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Multi-step isothermal bainitic transformation in medium-carbon steel

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The effect of multi-step low-temperature bainitic transformation on the microstructure and mechanical properties of a medium-carbon steel was investigated. Compared with the microstructure obtained by conventional bainitic transformation, the blocky microstructure was almost eliminated due to the formation of higher volumes of nanoscale bainitic–ferrite plates and film-like austenite, which lead to a refinement in the average thickness of the bainite plates. The samples with refined microstructure showed superior mechanical properties.

Keywords: Steels; Phase transformations; Microstructure; Mechanical properties; Multi-step super-bainite

Low-temperature bainitic steel has been extensively studied since it was first reported by Bhadeshia et al. [1–4]. The key to the excellent mechanical properties of bainitic steels are the nanoscale bainitic–ferrite plates and retained austenite [1]. The ultra-high strength of these steels is due to the presence of nanoscale bainitic microstructure and very high dislocation density, whereas their good ductility is attributed to the film-like austenite that exists between bainitic–ferrite plates [2,4]. In order to ensure thin bainitic–ferrite and film-like austenite, it is necessary to carry out the bainitic transformation at low temperatures [1]. On the other hand, lowering the B_s and M_s temperatures requires having a high carbon content, at the expense of lower toughness [5].

There are two essential morphologies of austenite in silicon-rich bainitic steels. There are films of austenite between the individual platelets (subunits) of bainitic–ferrite, and the coarser, more equiaxed blocks of austenite between non-parallel sheaves of bainite [6,7]. Because the blocks of austenite have a relatively lower stability in low- and medium-carbon steels, they may transform to martensite during the subsequent cooling to ambient temperature [8]. These blocky martensite/austenite (M/A) islands are hard, brittle and can deteriorate the toughness of the steel [9]. The coarse retained austenite islands are still unstable at low temperatures and do not contribute significantly to the toughness and ductility. This mostly because they are easily transformable to martensite under an externally applied load [10,11]. Therefore, it is desirable to reduce, or ideally eliminate, the blocky austenite in order to guarantee dimensional stability as well as high strength in various steels, e.g. bearing and tool steels. In the present work, a new multi-step low-temperature super-bainite transformation was developed to improve the mechanical properties of bainitic steels by refining the microstructure.

The steel used in this work was a 24 mm thick hot-rolled plate with a chemical composition of Fe–0.30C–1.46Si–1.97Mn–1.50Ni–0.30Cr–0.96Cu–0.25Mo wt.%. The heat treatment cycle used in this work is shown in Figure 1. In the multi-step low-temperature bainitic transformation, the first step is essentially a conventional bainite transformation to obtain a partially transformed bainitic microstructure. The following steps were carried out immediately after the first step in order to transform the retained austenite to nanostructured bainite. It should be noted that the subsequent stages are carried out at temperatures that are lower than the M_s of bulk alloy but higher than the M_s of partially untransformed austenite. Such low-temperature transformations can lead to much finer microstructures, e.g. resembling those seen in super-bainitic steels.

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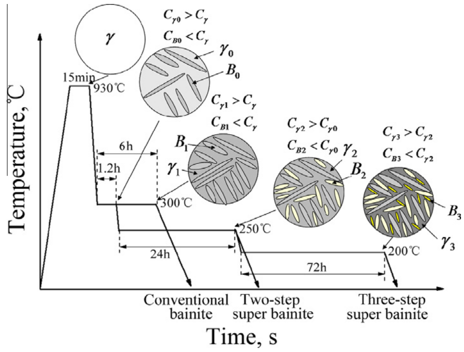

Figure 1. Heat treatment cycles and resultant microstructures during a multi-step low-temperature super-bainite transformation.

After austenitization at 930 °C for 15 min, sample 1 was isothermally transformed at 300 °C for 6 h. This was a one-stage thermal cycle, to produce conventional bainitic structure (i.e. conventional sample). Sample 2 was isothermally transformed at 300 °C for 1.2 h (designed for partial bainite transformation), then was immediately moved to another furnace where it was kept at 250 °C for 24 h (a two-step process, designed for super-bainite transformation). The first and second thermal cycles of sample 3 were identical to those of sample 2 but this sample had a third stage where it was kept at 200 °C for 72 h (a three-step process, designed for further super-bainite transformation). All isothermal cycles were carried out in salt bath furnaces and all samples were cooled down in air to room temperature.

The designed parameters of the above heat treatments were obtained by dilatometric experiments, which were conducted on a Gleeble 3500 thermal simulator using 6 mm diameter and 70 mm long cylindrical specimens.

Heat-treated samples were ground and polished using standard techniques and etched in 4 vol.% nital solution. Optical microscopy (OM, Olympus BM51) and scanning electron microscopy (SEM, Sirion 200) were used to examine the etched microstructures. Quantitative X-ray analysis was used to determine the volume fraction of retained austenite. For X-ray diffraction (XRD), the samples were scanned in an Xpert Pro MPD diffractometer, operating at 40 kV voltage, 45 mA current, using Cu K_α radiation. The 2θ scan angles ranged from 10° to 100° with a step size of 0.03342°. The retained austenite content was calculated using integrated intensities of the (2 0 0), (2 2 0) and (3 1 1) austenite peaks and the (0 0 2), (1 1 2) and (0 2 2) peaks of ferrite [12,13].

SEM and OM micrographs were used to determine the distribution, size (width), morphology and volume fraction of each phase. The true thickness t of lath-like phases was determined using the mean linear intercept $L = \pi t/2$ method [4] in a direction normal to the plates.

Vickers hardness values reported in this work are the average of at least 10 tests. The tensile specimens were made according to the GB/T 228-2002 standards and tested at room temperature. The impact toughness was measured using standard V-notched Charpy specimens at room temperature in accordance with GB/T 229-2007 standards and all reported values are the average of three measurements.

Figure 2 shows scanning electron micrographs of the three samples which were made and examined in this work. All samples contain some bainite sheaves (light area) and dark areas which are blocky martensite/austenite (Fig. 2a–c). The bainite sheaves consist of bainitic–ferrite plates and austenite films, which were very long and thin (Fig. 2d). The most evident difference among these three samples is the volume fraction and size of the martensite/austenite blocks. It is clear that volume fraction of M/A has been drastically reduced and the overall structure refined after the two-step or three-step bainitic transformations developed in this work. In Figure 2e and f, B_1 (∼150 nm thick) is conventional bainite obtained in the first step of the isothermal process. B_2 (∼80 nm thick) and B_3 (∼60 nm thick) are super-bainite obtained in the second and third steps of the isothermal process. It is obvious that the bainitic–ferrite plates and austenite films obtained in the second and third steps of the isothermal process are much thinner than that obtained in the first step.

The measured average size of blocky M/A and the thickness of bainitic–ferrite are given in Table 1. After the conventional bainite transformation at 300 °C for 6 h (sample 1), the average size of blocky M/A and thickness of bainitic–ferrite were 2200 and 150 nm, respectively. For the two-step bainite transformation (sample 2) and three-step bainite transformation (sample 3), these were reduced to 900, 120 nm, and 700, 110 nm, respectively. It is clear that the average size of blocky M/A was remarkably reduced. This is consistent with the microstructural observation of each sample, as shown in Figure 2a–c. The volume fraction of all observed phases in each sample is also given in Table 1. The quantitative measurements showed that although the total volume fraction of retained austenite was reduced, more of film-like austenite was generated (an increase from 0.12 to 0.15%). The volume fractions of film-like and blocky austenite could be estimated from the total volume fraction of retained austenite by X-ray analysis [14] and cross-checked using following equation. $V_{\gamma f}/V_{\gamma b} = (0.15V_{BF})/(V_\gamma - 0.15V_{BF})$, where $V_{\gamma f}$ and $V_{\gamma b}$ are the volume fraction of film-like and blocky austenite, respectively, and V_{BF} is that of the bainitic–ferrite.

Figure 3a shows the effect of the proposed multi-step transformation on the hardness and Charpy impact toughness of the three samples. The hardness was slightly increased in the lower-temperature multi-step transformations. The variations in the hardness were lower in the two-step and three-step samples, possibly

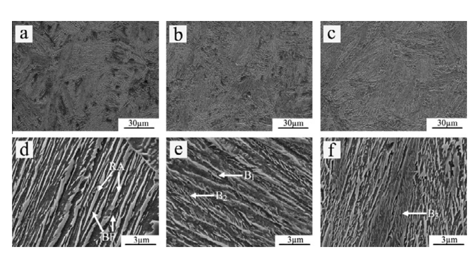

Figure 2. SEM micrographs (low and high magnifications) showing microstructure of various samples after (a, d) conventional bainite transformation, (b, e) two-step bainite transformation and (c, f) three-step bainite transformation.