Materials Science & Engineering A 661 (2016) 1–8

Contents lists available at ScienceDirect

Materials Science & Engineering A

journal homepage: www.elsevier.com/locate/msea

On structure-property relationship in nanostructured bainitic steel subjected to the quenching and partitioning process

Ping Luo [a], Guhui Gao [a,*], Han Zhang [b], Zhunli Tan [a], R.DK. Misra [c], Bingzhe Bai [a,d]

[a] Material Science & Engineering Research Center, School of Mechanical, Electronic and Control Engineering, Beijing Jiaotong University, Beijing 100044, China
[b] Max-Planck-Institut für Eisenforschung, Max-Planck-Str. 1, 40237 Düsseldorf, Germany
[c] Laboratory for Excellence in Advanced Steel Research, Department of Metallurgical, Materials and Biomedical Engineering, University of Texas at El Paso, TX 79968-0520, USA
[d] Tsinghua University, Key Laboratory of Advanced Material, School of Material Science and Engineering, Beijing 100084, China

ARTICLE INFO

Article history:
Received 23 October 2015
Received in revised form
28 January 2016
Accepted 2 March 2016
Available online 4 March 2016

Keywords:
Bainitic steel
Q&P process
Retained austenite
Mechanical property

ABSTRACT

We elucidate here the mechanistic contribution of the application of quenching and partitioning (Q&P) concept to a high carbon Mn-Si-Cr steel in obtaining a multiphase microstructure comprising of martensite/austenite and nanostructured bainite (bainitic ferrite and nanometer-sized film-like retained austenite) that exhibited tensile strength of 1923 MPa and total elongation of 18.3%. The excellent mechanical properties are attributed to the enhanced refinement of blocky austenite islands obtained by the Q&P process. The austenite was stabilized by both carbon partitioning from martensite and bainite transformation. Compared with conventional heat treatment to produce nanostructured bainite, the total time is significantly reduced without degradation of mechanical properties.

1. Introduction

The advanced high strength steels (AHSSs) with high ductility have been extensively studied with the aim of saving energy and raw materials and conserving the environment by decreasing the weight of steel components [1–4]. In this context, fine and dispersed retained austenite (RA) plays a significant role in balancing strength and ductility, which is attributed to transformation-induced plasticity (TRIP) effect [5–9].

A number of studies on microstructure-mechanical property relationship indicated that a major factor that influences the mechanical properties of steel is the stability of the retained austenite. Moreover, the stability of retained austenite is influenced by (i) the local carbon content in austenite [10,11], (ii) the constraining effect of phases surrounding the austenite [12,13], (iii) the grain volume of austenite [14], and (iv) the morphology [15,16]. Recently, some studies suggested that the size and morphology of RA are dominant factors in the stability of austenite because the carbon-content in the center of the blocky austenite was relatively low, and the larger blocky austenite easily transformed to martensite at small strains [17–19]. Consequently, a number of studies were carried out to tailor the morphology and size of the austenite by changing process parameters [15–19].

Quenching and partitioning (Q&P) process is viewed as an effective heat treatment to obtain microstructure with adequate amount of retained austenite [6,9,20]. Q&P heat treatment involves the following steps: (i) an initial quenching step to a temperature (Tq) between martensite-start temperature (Ms) and martensite-finish temperature (Mf) to form a certain fraction of carbon saturated martensite; (ii) a partitioning step at Tq or higher than Tq to allow carbon to diffuse from martensite to austenite to enhance the stability of austenite. Consequently, a microstructure consisting of carbon-depleted martensite and carbon-stabilized austenite is obtained.

Some studies also focused on refining austenite through alloy design and tailoring the process parameters (such as quenching temperature and partitioning temperature). However, the Q&P process was mainly used to enhance the mechanical properties of low and medium carbon steels, and the application of Q&P process to high carbon steels is rare [21–25].

In the present study, the Q&P concept was successfully applied to a high carbon Mn-Si-Cr steel (0.66C-2.2Mn-1.7Si-0.5Cr) in obtaining a multiphase microstructure comprising of martensite/austenite and nanostructured bainite (bainitic ferrite and nanometer-sized film-like retained austenite). The primary aspect of the process is that an appreciable fraction of nanostructured bainite was obtained during the partitioning step. The martensite

* Correspondence to: Material Science & Engineering Research Center, School of Mechanical, Electronic and Control Engineering, Beijing Jiaotong University, Beijing 100084, China.
E-mail address: gaogh@bjtu.edu.cn (G. Gao).

http://dx.doi.org/10.1016/j.msea.2016.03.006
0921-5093/

plates not only divided the untransformed austenite but also accelerated the bainitic transformation. More importantly, the austenite was refined by the application of Q&P process. We elucidate here the mechanism of stabilization of austenite and the relationship between microstructure and mechanical properties. To compare and contrast, conventional quenching-tempering and bainite austempering processes were also simultaneously studied.

2. Experimental procedure

The nominal chemical composition of the experimental steel was Fe-0.66C−2.2Mn-1.7Si-0.5Cr (in wt%). Si was added to suppress the precipitation of carbides during quenching and isothermal heat treatment. The alloy studied was in the form of forged plate. The forging process was carried out as follows: An ingot of 50 kg was reheated to 1200 °C and forged to 30mm thickness and the finishing-forging temperature was ~950 °C. The forged bars were subjected to homogenization at 1200 °C for 12 h. After homogenization, the bars were annealed at 900 °C for 2 h, followed by furnace cooling. The microstructure of the samples after the annealing treatment consisted of ferrite and pearlite (i.e. prior to all the following experiments), as shown in Fig. 1. The annealing is employed before heat treatment in order to eliminate the microstructure heredity and obtain relatively refined microstructure [26].

The dilatometry experiments were carried out to capture the transformation temperature and microstructural evolution using a dilatometer (Bähr D805 L) equipped with quartz push-rods. The steel samples were machined to cylindrical specimens of dimension 4 mm diameter and 10 mm height. To control the temperature, thermocouples of type S were welded to the surface of the specimens in the center.

Four different heat treatments were carried out with the specimens (15 mm × 30 mm × 70 mm in size), as shown in Fig. 2. The conventional Q&T process was as follows: cooling to ambient temperature (30 °C) at a cooling rate of about 1–2 °C /s after austenization at 880 °C for 45 min and then tempered at 250 °C for 12 h (Fig. 2a). The BAT-12 samples correspond to an isothermal bainite transformation process: after austenitization at 880 °C for 45 min, the samples were cooled to 250 °C (above the Ms temperature), and then austempered for 12 h (Fig. 2b). Compared to the BAT-12 sample, the austempering time of BAT-24 samples was extended to 24 h (Fig. 2c). The QPB process consisted of cooling to 130 °C (below Ms temperature) after austenitization, followed by an isothermal heat treatment at 250 °C for 12 h.

Microstructural characterization was carried out using a

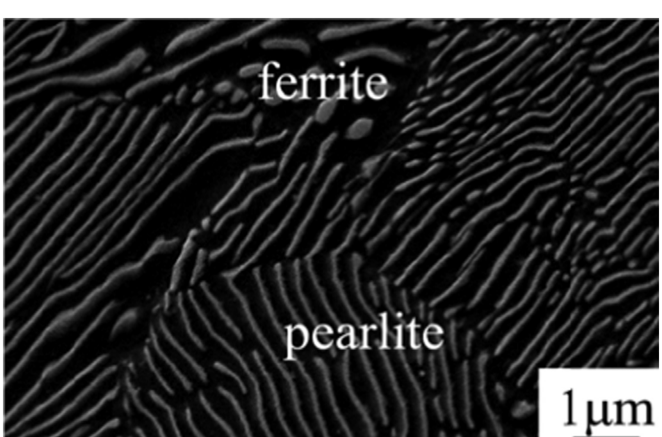

Fig. 1. The microstructure of the experimental steel after the annealing treatment.

combination of scanning electron microscopy (SEM; Zeiss EVO18, 20 kV) and transmission electron microscope (JEOL 2010, 200 kV). The samples for SEM were polished and etched with 2% nital solution. TEM studies were carried out using thin foils electropolished at −40 °C using 4% perchloric acid solution. The microstructure is analyzed through image processing software (Photoshop 7.0).

The volume fraction of retained austenite (RA) was measured by X-ray diffraction (XRD; Rigaku Smartlab, Cu Kα radiation) at a step of 0.02° and a counting time of 2 s per step. Rietveld analysis with MAUD software was used to calculate the diffraction data. The volume fraction of retained austenite was calculated after collecting the peak intensities of (200)γ, (220)γ, (311)γ, (210)α and (211)α. Since the carbon concentration plays an important role in governing mechanical and thermal stability of retained austenite, the carbon content in retained austenite was calculated using the following equation [27]:

$$x_c = \frac{\frac{\lambda_{k\alpha}}{2\sin\theta} \times \sqrt{8} - 3.572 - 0.0012x_{Mn} + 0.00157x_{Si} - 0.0056x_{Al}}{0.033} \quad (1)$$

where θ and $\lambda_{\kappa\alpha}$ stand for the angle of the (220)γ plane and the wavelength of X-ray Cu target with a value of 0.15406 nm; x_c, x_{Mn}, x_{Si}, x_{Al} are the chemical composition in retained austenite (in wt%).

Standard tensile samples with a gage diameter of 5 mm and gage length of 25 mm were used to determine the mechanical properties of the steels after each heat treatment using a SUNS 5305 tensile tester (MTS System, China). Three samples were tested for each condition and the average values obtained. An extensometer and a force sensor were used. The work hardening behavior was studied by applying the following classical Hollomon equation:

$$\sigma_t = K{\varepsilon_t}^{n_i} \quad (2)$$

where σ_t and ε_t are the true stress and true stain, respectively; K is the strength coefficient, and n_i is the instantaneous work hardening exponent. The instantaneous work hardening exponent, n_i, deduced from Eq. (2) is:

$$n_i = \left(\frac{\varepsilon_t}{\sigma_t}\right)\left(\frac{d\sigma_t}{d\varepsilon_t}\right) \quad (3)$$

3. Results

3.1. Microstructure

The microstructures of steels after each heat treatment are presented in Figs. 3 and 4. The microstructure of Q&T samples comprised of martensite, austenite, and a very small amount of nanostructured bainite (bainitic ferrite plus RA) (Fig. 3a). The bainitic ferrite (marked in Fig. 3a) was formed during tempering [28]. The BAT-12 microstructure consisted of thin bainitic ferrite and austenite which included film-like austenite and blocky austenite (not M/A island, analyzed in Section 4.1) (Fig. 3b). The size of film-like austenite was around 20–100 nm (shown by TEM image, Fig.4a), while that of blocky austenite was around 1–2 μm. It is suggested from Fig. 3b and c that there were insignificant differences in the microstructure of BAT-12 and BAT-24 samples, and is discussed below. The microstructure of QPB samples (Fig. 3d) comprised of martensite and nanostructured bainite and RA. The nanostructured bainite (bainitic ferrite plus RA) was produced during partitioning step (shown by TEM images in Fig. 4b). From the SEM micrographs, we can identify some blocky austenite in the BAT samples, while the blocky austenite was reduced and even eliminated in QPB samples, consistent with the previous work