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Deformation Temperature Dependence of Mechanical Properties and Microstructures for a Novel Quenching−Partitioning−Tempering Steel

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The present investigation on a designed high strength Fe−0.25C−1.48Mn−1.20Si−1.51Ni−0.05Nb (wt%) steel treated by a novel quenching−partitioning−tempering (Q−P−T) process was focused on deformation temperature dependence of mechanical properties and microstructures. The results indicate that the Q−P−T steel deformed at various deformation temperatures from −70 to 300 °C exhibits superior mechanical properties due to excellent thermal stability of retained austenite. The microstructural characterization by transmission electron microscopy (TEM) reveals that the high strength of the Q−P−T steel results from dislocation-type martensite laths and fcc NbC carbides or/and hcp ε-carbides precipitated dispersively in martensite matrix, while excellent ductility is attributed to the significant transformation induced plasticity (TRIP) effect produced by considerable amount of retained austenite. The relationship between mechanical properties and microstructures at different deformation temperatures was clarified.

KEY WORDS: Quenching−partitioning−tempering (Q−P−T); Mechanical property; Thermal stability; Retained austenite; Microstructural characterization

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1. Introduction

In an international attention of reducing carbon emissions, it is urgently required to investigate and develop advanced high strength steels (AHSSs) for saving energy and raw materials as well as protecting environment. The development of steels consisting of martensite and austenite is one of the most promising and innovative approaches for the creation of new AHSSs with improved properties of strength and ductility[1]. Speer et al.[2−4] proposed a novel heat treatment for producing martensitic steels: the so-called quenching and partitioning (Q & P) process in 2003. The Q & P steels have a composite microstructure containing carbon-depleted lath martensite and carbon-enriched stabilized retained austenite, thus exhibit a good combination of strength and ductility. However, since carbides are not permitted in the Q & P steels based on the “Constrained Carbon Paraequilibrium” (CCE) theory proposed by Speer et al.[2], the potential strength has not yet been fully excavated. In order to further raise the strength of steels, after absorbing the core idea of Q & P process, Hsu[5] proposed a quenching−partitioning−tempering (Q−P−T) process to modify the Q & P process by adding some precipitation strengthening elements in the Q−P−T steels. Like Q&P steels, the desired volume fractions of retained austenite and martensite in Q−P−T steels can be obtained by a proper Q−P−T process, *i.e.*, 1) selecting a suitable quenching temperature (T_q) between the start temperature (M_s) of martensitic transformation and the finish temperature (M_f) after cooling from a proper austenitizing temperature; 2) following a partitioning/tempering step, in which carbon atoms partition (diffuse) from supersaturated martensite into nearby austenite and precipitation of nano-sized carbides from martensite matrix, and the former leads to the stability of carbon-enriched retained austenite at room temperature. The Q−P−T steels exhibit a better combination of strength and ductility than Q & P steels[6,7] and other AHSSs[8−10]. The Q−P−T steels become a new family of AHSSs[6,7].

So far, few studies on deformation (experimental) temperature dependence of mechanical properties and microstructures for Q−P−T steels have been made. Therefore, a high strength Fe−0.25C−1.48Mn−1.20Si−1.51Ni−0.05Nb (wt%) Q−P−T steel with considerable amount of retained austenite was designed, and the mechanical properties and microstructures of the low carbon Q−P−T steel were studied, especially focusing on the stability of retained austenite in the Q−P−T steel in a wide range of deformation temperatures so as to evaluate the temperature range, in which the Q−P−T steel studied can be applied.

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2. Experimental

The chemical composition of the steel studied is listed in Table 1. The principle of composition design for this high strength steel is considered as follows. The steel contains a certain amount of carbon and manganese so as to reduce M_s temperature and increase the stability of austenite. Silicon is added to suppress brittle cementite (Fe_3C) formation[3,4], and an appropriate quantity of alloying element Nb can effectively not only refine the original austenite grain, but also lead to the formation of stable carbide, which causes grain-refinement strengthening and precipitation strengthening[5,6]. The A_{c3} and M_s temperatures were respectively determined to be 880 and 395 °C, based on dilatometric data obtained by a Gleeble-3500 thermal simulator.

The steel was melted in a medium frequency induction furnace from Laiwu Steel Group (Shandong, China), and then a hot-rolled plate with 12 mm thickness was prepared. The specimens with 2 mm thickness were cut from the hot-rolled plate. After cutting, they were subjected to the Q−P−T treatment, that is, the steels were austenitized at 930 °C for 300 s, followed by quenching into a molten salt bath at 300 °C (T_q) for 15 s. Then they were treated by partitioning and tempering at 400 °C for 30 s in another molten salt bath, and finally water-quenched to room temperature. The optimum quenching temperature was calculated according to the CCE theory[2] and the Koistinen−Marburger (K−M) equation[11]. The subsequent tempering temperature was selected at 400 °C for 30 s to escape from the tempering brittleness based on our previous experiment results[6,7].

Rectangular tensile samples were prepared with the gage length of 15 mm, width of 5 mm and thickness of 1.5 mm. Tensile tests at different deformation temperatures (from −70 to 400 °C) were carried out on an SANS 5105 tensile testing machine equipped with high temperature heating and low temperature cooling devices at an extension rate of 0.5 mm/min, respectively and the strain was measured by the change of gage length of tensile samples without extensometer due to elevated temperature tests. Before tensile tests, all the specimens were isothermally held at each target temperature for 600 s so that the entire specimen could be at a uniform temperature. Moreover, two specimens for each process were subjected to tensile tests and an average value of mechanical properties was calculated.

The thermal stability of retained austenite was determined by measuring the M_s temperature by electric resistance test, but the amount of retained austenite is hardly determined by electric resistance test. As a result, X-ray diffraction (XRD), as an alternative way, was employed to measure the volume fraction (V_{RA}) of retained austenite at room temperature. In order to ensure that the volume fraction of retained austenite in the undeformed samples before tensile tests at elevated temperatures is almost the same as that at room temperature, the specimen heated to a given temperature will be rapidly cooled to room temperature by water cooling. The volume fractions of retained austenite in the undeformed samples before tensile tests after isothermal holding for 600 s at each of deformation temperatures were determined by XRD with Cu$K\alpha$ radiation using a D/max-2550 X-ray diffractometer. The determination method is based on a direct comparison method of the integrated intensity of the austenite $(200)_\gamma$, $(220)_\gamma$ and $(311)_\gamma$ peaks and the martensite $(200)_\alpha$ and $(211)_\alpha$ peaks by using the formula[12,13]:

$$V_{RA} = \frac{1}{1+\frac{I_\alpha C_\gamma}{I_\gamma C_\alpha}} \quad (1)$$

where C_α and C_γ are the correlation coefficient of martensite and austenite, respectively; I_α and I_γ are the integrated intensity of martensite peak and austenite peak, respectively.

The undeformed and deformed samples after isothermal holding for 600 s at each of deformation temperatures were all selected for transmission electron microscope (TEM) observation. TEM specimens were prepared by mechanically polishing and then electropolishing in a twin-jet polisher using 5% perchloric acid and 95% ethanol at −20 °C. TEM observation was performed in a JEOL-2100F microscope operated at 200 kV.

3. Results and Discussion

3.1. Deformation temperature dependence of mechanical properties

The variations of ultimate tensile strength (UTS), yield strength (YS), total elongation (TEL) and product of strength and elongation (PSE) of Q−P−T steel, as functions of tensile temperature, are shown in Fig. 1. It can be seen that the mechanical properties of the samples exhibit a four-stage variation described as follows:

(1) Temperature regime I between −70 and 20 °C (−70 °C ≤ T ≤ 20 °C): Values of UTS, TEL and PSE sharply increase with decreasing deformation temperature, while YS increases slightly from 1043 to 1059 MPa, showing that the mechanical properties of the Q−P−T steel at low deformation temperatures are as good as that at room temperature (RT, 20 °C).

(2) Temperature regime II between 20 and 100 °C (20 °C ≤ T ≤ 100 °C): Values of UTS, YS, TEL, and PSE of the Q−P−T steel almost remain constant, showing the most stable stage of mechanical properties.

(3) Temperature regime III from 100 to 300 °C (100 °C ≤ T ≤ 300 °C): Values of UTS, TEL, and PSE exhibit the same tendency, *i.e.* including a slow increase at the beginning and a slight drop afterward as deformation temperature rises, while YS decreases slightly. When tensile specimens are deformed at 200 °C, the value of UTS can reach 1383 MPa accompanying 20.8% elongation (TEL); meanwhile, PSE exhibits a superior high value of 28766 MPa%. The tendency of mechanical properties in this elevated temperature range is similar to that of TRIP steels[14,15]. Obviously, the mechanical properties of the

Table 1 Chemical composition of the steel studied (wt%) and the measured A_{c3}, M_s and M_f (°C)

C	Si	Mn	Ni	Nb	P	S	A_{c3}	M_s	M_f
0.256	1.2	1.48	1.51	0.053	0.017	0.008	880 ± 5	395 ± 5	230 ± 5