



Letter

Producing superfine low-carbon bainitic structure through a new combined thermo-mechanical process



A B S T R A C T

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Recently, many steel researchers have been attempting to develop superfine low-carbon bainitic microstructure; however, the results are not satisfactory. In this paper, we applied a new thermo-mechanical process for achieving low-carbon superfine bainitic structure. By applying the new process, i.e. ausforming at temperatures above M_s followed by austempering at 355 °C, which is below M_s , we successfully obtained a superfine, ladder-like bainitic structure, with bainitic laths as thin as ~100 nm and Vickers hardness as high as ~500 HV, being of the same level of medium-carbon bainitic steels. This new process shows a potential for wide industrial applications.

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1. Introduction

Low-temperature bainitic steels, composed of nanoscale laths of bainitic ferrite and films of carbon-enriched retained austenite, have attracted much attention for their outstanding mechanical properties [1–3]. These ultrafine bainitic structures are obtained by bainitic transformation at lower isothermal temperatures above but close to the martensite start temperature (M_s). Thus, medium/high carbon steels are most suitable for producing such ultrafine bainitic structures, since a higher-carbon content tends to decrease M_s , favoring low-temperature bainitic transformation [2,3]. However, medium/high carbon steels show poor weldability and low toughness, and take too long time for bainitic transformation [3–6]. Accordingly, producing low-carbon bainitic steels with similarly ultrafine bainitic structure is much desirable for practical applications. However, it is not possible to obtain low-temperature bainitic structure in low-carbon steels via the conventional above- M_s isothermal transformation because of their high M_s . Recently, Yang and Bhadeshia [6] investigated the possibility of producing low-carbon low-temperature bainitic structure, by increasing the amount of alloying elements instead of carbon to decrease M_s , but the bainitic laths they obtained are coarsened. Long et al. [7] tried to obtain low-carbon low-temperature bainitic steels, by a slow cooling process in the bainite region; however, the process is so complicated. More recently, Zhao et al. [8] achieved a refined bainitic structure in low-carbon steels, via a simple process of austempering below M_s rather than above M_s ; however, the bainitic laths obtained are still not as fine as desired.

In the present study, a new process, i.e. ausforming above M_s followed by austempering below M_s , is applied, aiming to obtain a much refined bainitic structure in a low-carbon Si-rich steel. Ausforming is a thermo-mechanical process for structural refinement,

in which steel is plastically deformed in the austenite temperature range. Although ausforming is usually employed prior to quenching and tempering for improving martensite properties, recently this practice was also found to be effective in refining bainitic structure in medium/high-carbon steels, when applied prior to isothermal bainitic transformation (i.e. above- M_s austempering) [9–11]. In this work, ausforming is performed on supercooled austenite of a low-carbon Si-rich steel at various temperatures, and it is followed by austempering at a temperature below M_s .

2. Experimental procedures

The chemical composition of the steel is Fe-0.15C-1.41Si-1.88Mn-1.88Cr-0.36Ni-0.34Mo (wt%). The steel was melt in a 25-kg vacuum induction furnace. The ingot was hot-forged into square bars. The martensite start temperature, M_s , was measured to be 384 °C based on the tangent method [12], with the dilatometric experiment on a Gleeble-3500 thermo-mechanical simulator. Thermo-mechanical tests were performed also on the Gleeble-3500 thermo-mechanical simulator. The sample size for thermo-mechanical tests was 6 mm × 12 mm in the heating/deformation section. In the thermo-mechanical tests, samples were heated to 960 °C, held for 20 min, and then cooled down to a pre-determined ausforming temperature; then, the samples were compressively deformed at a reduction of 50% before cooling to the austempering temperature of 355 °C (which is below M_s); and finally, isothermal transformation was performed at 355 °C for 20 min prior to cooling to room temperature. The ausforming temperature chosen ranges from 780 to 400 °C for examining the effect of deformation temperature. Additionally, a process of austempering below M_s without prior ausforming was also performed for comparison.

Microstructures on the longitudinal sections of samples were examined by scanning electron microscopy (SEM) and transmission electron microscopy (TEM). The volume fraction of retained austenite (V_γ) was measured by the x-ray diffraction (XRD) method, using the integrated intensities of the (2 0 0), (2 2 0) and (3 1 1) austenite peaks and the (2 0 0), (2 1 1) and (2 2 0) ferrite peaks [13]. The Vickers hardness was measured on an FM-ARS 9000 Hardometer using a load of 1 kgf and a loading time of 10 s.

3. Results and discussion

Three typical dilation–temperature curves, one for below- M_s austempering without prior ausforming and the other two for below- M_s austempering with prior ausforming at 600 °C and 400 °C, are shown in Fig. 1a. The corresponding M_s temperatures for ausformed samples were determined using the tangent method [12]. Clearly, M_s decreases with ausforming; and with decreasing the ausforming temperature from 780 to 400 °C, the M_s decreases from 381 to 366 °C. This result is attributed to the increased strength of the austenite subjected to ausforming, which in turn increases the shear resistance of austenite-to-martensite transformation [14]. Moreover, decreasing the ausforming temperature further increases the strength of the supercooled austenite and hence the resistance of martensitic transformation, thereby further lowering M_s .

Fig. 1b–d shows the resultant SEM microstructures of the samples without prior ausforming and ausformed at 600 °C and 400 °C, respectively, corresponding to the three processes exhibited in Fig. 1a. Clearly, the bainitic ferrite in the two ausformed samples is much finer than in the non-ausformed sample. Additionally, there exist many coarse blocks of retained austenite (RA) in the non-ausformed sample, whereas both the amount and size of blocky RA in the two ausformed samples are much reduced.

Fig. 2 shows typical TEM micrographs of the samples without prior ausforming and ausformed at 600 °C and 400 °C. These micrographs demonstrate that all the microstructures are mainly composed of fine laths of bainitic ferrite and thin films of retained

austenite. However, in the ausformed-samples, there are a large number of dark bands (as indicated by arrows in Fig. 2b). And, the fine bainitic laths appear fragmented in the presence of dark bands, especially in the sample ausformed at the lowest ausforming temperature of 400 °C (Fig. 2c). Such a bainitic structure takes a ladder-like morphology. One may argue that such a ladder-like morphology may be due to microstructure breakage caused by ausforming. However, at a higher magnification (Fig. 2d), it is observed that these dark bands, traversing the bainitic laths, are composed of high-density dislocations. It suggests that these bainitic laths are not really fragmented, being still long and arranged in a roughly parallel manner (as in the non-ausformed sample). The formation of this ladder-like bainitic structure can be understood as follows. As schematically illustrated in Fig. 3, the initial equiaxial austenite grains with few crystal defects are evolved, after ausforming, into pancake-like supercooled austenite grains with plenty of dislocations in the form of deformation bands [15]. During the subsequent fast cooling to the austempering temperature, the deformation structure can be partly reserved, due to limited time for dynamic recovery. Since the high density of dislocations in the parent-phase austenite can be inherited by the product-phase bainite [16,17], these deformation bands are maintained, at least partially, after bainitic transformation at the austempering temperature. This may be the major reason for the formation of a ladder-like bainitic structure, with dark dislocation bands traversing bainitic laths.

It is further observed from Fig. 2 that the laths of bainitic ferrite are much thinner in the ausformed than in the non-ausformed samples, which is consistent with the observations by SEM (Fig. 1b–d). The true thickness, t_B , of bainitic laths was evaluated using $t_B = 2L_T/\pi$, where L_T is the mean linear intercept length measured in the direction normal to the laths [2,8]. The results are given in Fig. 4. Clearly, the average thickness of bainitic laths in the sample ausformed at 780 °C, ~175 nm, is reduced as compared with that in the non-ausformed sample, ~200 nm. Furthermore, with decreasing the ausforming temperature from 780 to 400 °C, the average lath thickness is reduced from ~175 to

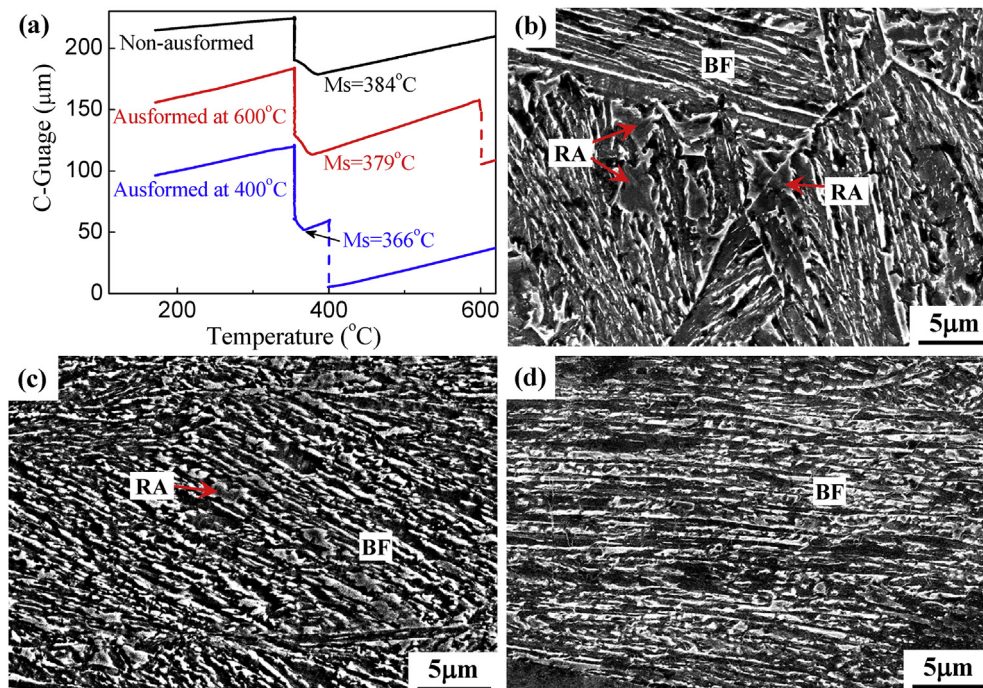


Fig. 1. (a) Dilation–temperature curves of the samples austempered without prior ausforming and after ausforming at 600 °C and 400 °C. SEM micrographs of the samples: (b) austempered without prior ausforming and austempered after ausforming at (c) 600 °C and (d) 400 °C. RA and BF indicate retained austenite and bainitic ferrite, respectively.

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