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On the correlation among dislocation density, lath thickness and yield stress of bainite

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ABSTRACT

The present work investigates quantitatively, for the first time, the correlation among dislocation density, lath thickness and yield stress of bainite. It is found that the dislocation density increases with the decrease of lath thickness in bainitic steels. Based on the correlation among dislocation density, lath thickness and yield stress, a physical model is proposed to predict the yield stress of bainitic steels, incorporating the contributions of dislocation strengthening as well as lath boundary strengthening. Furthermore, it is found that the dislocation strengthening gradually becomes more significant than lath boundary strengthening with the refinement of bainite lath, which explains the transition of strengthening mechanisms from lath boundary strengthening to dislocation strengthening when the lath thickness is below one micron.

1. Introduction

Bainitic steels have become an important steel grade of advanced high strength steels (AHSSs) due to their excellent combination of strength and toughness [1,2]. For the fully bainitic structures with moderate carbon content, boundary strengthening and dislocation strengthening are the two primary strengthening mechanisms which determine the yield stress of bainite [3]. Although many studies have analyzed the contribution of boundary strengthening to the yield stress of bainite [3–9], few of them studied quantitatively the contribution of dislocation strengthening, and thus are not able to decouple the contribution of dislocation strengthening and boundary strengthening [3]. In fact, previous studies found that the bainitic transformation temperature could affect the bainite lath thickness as well as the dislocation density in bainitic steels [10–12]. In other words, dislocation density varies with lath thickness during bainitic transformation. Therefore, it is inappropriate to take dislocation strengthening as a constant parameter for the analysis of bainite strength with varied bainitic lath thickness [3,6,13,14]. A proper estimation of dislocation strengthening and its contribution to the bainite strength therefore requires the knowledge of the relationship between dislocation density and bainite lath thickness. For the measurement of dislocation density by X-ray diffraction (XRD) [15–17], dislocation arrangement should be taken into consideration in order to separate its effect on the calculated dislocation density [14]. The convolutional multiple whole profile (CMWP) procedure incorporating dislocation arrangement is suitable to obtain the dislocation density from the XRD line profile [18–21]. For the measurement of bainite lath thickness, previous studies revealed that the measuring result of bainite thickness varies significantly with the selection of lath misorientation [4,22].

In summary, the respective contributions of dislocation strengthening and lath boundary strengthening to the yield stress of bainite have not yet been quantified for bainitic steels. In addition, the relation between dislocation density and lath thickness is also unknown. Therefore, the aims of present work are to investigate quantitatively the above two remained questions in bainitic steels.

2. Experiments

The cold-rolled steels with different C contents are employed for investigation here. The detailed chemical compositions and heat

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Table 1
Chemical composition and thermal cycles for the 0.25C bainitic steel.

Ref	C (wt.%)	Mn (wt.%)	Al (wt.%)	Austenitization	Bainite Transformation	Final cooling
0.25C-0Al-400	0.25	2.07	0.021	1000 °C/300s	400 °C/600s	Water quench
0.25C-0Al-500					500 °C/600s	
0.25C-0.5Al-400	0.247	2.07	0.53		400 °C/600s	
0.25C-0.5Al-500					500 °C/600s	
0.25C-1.5Al-400	0.249	2.07	1.54		400 °C/600s	
0.25C-1.5Al-500					500 °C/600s	

Table 2
Chemical composition and thermal cycles for the 0C bainitic steel.

Ref	C (wt.%)	Mn (wt.%)	Al (wt.%)	B (ppm)	Austenitization	Bainite Transformation	Final cooling
0C-0Al	0.004	2.94	0.03	16	1200 °C/600s	Continuous cooling 4 °C/s	
0C-1Al	0.004	2.83	1.03	16			

treatment cycles of these steels are shown in Table 1 and Table 2. These steels are termed as low carbon (0.25C) steels (Table 1) and ultra-low carbon (0C) steels (Table 2) hereafter for clarity. The addition of Al in some steel grades is used to suppress the carbide precipitation in bainitic structure. To achieve bainitic structures in 0.25C steels, an austenitization at 1000 °C for 300 s followed by isothermal holding at either 400 °C or 500 °C for 600 s is carried out using salt bath furnace. To obtain the same bainite microstructure in 0C steels [4], continuous cooling with a cooling rate of 4 °C/s is employed with austenitization at 1200 °C for 600 s using Linseis dilatometer L78 in quench mode. Tensile samples with a gauge dimension of 10 mm (length) x 4 mm (width) x 2 mm (thickness) are fabricated from the heat-treated plates along the rolling direction. The tensile tests are carried out on a universal testing machine with a strain rate of 10^{-3} s^{-1} at room temperature. The scanning electron microscopy (SEM) observations are carried out using the Hitachi S4800 FEG-SEM operated at 5 kV. The samples for SEM observation are etched using 2% nital solution for 30 s after conventional mechanical polishing of 1 μm. The transmission EBSD (t-EBSD) measurements are performed in Leo 1530 operated at 20 kV with a step size of 50 nm and the corresponding data is processed by HKL Channel 5. The transmission electron microscopy (TEM) observations are performed in a FEI Tecnai G220 scanning TEM (STEM) operated at 200 kV. The TEM samples are prepared by mechanical thinning down to 0.1 mm, then followed by twin-jet thinning in a solution of 5% perchloric acid and 95% ethanol (vol.%) at −30 °C with a potential of 40 V. For the dislocation density measurement, synchrotron XRD experiments are performed at beamline no. 14 B of Shanghai Synchrotron Radiation Facility (SSRF). A monochromatic X-ray beam with an energy of 18 keV, corresponding to a wavelength of 0.68879 Å, is employed. To record each line diffraction patterns, a dwell time of 0.5 s is used. To fully utilize the beam time without sacrificing the accuracy during measurement, the step size selected as 0.01° for interested peaks while the step size of other areas is chosen as 0.2°.

3. Results

The typical microstructures of bainite in 0C steels and 0.25C steels are shown in Fig. 1 (a) and (b), respectively. Most of the lath boundaries in 0C steels are less than 7° (Fig. 1(a)), while nearly all the lath boundaries in 0.25C steels transformed at 400 °C are the high-angle boundaries with misorientation larger than 15° (Fig. 1(b)). Since 0C steels contain ultralow carbon content and are transformed at high temperature, their bainite lath thickness are in general large (~1 micron) as reported in literature [3,4]. The spatial resolution of EBSD is therefore good enough for measuring the lath thickness using line intercept method in 0C steels [4]. However, for the 0.25C steels, the filmy retained austenite (RA) between bainite laths is difficult to be revealed by EBSD measurement due to their very fine size. Consequently, the lath thickness of bainite in 0.25C steels is determined from SEM images by using the same line

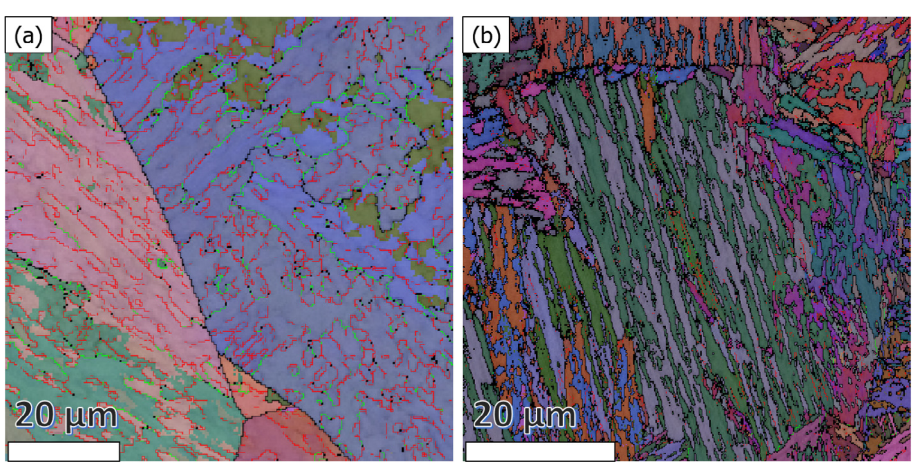

Fig. 1. EBSD all Euler maps of (a) the 0C-1Al bainitic steel and (b) 0.25C-1.5Al-400 bainitic steel. High-angle (misorientation >15°) boundaries are represented as black lines, while low-angle boundaries with 2–7° and 7–15° are represented as red and green lines, respectively. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)