

Microstructural evolution and consequent strengthening through niobium-microalloying in a low carbon quenched and partitioned steel

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ARTICLE INFO

Article history:

Received 27 April 2015

Received in revised form

10 June 2015

Accepted 16 June 2015

Available online 19 June 2015

Keywords:

Q–P steels

Nb-microalloyed

Refinement strengthening

Precipitation strengthening

Retained austenite

ABSTRACT

In the present study the determining role of niobium (Nb) on significant enhancement in mechanical properties in a low-carbon quenched and partitioned steel is elucidated. The study indicates that solute drag and precipitation pinning effect of Nb suppressed the recrystallization during hot deformation, leading to grain size refinement of hot-rolled steels. The cold-rolled and final microstructure after Q–P treatment was also refined because of refined hot rolled microstructure. Additionally, the degree of refinement was enhanced with increase in Nb-content. The tensile strength of the experimental steels was increased with increase in Nb-content from 1130 MPa in steel without Nb to 1210 MPa in steel with 0.048 wt% Nb. However, the total elongation first increased to 18% followed by a small decrease to 15%. The decrease in ductility is attributed to the consumption of carbon by precipitating NbC, which decreased the enrichment of austenite by carbon during partitioning, with consequent decrease in the stability of austenite. The decrease in the stability of retained austenite ultimately reduced the volume fraction of retained austenite and led to reduction in elongation.

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1. Introduction

The increasing demand on reduction in fuel consumption and safety of automobiles has led to continuous search for new advanced high strength steels with enhanced strength and ductility. The excellent mechanical properties obtained due to transformation of retained austenite to martensite in transformation-induced plasticity (TRIP) assisted steels has been the focus of recent attention [1,2]. TRIP steels are usually characterized by a ferrite–bainite matrix with a small fraction of martensite and retained austenite. Untransformed austenite, stabilized by carbon-enrichment during isothermal bainitic transformation, is retained at room temperature [3]. In view of the benefits associated with carbon partitioning, a novel heat treatment, quenching and partitioning (Q–P) process was designed to produce low carbon steels with a mixed microstructure consisting of carbon-depleted martensite and carbon-enriched retained austenite [4–6]. The Q–P process usually consists of a two-step heat treatment. The aim of quenching process is to obtain a microstructure consisting of supersaturated martensite and certain amount of retained austenite. The partitioning process is performed to accomplish carbon diffusion from supersaturated martensite to retained austenite. To maximize carbon

enrichment in retained austenite, cementite formation is suppressed by the addition of Si or Al [7,8]. The volume fraction of retained austenite as a function of quenching temperature was calculated by Speer et al. [9] based on the “constrained carbon paraequilibrium” (CCE) model by using Koistinen–Marburger relationship [10,11].

In CCE model, the formation of carbides was assumed to be absent in Q–P steels, which ignored the possibility of precipitation strengthening. However, the precipitation of carbides during the partitioning is inevitable, especially at a relatively high partitioning temperature. Similar views have been expressed in the literature [12–14]. In this regard, Hsu [15] proposed a novel heat treatment, referred as, quenching–partitioning–tempering (Q–P–T) process. In order to strengthen the steels, the carbide forming elements, such as Nb, Mo and V, were added to Q–P–T steels to form stable carbides during the partitioning processes. Compared with the Q–P steels, the Q–P–T steels exhibited a good combination of higher strength, because of precipitation strengthening, and adequate ductility [16]. It is well known that in addition to precipitation strengthening, Nb can refine the microstructure and introduce strengthening caused by grain refinement. Previous study [17] on Nb-microalloyed TRIP steels indicated that the addition of Nb can effectively control recrystallization and refine the grain size, which increased strength without compromising ductility. Also, solute Nb played an important role in stabilizing austenite and suppressing the transformation of austenite [18,17].

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Although there are studies reported in the literature with focus on the effect of Nb on microstructure and mechanical properties in quenched and partitioned steels [12–16], the effect of Nb concentration on microstructural refinement and consequent change in retained austenite fraction has not been discussed. Thus, in the present study, a series of low carbon Q–P steels with different Nb-content were systematically studied to explore the effect of Nb-content on the microstructure and mechanical properties, especially the variation in retained austenite fraction in steel with different Nb content.

2. Experimental procedure

The chemical composition of the three experimental steels is presented in Table 1. The alloying elements content of C, Mn, Si and Al was decided based on production cost, and is discussed in the previous study [19]. In view of the effect of Nb on microstructure and mechanical properties, different content of Nb were added into two of the three experimental steels in order to compare the steel without Nb. A 40 kg ingot was cast after melting in vacuum induction furnace. The ingots were homogenized at 1200 °C for 2 h, and then hot forged to slab of dimensions 100 mm width and 30 mm thickness. These bars were soaked at 1250 °C for 2 h and then hot rolled into sheets of 4 mm thickness after eight passes with starting and finishing temperatures of 1150 °C and 850 °C, respectively. Subsequently, these sheets were air cooled to room temperature and cold rolled to strips of thickness 1.2 mm after pickling in 10% hydrochloric acid.

In order to design an appropriate heat treatment process, the critical temperatures of A_{c1} , A_{c3} and M_s of the three experimental steels were first obtained by dilatometer tests and listed in Table 1. The schedule for Q–P heat-treatment cycle is schematically shown in Fig. 1. All the specimens were austenitized at 910 °C for 5 min, and then quenched to 260 °C. Subsequently, these quenched specimens were partitioned in a salt bath at 400 °C for partitioning at different times from 10 to 500 s. Finally, these specimens were quenched to room temperature in water.

Rectangular tensile specimens (width 12.5 mm, thickness 1.2 mm, and gage length 25 mm) were prepared from the longitudinal direction of the rolling direction after the heat treatment. Tensile tests were performed on a SANSMT-5000 tensile machine at room temperature at a strain rate of $2 \times 10^{-3} \text{ s}^{-1}$. Microstructure was analyzed by optical microscope (OM), scanning electron microscope (SEM) and transmission electron microscope (TEM). The volume fraction of retained austenite (RA) was measured via X-ray diffraction (XRD) with Cu K α radiation operated at 40 kV and 100 mA. Samples were scanned from 40° to 120° at a scanning rate of 2°/min. The volume fraction of RA (V_γ) was calculated by using the following equation [20,21]:

$$V_\gamma = \frac{1 \cdot 4I_\gamma}{I_\infty + 1 \cdot 4I_\gamma} \quad (1)$$

where I_γ and I_α are the integrated intensities of austenite and ferrite, respectively. In the present work, the diffraction lines of $(200)_{\alpha'}$, $(211)_{\alpha'}$, $(200)_\gamma$, $(220)_\gamma$ and $(311)_\gamma$ were employed to determine the value of V_γ [21].

3. Results

3.1. Microstructure observation

Fig. 2 shows the optical micrographs (OM) of the experimental steels after hot-rolling. It can be seen that the microstructure of all

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

Steels	C	Si	Mn	Al	Nb	A_{c3} (°C)	A_{c1} (°C)	M_s (°C)
No. 1	0.19	1.52	1.48	0.15	–	877	728	391
No. 2	0.18	1.48	1.44	0.15	0.025	895	735	385
No. 3	0.19	1.52	1.53	0.14	0.048	884	732	380

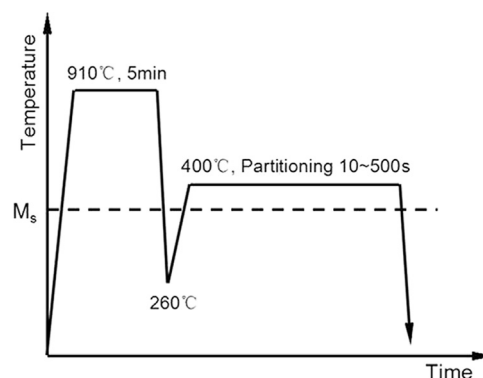


Fig. 1. Heat treatment cycle used in this study.

the hot-rolled steels consisted of ferrite and pearlite, except that the grain size of the experimental steels was gradually refined with increase in Nb content. The SEM micrographs of the three experimental steels after quenching and partitioning processes are presented in Fig. 3. Fig. 3a–c corresponds to the microstructure of steels 1, 2 and 3 with 5 s partitioning time, respectively, while Fig. 3d–f corresponds to 500 s partitioning. As shown in Fig. 3, the original austenite grain boundaries can be clearly observed, and the grain size of the original austenite of Nb-containing steels was smaller than Nb-free steel. The statistical results showed that the prior austenite grain size of steels 1, 2 and 3 was $8.5 \pm 1.5 \mu\text{m}$, $5.4 \pm 1.4 \mu\text{m}$ and $4.2 \pm 1.1 \mu\text{m}$, respectively. The martensite in all the steels indicated a roughening trend with increase in partitioning time, which has been reported in a low carbon Q–P steel [19]. It was difficult to distinguish retained austenite clearly in the SEM micrographs. The volume fraction of retained austenite in the experimental steels was measured by X-ray diffraction. The XRD pattern of the three experimental steels after Q–P treatment are presented in Fig. 4 and the corresponding calculated volume fraction of retained austenite is listed in Table 2. It is clear that the addition of Nb leads to increase in the volume fraction of retained austenite. However, excessive Nb-content decreases the volume fraction of retained austenite. The effect of Nb-content on the volume fraction of retained austenite is discussed below.

In order to distinguish retained austenite in experimental steels, TEM studies were carried out (Fig. 5). The existence of film-like retained austenite confirmed that the transformation of martensite during the quenching process had an effect on mechanically stabilizing the adjacent film-like austenite between the lath martensite due to the three-dimensional hydrostatic pressure, and constituted one of the objectives to stabilize retained austenite. It may be seen from the selected area electron diffraction (SEAD) patterns, that the retained austenite and martensite exhibit Nishiyama–Wassermann (N–W: $[001]\alpha \parallel [011]\gamma$) or Kurdjumov–Sachs (K–S: $[111]\alpha \parallel [011]\gamma$) relationship. Fig. 6 shows the TEM micrographs of precipitates distributed in the matrix in the experimental steels containing Nb. Based on the energy dispersive spectrometer (EDS) analysis, these particles in the experimental steels are NbC. The particles are of different size and majority of the precipitates are few nanometers in diameter. It is suggested that these precipitates form during the partitioning process and

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