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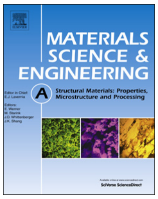

Low-temperature bainite in low-carbon steel

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ABSTRACT

The microstructures and the mechanical properties of 30MnSiCrAlNiMo low-carbon steel were systematically optimized by a series of heat-treatment processes, and the heat-treatment process of low-temperature bainite in low-carbon steel was explored. Results showed that the microstructure of low-temperature bainite in the low-carbon steel, containing a fine plate of carbide-free bainitic ferrite and a thin film of retained austenite, could be produced by continuous cooling transformation around the Ms temperature from $\mathrm{Ms}+10\ ^{\circ}\mathrm{C}$ to $\mathrm{Ms}-20\ ^{\circ}\mathrm{C}$ at a cooling rate of $0.5\ ^{\circ}\mathrm{C\ min^{-1}}$. A new model was proposed to evaluate the comprehensive mechanical properties of steel, which found that the low-temperature bainite had the best comprehensive mechanical properties compared to any other microstructures for the low-carbon steel. The higher dislocation density and finer bainitic ferrite plate in the low-temperature bainite resulted in the higher yield strength and the higher toughness, but relatively lower ultimate tensile strength owing to the lower work-hardening rate caused by the higher initial dislocation density. There were some very fine particles in the bainitic ferrite of the steel after isothermal treatment at higher temperature. The ultimate tensile strength and the low-temperature impact toughness of the steel decreased with the volume fraction of the retained austenite increasing, while the elongation initially increased with an increase in the volume fraction of the retained austenite ($<10\%$) and then remained constant.

1. Introduction

As bainite steels have both high strength and high toughness compared with austenite, pearlite and martensite steels, they have been widely manufactured and applied in many industrial fields, such as car, bearing, gear, railway systems (including rails and crossings) and so on [1–4]. Bainite rails and bainite crossings, being made of low carbon and low alloying steels, have received wide attention and recognition because of their good service performance. However, with the trend in the development of railways towards heavy load and high speed, there is an urgent need to further improve the comprehensive performance of bainite rails the bainite crossings to meet the requirements of railway development [5,6]. Therefore, the chemical composition design and the heat-treatment technology optimization of the low-carbon bainite steels used for railway systems offer great theoretical research and practical engineering significances.

Recently, in high-carbon steels a low-temperature bainite microstructure, which presents the best combination of strength, toughness and ductility, is composed of nano-bainitic ferrite lath and carbon-rich submicron-retained austenite [7–13]. Bhadeshia and co-workers first obtained and defined the low-temperature bainite under isothermal transformation at a low-temperature condition of $T=0.25$ Tm (Tm is the absolute melting temperature) for several days in some high-carbon high-silicon steels [7–11]. Zhang [12] incorporated the low-temperature bainite microstructure in a high-carbon Si–Al-rich steel by single-stage isothermal cooling heat treatment, which had a high hardness and high toughness. Hase [13] studied the low-temperature bainite through single-stage isothermal cooling and two-stage isothermal cooling and found that the bainitic ferrite plates after the two-stage isothermal cooling were much thinner than the single-stage isothermal cooling treatment, and their mechanical properties were also better. However, taking a wide view of the references related to this research area, the studies on low-temperature bainite mainly focused on the steels with high carbon concentrations, especially carbon concentrations varying from 0.7 to 1.0 wt%. A high carbon concentration reduces the maximum attainable volume fraction of bainitic ferrite, whereas low-carbon steels display too high Ms temperature, which increases the minimum transformation temperature for bainite formation, leading to coarser bainite microstructures and losing the characteristics of the low-temperature bainite [14]. So the low-temperature bainite in low-carbon steels has not yet been reported in the literature.

In fact, the heat treatment technology optimization of the bainite transformation for low-carbon steels is very effective and

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interesting. Gomez [15] found that a strong bainitic microstructure could be obtained by initial hot rolling followed by continuous cooling transformation from a high temperature. However, when continuous transformation was carried out from a medium temperature the microstructure was more complex [16]. The investigation of Soliman [17] showed that two-stage isothermal cooling could produce a better microstructure with outstanding mechanical properties than the single-stage isothermal transformation in a steel with 0.26 wt% C. We can predict that the low-temperature bainite in low-carbon steels exhibits excellent mechanical properties.

In order to explore the best mechanical properties and the low-temperature bainite microstructure of low-carbon steel, it is necessary that the chemical compositions and the heat-treatment processes of the steel are designed and optimized carefully. In this study we designed a new steel with 0.3 wt% C and other suitable alloying elements, such as Mn, Cr, Si and Al, and systematic heat treatment processes were carried out, including oil cooling, air cooling, single-stage isothermal cooling, two-stage isothermal cooling and continuous cooling transformation after austenization. The heat-treatment process that produced the low-temperature bainite microstructure in the low-carbon steel was explored.

2. Materials and experimental procedures

The chemical compositions of the steel used in this study were 0.30C–1.58Mn–1.44Si–1.13Cr–0.45Ni–0.48Al–0.40Mo–0.004S–0.005P (wt%). In the steel, Mn can depress the Ms temperature, and improve the stability of the austenite; Cr can reduce the bainite starting temperature and improve the strength of the bainite [18,19]. Si and Al both inhibit the precipitation of cementite, Si improves the stability of the retained austenite [10], and Al tends to increase the phase transformation driving force [11] and replace part of Si [20].

The Ms temperature of the steel was tested to be 335 °C on a Gleeble-3500 thermo-mechanical simulator. All samples were austenized at 930 °C for 45 min. To obtain different microstructures, five classes of heat treatment process were carried out after the austenization, *i.e.* oil cooling (OC), air cooling (AC), single-stage isothermal cooling (SIC), two-stage isothermal cooling (TIC) and continuous cooling (CC). For the SIC, samples were immediately transferred from the austenization temperature to a salt bath and kept at different temperatures (320, 330, 340, 350 and 360 °C) for 1 h, and then cooled down to room temperature (RT) in air. For the CC, samples were continuously cooled from Ms+10 °C to Ms−20 °C (345–315 °C) at the cooling rate of 0.5 °C min^{-1}. For the TIC, samples were kept at 345 °C for 20 min, then at 315 °C for 40 min in two molten salts and eventually cooled down to RT in air. Finally all samples were reheated to 320 °C and held for 1 h, then cooled down to RT in air. In this study the molten salt was composed of sodium nitrite and potassium nitrate (1:1 in weight).

The tensile testing was carried out with cylindrical samples at RT on an MTS material testing machine with a crosshead speed of 0.3 mm/min. The impact toughness was measured at +20 °C and −40 °C using a 300 J Charpy testing machine; the sample size was 10 mm × 10 mm × 55 mm. The hardness of the samples was tested by a TH501 Digital Rockwell Hardness Tester.

The samples for metallographic observation were mechanically ground, chemically polished and etched with 3% Nital; the microstructures were then examined using an optical microscope. Microstructures were examined using a TEM (Hitachi H-800) operating at 200 kV. Foils for the TEM were cut into 0.4 mm thicknesses, ground down to 30 μm by SiC abrasive paper, and then thinned to perforation on a TenuPol-5 twin-jet unit with an electrolyte consisting of 7% perchloric acid and 93% glacial acetic acid. X-ray experiments were conducted using a D/max-2500/PC X-ray diffractometer and a scanning rate of 2° min^{-1} over the range from 30° to 120° with unfiltered Cu*Ka*.

3. Results and analysis

Table 1 shows the mechanical properties of the 30MnSiCrAlNiMo steel after different heat treatments and the tensile engineering stress–strain curves for all of the samples are shown in Fig. 1. It can be seen that the samples treated by the AC and the OC exhibit lower ductility and toughness but higher strength and hardness than that treated by the SIC. For the samples treated by

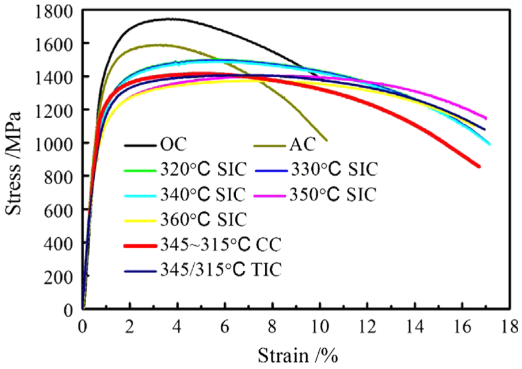

Fig. 1. Tensile stress–strain curves of the steel subjected to different heat treatment processes.

Table 1
Mechanical properties of samples subjected to different heat-treatment processes.

Treatment process	El (%)	RA (%)	YS (MPa)	UTS (MPa)	a_{KU} (+20 °C J/cm^2)	a_{KU} (−40 °C J/cm^2)	HRC
OC	10.1	50.1	1389	1743	89	–	48
AC	10.3	53.0	1274	1591	117	–	46
SIC							
320 °C	15.4	52.6	1071	1499	120	–	45
330 °C	17.2	56.9	1086	1493	130	–	45
340 °C	17.2	54.3	1073	1487	143	96	44
350 °C	17.0	53.8	1012	1405	134	95	43
360 °C	16.5	55.8	1057	1371	118	88	42
CC							
345 – 315 °C	16.8	57.1	1200	1416	155	99	45
TIC							
345/315 °C	16.9	58.3	1049	1405	154	90	44