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Effect of partitioning procedure on microstructure and mechanical properties of a hot-rolled directly quenched and partitioned steel

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ABSTRACT

Hot-rolling direct quenching and partitioning (HDQP) processes distinguished by the dynamical partitioning procedures and the isothermal partitioning procedures were applied to a low-carbon steel to investigate the differences in the microstructure and the mechanical properties. Microstructures were characterized by means of EPMA, EBSD, TEM and XRD. Mechanical properties were measured by uniaxial tensile tests. Results show that the microstructures of the HDQP sheets are characterized by lath martensite and film-like inter-lath retained austenite. The dynamically partitioned sheets possess narrower martensite laths with higher dislocation densities, compared with the isothermally partitioned sheets. The martensite lath broadening, the dislocation density reduction and the carbide coarsening exist with decreased cooling rate or with prolonged partitioning time. The coarse carbides appearing in the sheet partitioned longer than 5 min promote the decomposition of austenite. X-ray diffraction (XRD) detection results of the specimens with different plastic strains indicate that the retained austenite with the carbon concentration below 1.5 wt% can perform a better transformation behavior with the plastic strain under 5%. The isothermal partitioning processes can improve the average concentration and homogeneity of carbon in the retained austenite but make up part of the retained austenite too stable. Mechanical property results show that the dynamically partitioned sheets possess higher strengths about 1500–1600 MPa and similar elongations about 14–16% with excellent products of strength and elongation (PSE) about 22,000–25,000 MPa%. It is concluded that a dynamical partitioning procedure is preferable for obtaining a HDQP steel with excellent mechanical properties.

1. Introduction

In recent years, the researchers have made unremitting effort to reduce the weights of steel parts in automobile industry for the requirement of energy saving and environment reasons [1]. Advanced high strength steels (AHSS) with adequate properties of strength and ductility met the requirements of both weight reduction and sufficient safety of car then developed rapidly [2]. Typical AHSS such as dual-phase (DP) steel, martensitic steel, complex phase (CP) steel and transformation induced plasticity (TRIP) steel have attracted much attention. The TRIP effect of retained austenite has been widely used to design steel with both high strength and high ductility [3]. The systematic studies on stabilization of austenite in bainitic microstructure [4–8] and the discovery of inter-lath retained austenite films in as quenched low-carbon martensite [9] have established the foundation of a novel steel heat treatment so called the quenching and partitioning (Q&P) process, which was proposed by Speer et al. to produce high-strength steels consisting of martensitic matrix and retained austenite [10,11].

A lot of research work has been carried out on Q&P steel. Most investigations to date focus on the hot-rolling off-line heat treatment or the heat treatment of cold-rolled sheet [12–15]. The feasibility of hot-rolling direct quenching and partitioning (HDQP) process was also mentioned by Speer et al. [16] but little work about it has been done, except for some valuable results obtained by Thomas et al. via Gleeble simulation [17]. It should be mentioned that a concept of dynamical partitioning process was reflected as non-isothermal partitioning in the study of Thomas et al. The HDQP process can save much energy by replacing the reheating process with making use of the residual deformed temperature to achieve the Q&P heat treatment. The unique deformed austenite condition may have a specific effect on the martensite transformation and the stability of the retained austenite after a Q&P treatment. Therefore, the HDQP process is well worth studying.

In this work, HDQP processes with different partitioning procedures were put into practice based on the thermo-mechanical control process (TMCP) technology and the ultra-fast cooling (UFC) technology. The effects of the partitioning procedure on the microstructure,

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the stability of the retained austenite and the mechanical properties of a HDQP steel were investigated meticulously.

2. Experimental material and procedure

The tested steel (as Table 1) was melted in a vacuum furnace and then forged into a billet with a section dimension of 60 mm × 60 mm. The critical temperatures were measured by dilatometer analyses, leading to A_{C1}=707 °C, A_{C3}=905 °C, M_s=388 °C and M_f=150 °C.

Two kinds of HDQP treatments with dynamical partitioning processes and isothermal partitioning processes are schematically shown in Fig. 1. The slabs with the same thickness of 60 mm were austenized at 1200 °C for 2 h then hot rolled to 4 mm through seven passes with the finish rolling temperatures of about 900 °C. Subsequently, two sheets were directly quenched to room temperature with different cooling rates (Nos. 1 and 2) and two sheets (Nos. 3 and4) were directly quenched to 270–280 °C (275 °C for No. 3 and 280 °C for No. 4) then cooled to room temperature by laminar cooling (No. 3) and air cooling (No. 4). The essential difference among these four processes is the cooling rate in the martensite transformation temperature interval (from the M_s to the M_f). Another four sheets (Nos. 5, 6, 7 and 8) were directly quenched to 270–290 °C (the actual values for No. 5, No. 6, No. 7 and No. 8 sheets are 290 °C, 285 °C, 278 °C and 284 °C, respectively) then isothermally partitioned in a resistance heating furnace at 390 °C for 1 min (No. 5), 2 min (No. 6), 5 min (No. 7) and 15 min (No. 8), and finally air cooled to room temperature. The essential difference among these four processes is the isothermal partitioning time.

The tensile test specimens with a width of 5 mm and a thickness of 4 mm and a gauge length of 25 mm were cut with their axis oriented parallel to the rolling direction. The tensile test was performed on a CMT5105-SANS machine at room temperature with a draw speed of 1 mm/min. Three specimens for each process were used and the average values were calculated.

The volume fraction and the average carbon concentration of retained austenite were measured at room temperature using a D/max2400 X-ray diffractometer (operated at 56 kV, 182 mA). Three specimens for each process were used and the as rolled surface of each specimen was detected then the average values were calculated. A Cu Kα radiation was used and a 2θ-range from 40° to 120° was step-scanned with a scanning speed of 2°/min. The specimens for X-ray diffraction (XRD) were finally electropolished with an electrolyte consisting of 650 ml alcohol, 100 ml perchloric acid and 50 ml distilled water at 31 V for 26 s at 20 °C to minimize the error for the possible strain induced martensite transformation during the grinding process.

Table 1
Chemical composition of the tested steel (wt%).

C	Si	Mn	Al	V	Cr	S	P
0.21	1.67	1.65	0.01	0.20	0.03	0.0015	0.0049

The (200), (220) and (311) austenite peaks and the (200) and (211) ferrite peaks were taken into consideration for the calculation of the amount of retained austenite according to [18]

$$V_\gamma = 1.4I_\gamma/(I_\alpha + 1.4I_\gamma) \quad (1)$$

where V_γ is the volume fraction of retained austenite, I_γ and I_α are the average integral intensities of the austenite peaks and the ferrite peaks.

The austenite carbon concentration was calculated by [19]

$$C_\gamma = (a_\gamma - 3.547)/0.046 \quad (2)$$

where C_γ is the carbon concentration in weight percent and a_γ is the lattice parameter of the austenite in Angstroms, which is estimated by Eq. (3) based on the (200) austenite peak.

$$a_\gamma = \frac{\lambda\sqrt{h^2+k^2+l^2}}{2\ \sin\ \theta} \quad (3)$$

where λ, ($h\ k\ l$), and θ are the wavelength of the radiation, the three Miller indices of a plane and the Bragg angle, respectively.

The volume fractions and the average carbon concentrations of the retained austenite of the specimens deformed with different plastic strains were also measured using the above method. But just one specimen for each plastic strain was used because it is really hard to get two specimens deformed with the same plastic strain.

The dislocation densities of the martensite were estimated by using the measurements of the line broadenings of the (110) and (220) peaks by a D/max2400 X-ray diffractometer with a Cu Kα radiation at 56 kV and 182 mA. Each peak profile was built from a single scan at a scanning speed of 0.2°/min in 2θ. Just one specimen for each process was used and the as rolled surface of each specimen was detected. The details of the method to estimate the dislocation density can be found in the published work [20].

Microstructure characterizations were carried out with a JXA-8530F electron probe microanalyzer (EPMA) and a Zeiss Ultra-55 field emission scanning electron microscope (SEM) equipped with an electron backscattered diffraction (EBSD) system. Selected specimens were evaluated by a transmission electron microscopy (TEM-TECNAI G220) at an accelerating voltage of 200 kV. For the microstructure observation in EPMA, specimens were ground and polished mechanically then etched by 4% nital for 15 s. The specimens were electropolished with an electrolyte consisting of 650 ml alcohol, 100 ml perchloric acid and 50 ml distilled water at 31 V for 26 s at 20 °C before the EBSD analyses with a step size of 20 nm. The specimens for TEM were firstly ground to a thickness of 40 μm then electro-polished at −20 °C in a two-jet machine.

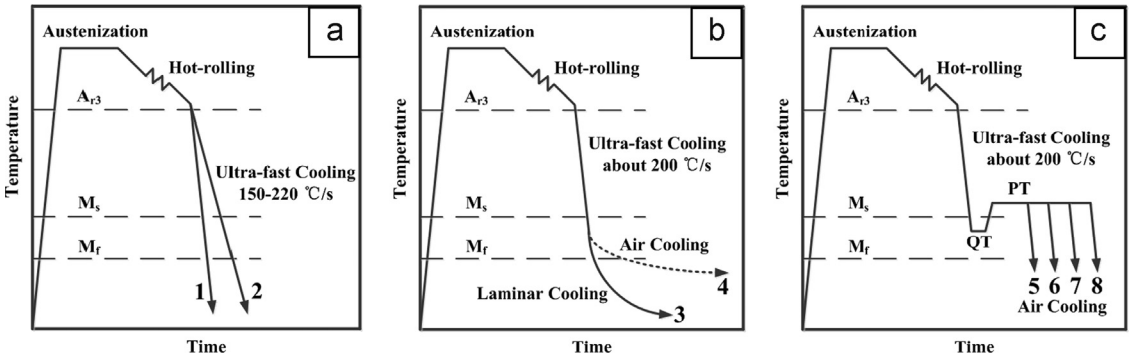

Fig. 1. Schematic thermal profiles of the HDQP processes: (a) and (b) the dynamical partitioning processes; (c) the isothermal partitioning processes.