flake-like retained austenite and exhibits low tensile strength and high impact toughness. When the phase transformation temperature is less than 320 °C, the lower bainite consisting of thinner lath-like bainitic ferrite and film-like retained austenite is formed, which exhibits excellent combination of high tensile strength and impact toughness, this type of bainite is thus termed as the low-temperature bainite.

Tensile testing was performed in an MTS (MTS Servo-Hydraulic Test System, Landmark. 100 kN with 370.10 load frame) material testing machine at room temperature with a crosshead speed of 3 mm/min. Tensile samples with 25 mm gauge and 5 mm diameter were machined, and three samples were tested for each process. The impact toughness was measured at room temperature by using a 300 J Charpy testing machine. The size of the sample was 10 mm × 10 mm × 55 mm, with a 2 mm wide U-notch.

The low-cycle fatigue testing was performed on an MTS material testing machine. Samples with 10 mm gauge length and 5 mm gauge diameter were machined and then polished with emery papers of 320–2000 grit silicon carbide. The tests were controlled with total strain amplitudes ($\Delta\varepsilon_t/2$) of 0.52%, 0.60%, 0.70%, and 0.80%. A sinusoidal waveform ($R = -1$) at a constant strain rate of $6 \times 10^{-3}\ s^{-1}$ was used. Three samples were tested for each set of parameters. The fractured samples

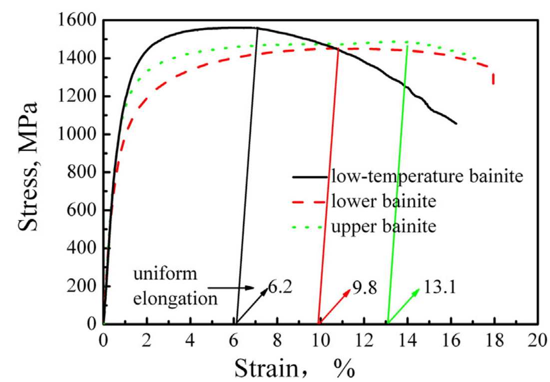

Fig. 2. Tensile stress/strain curves of three kinds of bainite samples.