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Microstructure and partitioning behavior characteristics in low carbon steels treated by hot-rolling direct quenching and dynamical partitioning processes

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ABSTRACT

In this work, a new process and composition design are proposed for "quenching and partitioning" or Q&P treatment. Three low carbon steels were treated by hot-rolling direct quenching and dynamical partitioning processes (DQ&P). The effects of proeutectoid ferrite and carbon concentration on microstructure evolution and mechanical properties were investigated. The present work obtained DQ&P prototype steels with good mechanical properties and established a new notion on compositions for Q&P processing. Microstructures were characterized by means of electro probe microanalyzer (EPMA), scanning electron microscopy (SEM), electron backscatter diffraction (EBSD), transmission electron microscopy (TEM) and X-ray diffraction (XRD), especially the morphology and size of retained austenite. Mechanical properties were measured by uniaxial tensile tests. The results indicated that introducing proeutectoid ferrite can increase the volume fraction of retained austenite and thus improve mechanical properties. TEM observation showed that retained austenite included the film-like inter-lath austenite and blocky austenite located in martensite/ferrite interfaces or surrounded by ferrites. It was interesting that when the carbon concentration is as low as ~0.078%, the film-like inter-lath untransformed austenite cannot be stabilized to room temperature and almost all of them transformed into twin martensite. The blocky retained austenite strengthened the interfaces and transformed into twin martensite during the tensile deformation process. The PSEs of specimens all exceeded 20 GPa.%.

1. Introduction

With the rapid development of automobile industry, the lightweight and safety of automobile steels are emphasized [1]. Hence, the advanced high strength steel (AHSS) has become a focus recently [2], because of its good combination of strength and ductility. Quenched and partitioned steel (Q&P) [3–5] proposed by Speer et al. in 2003 is a representative one of AHSS including the following sequences. Firstly, the steel is full or partly austenitized and then quenched to a pre-determined temperature (QT) in between the martensite-start temperature (Ms) and the martensite-finish temperature (Mf) to form a microstructure consisting of martensite, ferrite (if the steel was intercritically austenitized) and untransformed austenite. Then, the steel is either isothermally held at QT (which is called 1-step partitioning) or brought to a higher partitioning temperature (PT) (2-steps) allowing carbon to diffuse from the supersaturated martensite into the untransformed austenite. As a result of carbon enrichment during partitioning step, the Ms. of the untransformed austenite is lowered. In this way, the metastable austenite is retained in the steel after the final quenching to the room temperature. This cycle aims at producing microstructures consisting of carbon-depleted martensite and retained austenite which possess good comprehensive properties due to the high strength of martensite and the TRIP effect of retained austenite [6,7].

In traditional Q&P concept, the experimental materials with concentrations of C higher than 0.2 (wt.%) are considered to be appropriate for Q&P processing and in this way, much more retained austenite could be obtained. In fact, depending on the steel chemistry and the Q&P treatments parameters, there exist competing reactions during partitioning procedure, such as bainite [8,9] and carbides formation [10], even in low-carbon steels [8] and in high-carbon steels [11,12], even when containing a high amount of Si [13]. The competing reactions are disadvantageous to enrich retained austenite, and this proved that the amount of retained austenite did not only depend on carbon concentration and not all the carbon was used to stabilize austenite. Hence, the lower carbon steels may also be appropriate for Q&P processing and a desired amount of retained austenite may be obtained through the coupling effects of original microstructure and partitioning procedure.

Recently, most of the studies about Q&P steel focused on obtaining high strength steels by designing high carbon or high alloy composition, however, the elongation of the steels is always lower than 20%. The mismatch of strength and elongation leads to bad formability and some

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Table 1
Chemical compositions (wt.%) and critical temperature (°C) of the experimental steels.

Steel	C	Si	Mn	Ae3	Ms
A	0.19	1.60	1.60	846	398
B	0.12	1.55	1.55	868	429
C	0.078	1.55	1.61	887	447

problems in application. Generally, low carbon Si-Mn steel without other alloying elements was difficult to obtain high PSE (product of strength and elongation). However, some recent investigations noted that Q&P steels with proeutectoid ferrite possessed low yield strength and good elongation which lead to improvement of comprehensive mechanical properties, but the effects of proeutectoid ferrite are not clear yet, especially in low carbon steel. Furthermore, the traditional Q&P treatment mainly focused on the hot-rolling off-line Q&P treatment and the Q&P treatment of cold-rolled sheet, resulting in high energy consumption and complex heat treatment processes. In recent years, the directly quenching and partitioning (DQ&P) [14] process has attracted many researchers' attentions. Compared with traditional Q&P treatment, DQ&P has the following advantages [14,15]: 1) The directly quenching after deformation can make the best of the residual heat for partitioning, which is more simplified and energy-efficient. 2) The combination of DQ&P process and thermo mechanical control process (TMCP) is favorable to obtaining the desired microstructure and good mechanical properties. 3) High density dislocation and fine grains can improve the mechanical properties, such as work hardening capacity, strength and elongation. 4) It can save alloy elements. Moreover, the present research mainly focuses on isothermal partitioning procedure. For matching to the thermal process characteristics of hot strip mill processing, where there is no capability for either reheating or isothermal partitioning, the investigation of dynamical partitioning process proposed by Thomas [12] is of importance. The dynamical partitioning process is considered to be a good way for carbon diffusion. And it means that the quenching temperature is equal to coiling temperature and serves as initial partitioning temperature.

In this work, in order to study the effect of the dynamical partitioning process in low carbon steels on the microstructure evolution, three low carbon steels were treated by DQ&P process. In addition, the influence of the proeutectoid ferrite on different features of the retained austenite and their impacts on the mechanical properties were also investigated.

2. Experimental Procedure and Materials

The chemical compositions of the steels used in this study are listed in Table 1. Steels were melt in a vacuum induction furnace and then forged into a billet with the section dimension of 60 mm × 40 mm. The critical temperature of Ae_3 was calculated by Thermo-calc 5.0 and Ms. was calculated by empirical formula [16]. The schematic thermal profiles of the processes are illustrated in Fig. 1. Three processes have the same austenization and hot rolling procedures. But process 1 represents direct water quenching after hot rolling (HR) and then coiling from the QT. Process 2 includes air cooling process after hot rolling, water quenching to QT and coiling from the QT. Process 3 includes air cooling process after hot rolling and water quenching to room temperature. The partitioning step occurs during coiling from the quenching temperature to room temperature. Specifically, the slabs were austenized at 1200 °C for 1.5 h and then hot-rolled from 40 mm to 18 mm thickness though 2 passes at about 1120 °C. When air-cooled to 920 °C, the plates were again hot-rolled to 4 mm though 4 passes with a finish rolling temperature about 880 °C.·Then the five plates underwent different heat treatment processes (see Table 2).

The tensile samples with dimensions of 12.5 mm in width, 4 mm in thickness and 50 mm in length were prepared along the rolling direction and tested on a CMT5105-SANS machine at room temperature with an extension rate 2 mm/min. The ultimate tensile strength (UTS), 0.2% yield strength (YS) and elongation were obtained based on the average of three tests for each plate.

The distributions of elements of selected specimen were investigated by a JXA-8530F electro probe microanalyzer (EPMA) equipped with energy dispersive X-ray spectrum (EDS) system at an operating voltage of 20 kV, current of 2×10^{-8}A and a step size of 40 nm. The microstructure characterization was carried out using a Zeiss Ultra-55 filed emission scanning electron microscope (SEM) equipped with an electron backscattered diffraction (EBSD) system. The EBSD technique was used to identify the present phases. For observations of fine structure of microstructure, transmission electron microscope (TEM) investigation was carried out using a TECNAL G220 microscope at an operating voltage of 200 kV. For SEM and EPMA observation, the specimens were grounded and etched by 4% nital for 10–15 s. The specimens for EBSD analyses with a step size of 40 nm were firstly grounded and then electro-polished using electrolyte containing alcohol, perchloric acid and water with a proportion of 13:2:1 at room temperature. The current is about 1.2 A and the time is about 25 s for electro-polishing process. The TEM specimens were firstly grounded to a thickness of 45 μm and then electro-polished at −20 °C in a twin-jet machine.

The amount and average carbon concentration of residual austenite were measured at room temperature by a D/max2400X-ray diffractometer (operated at 56 kV, 182 mA) with Cu Kα radiation at room temperature. The test surfaces along the rolling direction were electro-polished to eliminate the stress of surface. And samples were scanned over a 2θ range from 40° to 110° with a step of 0.04°/s including several important ferrite and austenite peaks. The integrated intensity of ferrite peaks of (200), (211) and austenite peaks of (200), (220) and (311) were used to calculate the volume fraction of austenite by Jade version

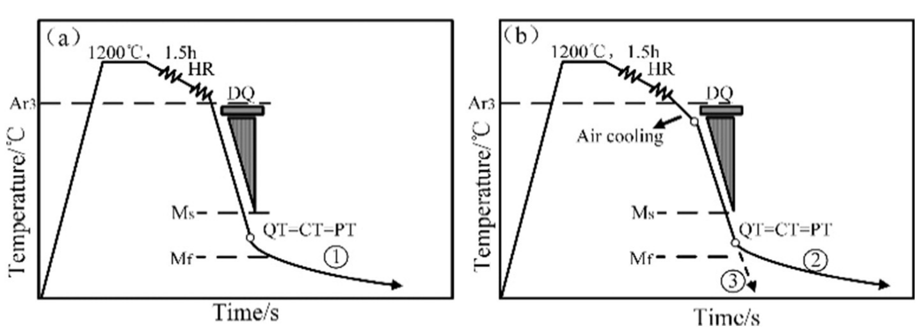

Fig. 1. Schematic thermal profiles of the process: Compared with process (a), the process (b) includes air cooling, aiming at introduction of proeutectoid ferrite. The specimens for process 1 and 2 were cooled inside the furnace to room temperature and the coiling cooling rate was about 60 °C/h for partitioning. "Ar3"represents the temperature of ferrite formation in the cooling process of prior austenite. "HR" means hot rolling. "DQ" means directly quenching. "QT" means quenching temperature. "CT" means coiling temperature. "PT" means initial partitioning temperature.