



Structure-property relation in a quenched-partitioned low alloy steel involving bainite transformation

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ABSTRACT

The impact of bainite transformation during initial quenching and partitioning steps on the microstructural evolution was studied in a Fe-0.4C-2.0Mn-1.7Si-0.4Cr (wt%) steel. By optimizing quenching cooling rate and partitioning time, the final microstructure comprised of initial-quenched bainite, carbon-depleted martensite, bainite formed during partitioning, and final-quenched martensite, together with retained austenite. High volume fraction of retained austenite with desired carbon-content was obtained by prolonging the partitioning time to 2700 s. The initial-quenched bainite, bainite formed during partitioning, and martensite provided carbon atoms to austenite, leading to the formation of retained austenite with different degree of stability. Consequently, a good combination of strength and elongation (ultimate tensile strength: 1688 MPa, total elongation: 25.2%) was obtained.

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1. Introduction

There is currently a strong demand for high strength steels with good ductility to reduce the weight of steel components for automotive and railway applications. Advanced high strength steels (AHSS) with adequate toughness and formability, such as dual-phase (DP), transformation induced plasticity (TRIP) and multiphase steels are being developed to meet the demands of the automotive industry [1,2]. Quenching and partitioning (Q&P) process is one of the most promising methods to obtain a good combination of strength and ductility [3–6]. Generally, the Q&P process consists of two steps: the first step involves quenching the steel to a temperature (T_q) between martensite-start (M_s) temperature and martensite-finish (M_f) temperature after partial or completed austenitization such that carbon-supersaturated martensite and untransformed austenite are obtained. Subsequently, the steel is held at T_q or slightly above T_q to promote carbon diffusion from martensite to austenite and render retained austenite stable. Based on the Q&P theory, a modified quenching, partitioning and tempering (Q-P-T) processes was proposed to combine the TRIP effect with precipitation strengthening, which further improves the mechanical properties [7,8]. The earlier studies of

Q&P or Q-P-T process suggested that carbon-depleted martensite and retained austenite was obtained in the absence of bainite transformation during the partitioning process [1–8]. It was also suggested that the formation of bainite during the Q&P process was favorable for further improvement of strength, ductility and toughness through the introduction of additional carbon-enriched retained austenite with high stability [9–12].

The Q&P or Q-P-T process involving the formation of carbide-free bainite during quenching step (abbreviated as bainite-based Q&P, i.e., BQ&P or BQ-P-T process) can significantly improve the mechanical properties of steels [9,12]. The multi-phase microstructure of BQ&P steels comprised of bainite, martensite and retained austenite, resulting in high product of tensile strength and elongation (PSE) of ~ 42 GPa%. However, the effect of carbide-free bainite on microstructural evolution continues to be unclear and requires further studies.

Numerous studies have reported the presence of bainite transformation during Q&P treatment [10–14], but there still exists some uncertainty on the role of bainite transformation. One view point is that the bainite transformation has a competing effect with respect to carbon partitioning from martensite to austenite. Consequently, the carbon enrichment is delayed and the volume fraction of retained austenite is reduced [13,14]. On the other hand, the formation of carbide-free bainite plays the same role as in TRIP treatment, contributing to the stabilization of austenite through additional carbon diffusion during partitioning [9–12].

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Thus, it is important to understand bainite transformation and how it influences microstructure during the partitioning step in Q&P steels.

In this study, a Fe-0.4C-2.0Mn-1.7Si-0.4Cr steel was designed to obtain the best combination of mechanical properties via Q&P process involving bainite transformation. The objective is to explore the role of bainite transformation on microstructural evolution, especially the formation of retained austenite in the attempt to acquire a better understanding of the Q&P process.

2. Experimental procedure

The nominal chemical composition of experimental steel in wt% was Fe-0.4C-2.0Mn-1.7Si-0.4Cr. The composition was designed on the basis of Mn-containing bainitic steel [15,16]. Si was added to prevent the formation of carbides and promote the formation of carbide-free bainite during quenching and partitioning steps. A 50 kg ingot of the experimental steel was cast, reheated at 1200 °C and forged to 30 mm × 80 mm × 500 mm dimension with a finish-forging temperature of 950 °C. The forged plate was annealed after austenitization at 900 °C for 2 h. The microstructure of as-received steel consisted of ferrite and pearlite prior to subsequent dilatometry experiments.

The dilatometry tests were conducted using Bähr DIL805L quenching equipment with quartz push-rods, and cylindrical hollow samples of dimensions 4 mm × 10 mm. The temperature was monitored by a type-S thermocouple spot welded on the surface of the specimen. The quenching gas was nitrogen (N₂). The A_{c1}, A_{c3} and M_s temperatures were measured by dilatometer, and were 760 °C, 840 °C and 252 °C, respectively. The phase change during partitioning and tempering was studied using the relationship of change in length and volume (Eq. (1)) [17]:

$$\frac{\Delta L}{L_0} = \frac{\Delta V}{3V_0} \quad (1)$$

where ΔL is the change in length of samples during partitioning or tempering step, L_0 is the initial length of the samples at the beginning of quenching or partitioning.

A schematic of BQ (bainite-based quenching), BQ&P and bainite austempering (BAT) processes is presented in Fig. 1. According to our previous study, the bainite/martensite multiphase microstructure was obtained during the quenching step, when the cooling rate was between 0.25 °C/s to 30 °C/s [9,12]. Hence, in order to realize bainite formation during the initial quenching step in the study, the cooling rate during the BQ step was set as 1 °C/s. The BQ process consisted of austenitization at 900 °C for 5 min, followed by cooling at 1 °C/s to room temperature. The BQ&P process contained a cooling step at 1 °C/s to 200 °C (below M_s) after austenitization and a subsequent partitioning step at 360 °C.

The BAT samples had identical austenitization condition except for austempering at 360 °C. Both partitioning and austempering time was between 100 and 7200 s.

Specimens for metallographic examination were prepared by standard grinding and polishing technique and etched using 2% nital solution. Optical microscopy (OM, ZEISS, Scope A₁) and scanning electron microscope (SEM, ZEISS-EVO18) were carried out to study the microstructure. Fine-scale microstructure was characterized by transmission electron microscope (FEI TECNAI G20) operated at 200 kV. TEM observations were carried out on thin foils electro-polished using a solution of 4% perchloric acid. The volume fraction of retained austenite and austenite lattice parameter a_γ were measured by X-ray diffractometer (Rigaku Smartlab, Cu K α radiation) at a step width of 0.01° and a counting time of 2 s/step. The Rietveld analysis with MAUD software was employed for diffraction data analysis. The retained austenite fraction was estimated by measuring the peak intensity of (200) γ , (220) γ , (311) γ , (200) α and (211) α . The austenite lattice a_γ was calculated using Nelson-Riley extrapolation approach [18]. The carbon concentration, x_C , of retained austenite was estimated using Eq. (2) [19]:

$$a_\gamma = 0.3556 + 0.00453x_C + 0.000095x_{Mn} + 0.00056x_{Al} \quad (2)$$

where a_γ is the austenite lattice parameter (nm), x_C , x_{Mn} and x_{Al} are the concentration of carbon, manganese and aluminium in austenite (wt%), respectively.

The BQ&P treatments for salt bath experiments were selected on the basis of results obtained with the dilatometer. Samples of dimensions 15 mm × 15 mm × 70 mm were austenitized at 880 °C for 45 min, followed by cooling at 1 °C/s to 200 °C, and subsequent partitioning at 360 °C for different time. The BQ&T process was conducted in comparison: the sample was austenitized at 880 °C for 45 min, followed by cooling at 1 °C/s to room temperature, and subsequent tempering at 280 °C for 2 h. Standard tensile samples with a gage diameter of 5 mm and a gage length of 25 mm were used for tensile tests using SUNS 5305 tensile testing machine (MTS Systems, P.R. China, and standard GB/T228-2002). Three samples were tested for each process and average values were obtained.

3. Results and discussion

3.1. Microstructure prior to partitioning step

The phase volume fraction and morphology prior to the partitioning step has a significant influence on the final microstructure. In this regard, the fraction of bainite and martensite measured by dilatometer as a function of quenching temperature (T_q) is presented in Fig. 2. The dilatometric curves indicated that a fully

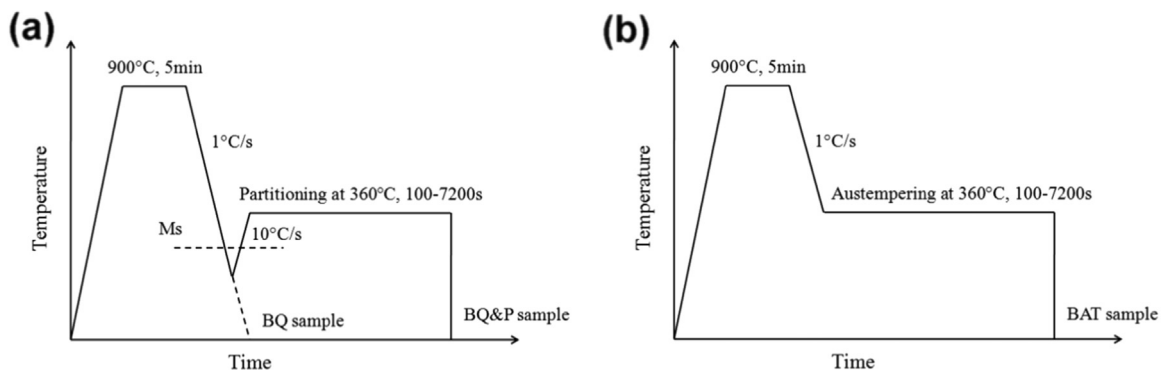


Fig. 1. Schematic of (a) BQ, BQ&P and (b) bainite austempering (BAT) processes for dilatometry experiment.

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