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Application of Quenching-Partitioning-Tempering Process in Hot Rolled Plate Fabrication

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Abstract. The quenching-partitioning-tempering (Q-P-T) process, based on the quenching and partitioning (Q&P) treatment, has been proposed for producing high strength steels containing significant fraction of film-like retained austenite and controlled amount of fine martensite laths. In this study, a set of Q-P-T processes for C-Mn-Si-Ni-Nb hot rolled plates are designed and realized. The steels with Q-P-T processes present a combination of high strength and relatively good ductility. The origin of such mechanical properties is revealed by microstructure characterization.

Introduction

The demand for steels with increased strength and well balanced formability has strongly been increasing over the last years because of the concern on decreasing weight of steel parts [1-2]. Advanced high-strength steels such as dual-phase [3], transformation induced plasticity (TRIP) [4], and bainitic steels [5-7], have been studied and used intensively to meet the above requirements.

Carbon-enriched retained austenite, as a soft phase, yields considerable contribution to formability and energy absorption of steels (for example in TRIP steels) [8]. Speer et al. [9] developed a new heat treatment procedure named quenching and partitioning (Q&P) process for producing austenite-containing martensite steels, based on a new understanding of hypothesized carbon partitioning between martensite and retained austenite. Different from conventional quenching and tempering (Q&T), the Q&P process involves quenching steels to a temperature (T_q), normally above the room temperature, between the martensite-start (M_s) temperature and the martensite-finish (M_f) temperature, followed by a partitioning treatment at quenching temperature T_q (one-step), or above T_q(two-step). This process is designed to make carbon diffuse (partition) from the supersaturated martensite to the retained austenite so as to stabilize retained austenite phase at room temperature. With the microstructure of martensite laths and considerably high amount of retained austenite, Q&P steels possess much higher strength with guaranteed ductility comparing to TRIP steels of the same chemical composition [10-11].

In Q&P treatment, the formation of carbides during partitioning is suppressed by the addition of Si and/or Al in order to stabilize austenite, however, the precipitation strengthening is excluded. [9]. Therefore, a heat treatment procedure named quenching–partitioning–tempering (Q–P–T) is proposed by Hsu [12] for further raising the strength of steels by emphasizing the application of precipitation strengthening in Q&P steels. The details of Q-P-T approach include following aspects: (i) The alloying elements such as (Nb, Mo and V), leading to the formation of stable carbides or/and the grain refinement, are added in Q&P steels; (ii) The carbon content is somewhat higher than that of Q&P steels so as to compensate the carbon consumed by the formation of carbides in martensite matrix; (iii) the temperature and time of the carbon partitioning depend on those of carbide precipitation. Previous researches [13-15] showed that Q-P-T steels presented higher tensile strength without decreasing the ductility.

Great progress has been made in improving the performance of sheet steels with the thorough research of Q&P and Q-P-T process, but there are few studies about the application in production of hot-rolled thick plates. The aim of the present work is to design suitable Q-P-T processes for C-Mn-Si-Ni-Nb hot-rolled plates with a thickness of 12 mm and to establish a link between the microstructures and the mechanical properties.

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Material Design and Experimental Procedures

Table 1 Chemical composition of steels (in wt %) and measured transformation temperatures (°C)

steel	C	Si	Mn	P	S	Ni	Nb	Ac_3	M_s	M_f
Alloy 1	0.199	1.18	1.44	0.0131	0.0056	0.992	0.0526	890	405	255
Alloy 2	0.256	1.2	1.48	0.0172	0.0079	1.51	0.0532	880	370	235

The chemical composition of the steels investigated in the present work is listed in Table 1. The Ac_3, M_s and M_f temperatures of the present steels were determined from dilatometric data obtained by a Gleeble-3500 thermal simulator. The steels were manufactured as $85 \times 60 \times 12 mm^3$ plates. Different heat treatment processes are schematically presented in Fig. 1. As mentioned above, in our Q-P-T processes the partitioning temperature depends on (equal to) tempering temperature.

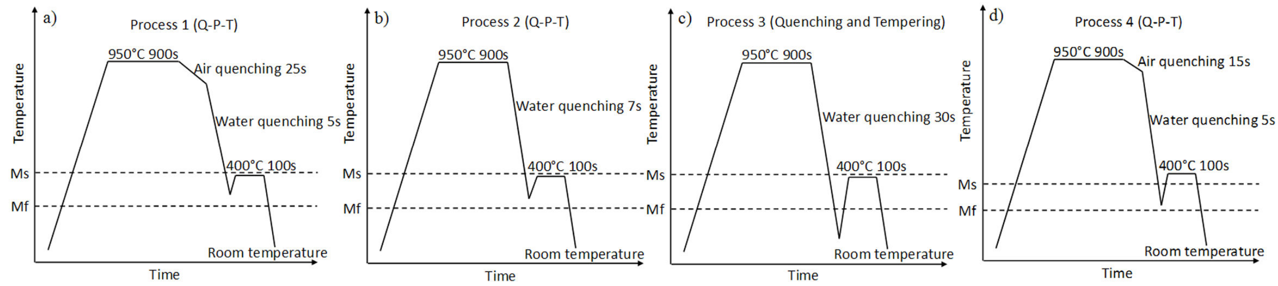

Fig.1 Schematic diagrams of heat treatment processes: (a), (b) and (c) for Alloy 1; (d) for Alloy 2

Tensile specimens with a circular section of 4 mm diameter and a gauge length of 20 mm were tested at room temperature using a Zwick T1-FR020TN A50 tensile testing machine equipped with a 20 kN load cell. The speed of crosshead was set as 0.5 mm/min in all experiments.

The microstructures of the steels were characterized by both Scanning Electron Microscopy (SEM) and Transmission Electron Microscopy (TEM). SEM investigation was carried out on JSM-6460 after etching the specimens by Nital. Specimens for TEM were prepared by mechanical polishing and electro-polishing in a twin-jet polisher using the electrolyte consisted of 4% perchloric acid and 96% ethanol solution. The foils were examined in a JEM 2100F microscope (JEOL) at an operating voltage of 200 kV.

Quantitative X-ray diffraction analysis was performed to determine the fraction of retained austenite. After grinding and final electro-polishing, the samples were etched to obtain an undeformed surface. They were then step-scanned in a D/max 2550 X-ray diffractometer with a scanning speed (2θ) of 5°/min over the 2θ range of 35-105°, using unfiltered Cu K_α radiation. The diffractrometer was operated at 35 kV and 200 mA. Retained austenite content was calculated by comparing with the integrated intensities of the (200)α, (211)α, (200)γ, (220)γ and (311)γ diffraction peaks [16].

Results and Discussion

Table 2 Tensile properties of Q-P-T steels at room temperature

Steel / process		Yield Strength (MPa)	Uniaxial Tensile Strength (MPa)	Elongation (%)
Alloy 1	Q-P-T 1	750±28.4	990±32.6	23±2
	Q-P-T 2	930±34.2	1110±7.4	15±1
	Q&T 3	1143±30.5	1291±25.1	10.9±0.2
Alloy 2	Q-P-T 4	990±57.8	1270±7.6	16.5±1

Mechanical properties. Table 2 shows the effect of processes and chemical composition on tensile properties of Q-P-T steels, and following viewpoints can be drawn readily: (1) Comparing three processes for alloy 1, process 2 brings the best combination of strength and ductility. (2) For process 3(Q&T), long immersion time leads to so low quenching temperature that martensite transformation takes place almost completely with little retained austenite, which results in the highest strength and the worst ductility. (3) Comparing Q-P-T process for alloy 2 to those for alloy 1, increasing content of C and Ni together to Q-P-T steels obviously increases the tensile strength without decreasing the ductility too much. Besides, it should be pointed out that the section of tensile specimens is limited to 4 mm diameter due to the maximum load of 20 kN on the tensile

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testing machine. As a consequence, tensile properties of the whole plates with a thickness of 12 mm should be better, and the results in Table 2 just show the tensile properties near the center of the samples.

Microstructure characterization. The SEM micrographs of the steels treated with different processes are shown in Fig. 2. From Fig. 2 (a)-(c), there's no significant difference in the general feature of lath-like martensite configuration except that martensite in sample with process 3 is finer. It is also clear that higher content of C and Ni leads to a finer lath martensite with only a little change in the time of air cooling and water quenching, as shown in Fig. 2. It is worth mentioning that retained austenite is not distinguishable from martensite because of its relatively small content and fine size.

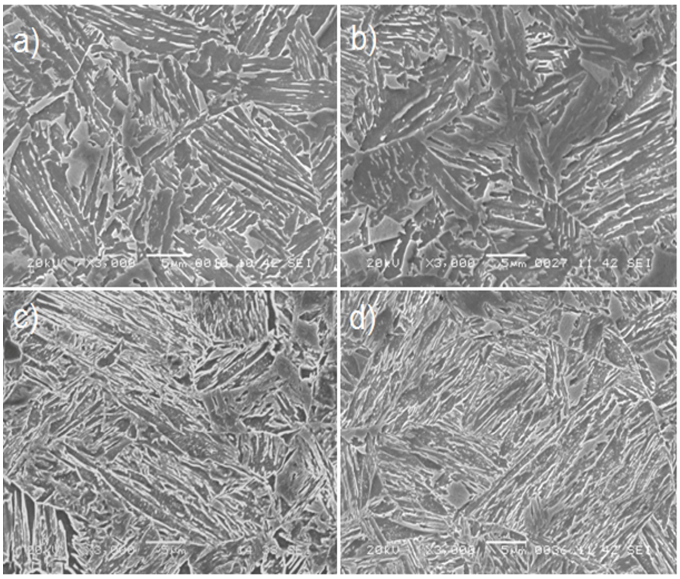

Fig. 2 SEM micrographs of steels with different processes: (a) process 1, (b) process 2 and (c) process 3 for Alloy 1, (d) process 4 for Alloy 2.

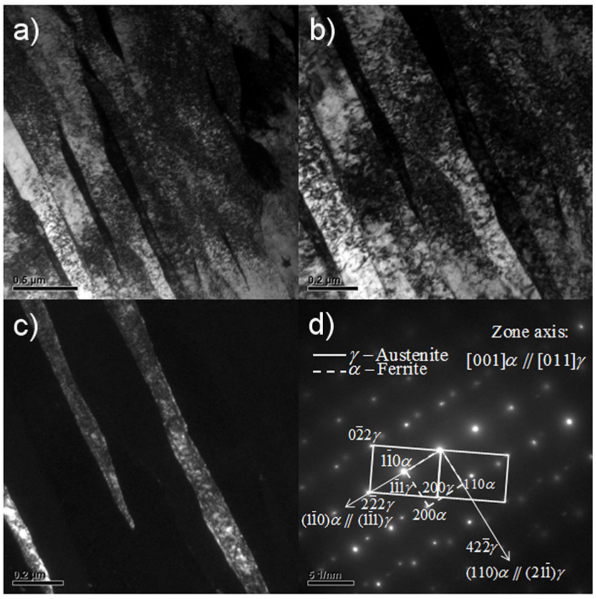

Fig. 3 TEM micrographs of the sample with process 1: (a) bright-field image, (b) enlarged bright-field image of (a), (c) center dark-field image of retained austenite, and (d) SEAD pattern of (c).

TEM analysis was carried out for further identification of various phases in Q-P-T steels. Fig.3 (a) shows dislocation-type lath martensite in samples with film-like retained austenite between martensite laths. From Fig.3 (c) and (d), it can be seen that the average width of martensite is about 200 nm and the average thickness of film-like retained austenite is less than 80 nm, respectively. The orientation relationship between martensite and retained austenite is identified by selected-area electron diffraction (SAED) in Fig. 3(b) as well-known Nishiyama–Wasserman relationship: [001]α // [011]γ, $(1\bar{1}0)\alpha$ // $(1\bar{1}1)\gamma$. As a result, fine microstructure consisting of lath martensite and film-like retained austenite leads to a good combination of strength and ductility in Q-P-T steels. In addition, our work also reveals the Nb-carbide precipitates which has been reported in Ref [13-15].

The volume fraction of retained austenite in samples is determined quantitatively by XRD. Since the thickness of the samples investigated in the present work reaches 12 mm, temperature distribution of the whole samples was not uniform during the processes, especially along the thickness direction. For process 3, retained austenite content, which remains less than 3% along the thickness direction because of complete martensite transformation, is difficult to be quantified. For the other three processes, cooling rate decreased sharply from surface to center along the thickness of steels during quenching, and quenching temperatures at different sites of the steel changed gradually in the same Q-P-T process leading to a gradient of microstructures and tensile properties. It is obvious that retained austenite content in the center is larger than that near the surface, indicating that Q-P-T process is much more effective for ductility improvement at center part of the steels with a certain thickness, as shown in Fig.4. It also can be observed that there is a definite relationship between the volume fraction of retained austenite and the ductility, i.e., the higher content of the retained austenite, the better ductility.

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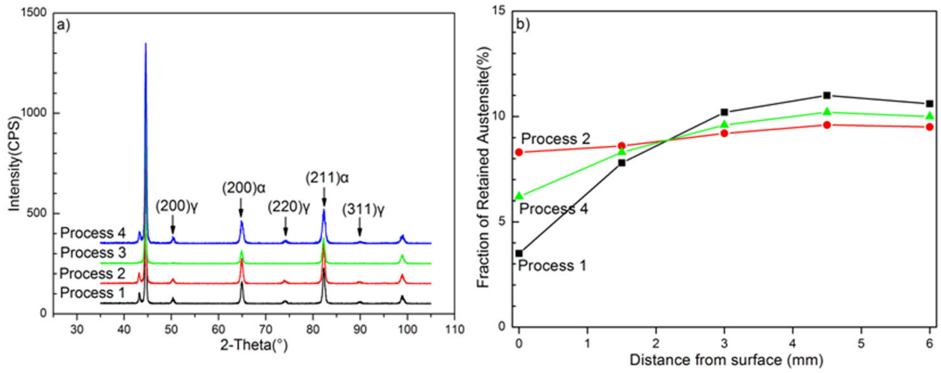

Fig. 4 (a) XRD spectra for center areas of the steels with different processes, and (b) retained austenite contents as a function of distance from surface.

Conclusions

An improved process named quenching-partitioning-tempering (Q-P-T) has been used to design the optimum heat treatment of C-Mn-Si-Ni hot-rolled plates with a thickness of 12 mm. Q-P-T steels, with a mixture microstructure of fine lath martensite and film-like retained austenite, have achieved a combination of high tensile strength (above 1000MPa) and relatively good ductility (above 15%). The origins of such mechanical properties are analyzed and summarized as follows:

(1) The high-tensile strength of Q-P-T steels is attributed to the fine lath martensite matrix, which has an average width of about 200 nm and acts as a hard phase.

(2) The film-like retained austenite with an average width of 80 nm, having a relatively high content (10%) at room temperature and acting as a soft phase, enhances the elongation of hot-rolled plates.

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