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Microstructure-property relationship in bainitic steel: The effect of austempering

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ABSTRACT

The bainite/martensite multiphase microstructure was studied in 0.22C-2.0Mn-1.0Si-0.8Cr-0.8(Mo+Ni) (wt%) bainitic steel subjected to austempering between 325 °C and 400 °C to elucidate the toughening mechanism and the determining role of martensite/austenite (M/A) constituents obtained through various heat treatment. Steel austempered at higher temperature had lower strength and poor toughness, because of the wide bainitic ferrite lath and blocky M/A constituents. Bainite with similar crystallographic orientation to lath martensite was formed and exhibited a typical K–S relationship. The samples austempered below martensite-start (Ms) temperature exhibited an excellent impact toughness at room temperature, due to the superfine sub-plates in lower bainite blocks. Meanwhile, air-cooled toughness at low temperature was superior to the steel austempered at 325 °C, because of its finer effective grain size. The relationship between microstructure and mechanical properties was studied using a combination of SEM, TEM and crystallographic analysis.

1. Introduction

Bainitic steels are being widely used for structural application because of low cost, simple processing, high hardenability and excellent mechanical properties [1–4]. Previous studies indicated that bainitic steels with good combination of strength and toughness can be obtained by environment-friendly air-cooling process [5]. Bainitic steel has been successfully used in heavy haul railway [6–8], for its excellent combination of microstructure and mechanical properties, where bainite/martensite (B/M) multiphase microstructures of bainitic rail steels show superiority to traditional pearlitic rail [9,10].

Mechanical properties of high-strength steels with B/M microstructure are greatly affected by many factors, such as size, shape, distribution of different phase etc. [11]. Thus, bainitic steels exhibit different properties based on the microstructure obtained after various cooling process [12]. Several types of bainite can be obtained during continuous cooling process, such as granular bainite and lath bainite. Granular bainite formed at relative high temperature [13–17] consists of plates as well as martensite/austenite (M/A) constituents [14]. As a critical multiphase in granular bainite, the M/A constituents with various size and morphology have significant effect on mechanical properties [18]. Compared to the granular bainite, lath bainite is formed at lower temperature [19,20]. Also, mixed type of bainite can co-exist after continuous cooling process. During continuous air-cooling after hot rolling, 20Mn2SiCrMo bainitic rail steels have a microstructure consisting of bainite and martensite [6].

Air-cooling procedure results in mixed type of bainite (granular and lath bainite). It was observed in large-scale industrial production that short-time austempering treatment would significantly influence the final properties of air-cooled bainitic rail steel. However, the definite effect of austempering process parameters, especially the holding temperature on the microstructure and mechanical properties is still unclear. Therefore, this research is aimed at studying the effect of austempering temperature on the microstructure and properties of an industrial Mn–Si–Cr bainitic steel, especially focusing on the crystallographic characteristics of bainitic ferrite (BF) blocks in packets and the transformation process at different temperatures. Effective grain size, packet and block in microstructure were obtained by EBSD.

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2. Experimental procedures

The experimental bainitic rail steels had nominal chemical composition of 0.22C-2.0Mn-1.0Si-0.8Cr- 0.8(Mo+Ni) (wt%). The steel was obtained as an ingot of 50 kg, reheated at 1200 °C and forged to 30 mm × 80 mm × 500 mm with a finish-forging temperature of ~950 °C. Samples of dimensions with 15 mm × 30 mm × 70 mm were cut from the forged billets for isothermal simulation cooling processes. Considering production data, the heat treatment was designed as follows (Fig. 1). After austenitization at 880 °C for 45 min, the samples were air-cooled to 400 °C, 375 °C, 350 °C, 325 °C and then isothermally held at the selected temperature for 15 min, respectively. After isothermal treatment, specimens were cooled at a very slow cooling rate of 0.05 °C/s to room temperature inside the furnace (without vacuum). Another sample was cooled in air to room temperature directly after austenitization for comparison. Subsequently, all the samples were tempered at 250 °C for 4 h. Standard tensile samples with a gage diameter of 5 mm and a gage length of 25 mm were prepared for tensile tests using a SUNS 5305 tensile testing machine (MTS Systems, China). Two samples were tested for each process and the average tensile values were recorded. Impact tests were performed using standard Charpy U-notch specimens (10 mm × 10 mm × 55 mm, standard EN10045) using JB-30A impact tester device at 20 °C and −40 °C. Three specimens were used for each test.

Microstructures were characterized by scanning electron microscopy (SEM, ZEISS EVO18, 20 KV) after polishing and etching in 2% nital solution. Different types of retained austenite and sub-plates were characterized by transmission electron microscopy (TEM, FEI TECNAI G20, 200 KV). TEM observation was carried out on thin foils electro-polished by using a solution of 4% perchloric acid. The volume fraction of retained austenite (RA, vol%) was measured by X-ray diffractometer (Rigaku Smartlab, CuKa radiation) at a step width of 0.01 μm and a counting time of 2 s/step using Φ10 mm × 2 mm samples. The Rietveld analysis with MAUD software was used for calculation from diffraction data. The retained austenite fraction was calculated using a direct comparison method based on the integrated intensities of (200), (220) and (311) austenite peaks, and those of (200) and (211) of ferrite peaks.

Electron backscattered diffraction (EBSD) analysis was carried out using an X-Max^N of Oxford in Zeiss Evo-18 filament emission SEM at 20 kV, and it was performed at a tilt angle of 70° and step size of 0.15 μm to study crystallographic orientation and misorientation. Samples for EBSD analysis were first ground and mechanically polished, and then electropolished for stress relieving in an electrolyte of 5% perchloric acid and 95% ethanol at 30 V for 20 s. The data was post-processed with Channel 5 flamenco software provided by Oxford HKL Technology. The effective grain size was also calculated by the Grain Statistics module in HKL software and the misorientation was set as 15°.

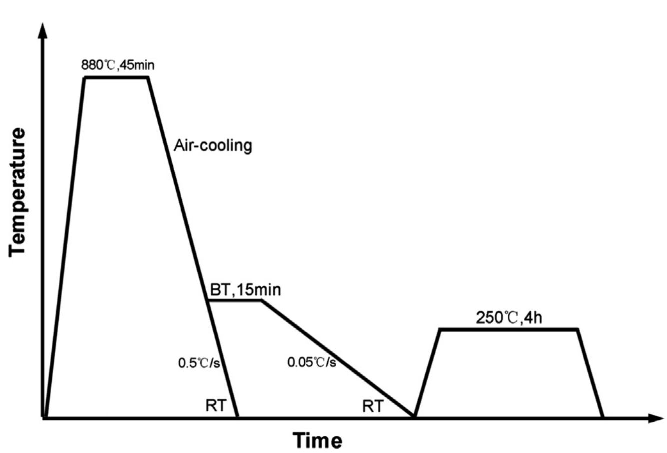

Fig. 1. Schematic illustration of the heat-treatment processes.

Dilatometric measurements were carried out using Φ4 mm × 10 mm cylinders on a Bähr D805L quenching device installed with quartz push-rods, to capture information on microstructural evolution during bainite transformation and tempering. Continuous cooling transformation curve (CCT) of bainitic steel was also measured using the same equipment. The temperature was monitored by a type-S thermocouple spot welded on the surface of the cylinders. Nitrogen was used as quenching medium. The microstructure evolution during isothermal temperature transformation and tempering is reflected by length change ΔL (also related to volume change ΔV, Eq. (1) [21]):

$$\frac{\Delta L}{L_0} = \frac{\Delta V}{3V_0} \tag{1}$$

where ΔL is the length change during tempering, L_0 is the initial length before tempering and V_0 is the initial volume.

3. Results and discussion

3.1. Mechanical properties

The mechanical properties of bainitic steels with different austempering temperature (AT) were presented in Fig. 2. Austempering had a significant influence on the mechanical properties. The tensile strength was between 1200–1400 MPa. Also, both the tensile and yield strength declined with AT increased (Fig. 2(a)). In contrast, elongation rose with AT going up on the whole. It was worth pointing out that the strength and elongation after austempering at 325 °C was closed to the air-cooled.

The impact properties were presented in Fig. 2(b). The room temperature impact toughness was significantly enhanced with decreasing AT. Peak value of room temperature impact toughness was 142 J, after austempering at 325 °C. Samples austempered at 400 °C had the lowest impact toughness at room temperature. Specimens austempered at 325 °C exhibited superior room impact toughness than the air-cooled. Low temperature impact toughness deteriorated with increasing AT. Interestingly, results showed that air-cooled samples had optimal low temperature impact properties, which was better than that of samples austempered at 325 °C.

3.2. Microstructure

According to the continuous cooling transformation (CCT) curve (Fig. 3), the B/M multiphase microstructure consisting of martensite, lath bainite and granular bainite could be obtained during continuous air cooling. As shown in CCT curve, changing cooling rates could yield different types of bainite (granular bainite, upper bainite and lower bainite), which were formed in different temperature region. Therefore, austempering temperature could influence the types of bainite existing in the final microstructure.

The SEM micrographs of samples austempered at different temperatures were shown in Fig. 4. The microstructure of air-cooled sample consisted of bainite (B), martensite (M) and retained austenite (Fig. 4(a)). The lath martensite showed typical tempering characteristic, and the bainite was also mostly lath bainite. Also, experiencing low temperature tempering, the bainite ferrite laths tended to merge, and at the same time, some unstable retained austenite decomposed.

Compared to the air-cooled, the microstructure of samples austempered at 325 °C indicated an apparent difference (Fig. 4(b)).