

## Variation in retained austenite content and mechanical properties of 0.2C–7Mn steel after intercritical annealing

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**Abstract:** The effects of annealing time and temperature on the retained austenite content and mechanical properties of 0.2C–7Mn steel were studied. The retained austenite content of 0.2C–7Mn steel was compared with that of 0.2C–5Mn steel. It is found that 0.2C–7Mn steel exhibits a similar variation trend of retained austenite content as 0.2C–5Mn steel. However, in detail, these trends are different. 0.2C–7Mn steel contains approximately 7.5vol% retained austenite after austenitization and quenching. The stability of the reversed austenite in 0.2C–7Mn steel is lower than that in 0.2C–5Mn steel; in contrast, the equilibrium reversed austenite fraction of 0.2C–7Mn steel is substantially greater than that of 0.2C–5Mn steel. Therefore, the retained austenite content in 0.2C–7Mn steel reaches 53.1vol%. The tensile results show that long annealing time and high annealing temperature may not favor the enhancement of mechanical properties of 0.2C–7Mn steel. The effect of retained austenite on the tensile strength of the steel depends on the content of retained austenite; in contrast, the 0.2% yield strength linearly decreases with increasing retained austenite content.

**Keywords:** manganese steel; annealing; austenite; mechanical properties

### 1. Introduction

In recent years, increasing attention has been paid to the research and development of next-generation automobile steels that exhibit a good combination of high strength and high ductility [1–2]. In general, both TRIP steels and TWIP steels already exhibit an excellent combination of strength and ductility. However, because TWIP steels contain high concentrations of alloying elements, they are inherently expensive. In addition, the poor manufacturability of TWIP steels makes the cost-effective production of TWIP steel sheets for modern automobiles difficult [3]. In contrast, some relatively cost-efficient TRIP steels have been developed and widely used in the automobile industry [4]. However, because of their limited ductility, these TRIP steels cannot meet the increasingly stringent requirements of modern vehicles. The research and development of new steels is therefore necessary.

In TRIP or TWIP steels, the TRIP or TWIP effects [5–12] of metastable retained austenite can efficiently improve the

ductility of steels; increasing the metastable austenite fraction is therefore expected to be a feasible approach for enhancing the ductility of steels [13–16]. Recently, some medium-manganese steels with good mechanical properties have been reported by Merwin [17]. Some new medium-manganese steels reported in our previous study [18–21] also exhibit the excellent mechanical properties that are substantially better than those of conventional TRIP steels and are comparable to those of TWIP steels. However, in our previous study [18–21], 0.2C–5Mn steel was primarily focused on; the steel with other Mn contents, such as 0.2C–7Mn steel, was not carefully studied. Therefore, in the present study, the effects of annealing time and temperature on 0.2C–7Mn steel were intensively studied by intercritical annealing to determine the variation in retained austenite content and mechanical properties of steel.

### 2. Experiment procedures

The phase diagram for 7Mn steel was calculated using

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the Thermo-Calc software and the TCFE6 database; the results are shown in Fig. 1, where the red dashed line represents the phase transformation process of 0.2C–7Mn steel. The critical temperatures for 0.2C–7Mn steel are 605°C for the eutectoid transformation in equilibrium ( $Ae_{1,}$ ) and 685°C for the solid-liquid transition in equilibrium ( $Ae_{3,}$ ). On the basis of the calculation results, three annealing temperatures (620, 650, and 680°C) were selected. These three temperatures were located at the lower, middle, and upper part of the  $\alpha/\gamma$  two-phase region, respectively.

The 0.2C–7Mn steel used in this study was prepared using a high-frequency induction furnace. The chemical composition of the steel is shown in Table 1. After the smelting process, the steel was cast into ingots and forged into rods, followed by 2 h of homogenization at 1250°C. In the next step, the rods were cut into specimens; the specimens were then heat-treated as follows: (a) austenitization at 850°C for 30 min followed by water quenching; (b) intercritical an-

nealing at 620, 650, and 680°C for 10 s, 30 s, 1 min, 10 min, 1 h, 6 h, 12 h, and 36 h, followed by a second water quenching.

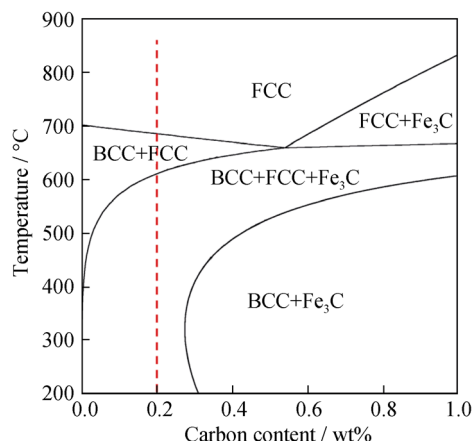


Fig. 1. Phase diagram of 7Mn steel calculated using Thermo-Calc and the TCFE6 database.

Table 1. Chemical composition of the steel prepared in this study

C	Mn	Si	P	S	N	Al	Ti	Fe
0.2	6.99	<0.01	<0.005	0.006	0.003	<0.005	<0.005	Balance

After the heat treatments, the mechanical properties of the specimens were subjected to tensile testing. The tensile tests were performed using longitudinal specimens according to standard GB/T 228.1-2010.

In this study, the equilibrium volume fraction of reversed austenite and its manganese and carbon concentrations were calculated using Thermo-Calc and the TCFE6 database. The volume fraction of retained austenite in the samples was measured by X-ray diffraction (XRD), and the microstructure of each specimen was observed by transmission electron microscopy (TEM). Samples for XRD were mechanically ground, polished, and then etched. Samples for TEM were ground to thin films with a thickness less than 50  $\mu\text{m}$ ; these films were subsequently electropolished using a

twin-jet machine in a solution of 5vol% perchloric acid and 95vol% alcohol at approximately  $-25^\circ\text{C}$ .

### 3. Results and discussion

#### 3.1. Variation in content of retained austenite in 0.2C–7Mn steel after intercritical annealing

Fig. 2(a) shows the TEM microstructure of the 0.2C–7Mn steel sample subjected to 1 h of annealing, followed by water quenching. It exhibits an ultrafine lath structure similar to that of 0.2C–5Mn steel in Fig. 2(b) after the intercritical annealing and quenching process. Thus, the phase transformation behavior in 0.2C–7Mn steel may be similar to that in 0.2C–5Mn steel. However, Fig. 2 also

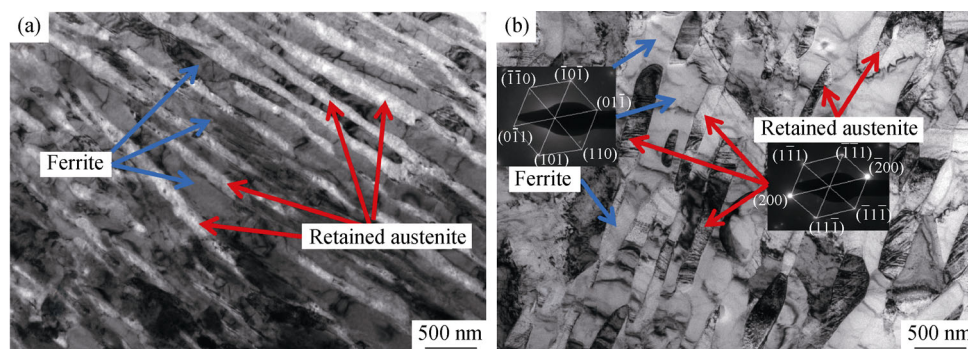
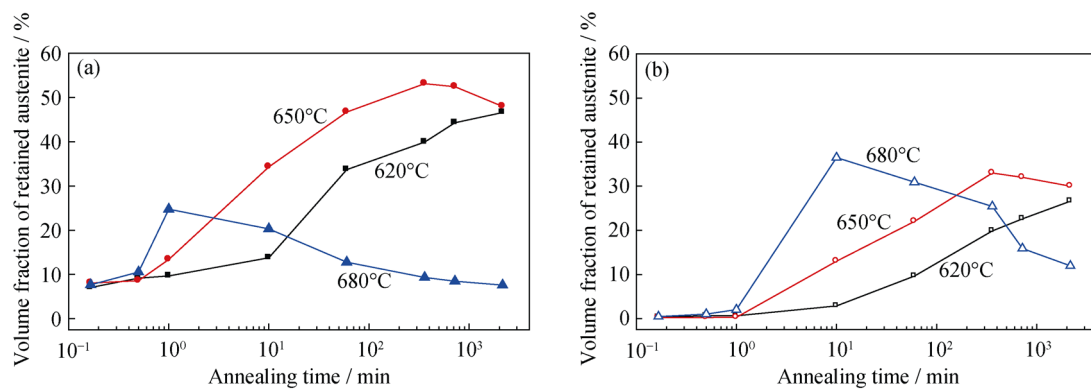


Fig. 2. TEM images of 0.2C–7Mn steel sample annealed for 1 h (a) and 0.2C–5Mn steel sample annealed for 36 h [21] (b) after intercritical annealing at 620°C.

shows that after only 1 h of annealing, the width of retained austenite lath in 0.2C–7Mn steel already approaches that in 0.2C–5Mn steel annealed for 36 h. Thus, the austenite fraction in 0.2C–7Mn steel increases faster than that in 0.2C–5Mn steel, indicating that the phase transformation behavior in the two steels differs substantially.

Fig. 3 shows the variation in the volume fraction of retained austenite measured by XRD for samples water-quenched from each heat treatment temperature (620, 650, and 680°C in the two-phase region) as a function of annealing time. Compared with 0.2C–5Mn steel in Fig. 3(b), such a gradual reversion behavior in 0.2C–7Mn steel indicates that it also undergoes a diffusional phase transfor-



**Fig. 3.** Variation in volume fraction of retained austenite with time for samples after annealing at 620°C, 650°C, and 680°C and subsequent quenching: (a) 0.2C–7Mn steel; (b) 0.2C–5Mn steel.

In detail, the variation in retained austenite content in 0.2C–5Mn steel reported in our previous study [21] and that in 0.2C–7Mn differ substantially. First, the initial microstructure of the 0.2C–5Mn steel sample before intercritical annealing is a full martensite structure; no or very little austenite is retained after austenitization and water quenching. Thus, the reversed austenite must nucleate first and then grow. In contrast, in 0.2C–7Mn steel, the initial microstructure contains approximately 7.5vol% of retained austenite; thus, the reversed austenite can grow from the ultrafine retained austenite. Consequently, the austenite would form faster in 0.2C–7Mn steel than that in 0.2C–5Mn steel.

The results in Fig. 3(a) indicate that after just 1 min of annealing, the retained austenite content reaches a maximum of 24.7vol% in 0.2C–7Mn steel annealed at 680°C. The results in Fig. 3(a) also show that after 10 s of annealing, the austenite content under all annealing temperatures exhibits almost no change, remaining approximately 7.5vol%. After 30 s of annealing, the austenite content in specimens annealed at 620 and 650°C also shows very little increase. The austenite content in the specimens annealed at 680°C increases slightly, to approximately 10vol%. After 1 min of

annealing, the austenite content in the specimens annealed at 680°C reaches the maximum value of 24.7vol%. As the annealing time is increased further, the content of retained austenite gradually decreases and finally approaches the initial retained austenite content of 7.5vol%. This behavior is attributed to the low stability of reversed austenite [21].

In general, the stability of reversed austenite can be determined by the martensite start temperature ( $M_s$ ), which in turn can be estimated by the equation proposed by Mahieu *et al.* [22].

$$M_s = 539 - 423[C] - 30.4[Mn] - 7.5[Si] + 30[Al], \text{ } ^\circ\text{C} \quad (1)$$

where [C], [Mn], [Si], and [Al] are the mass fraction of carbon, manganese, silicon, and aluminum, respectively, in austenite.

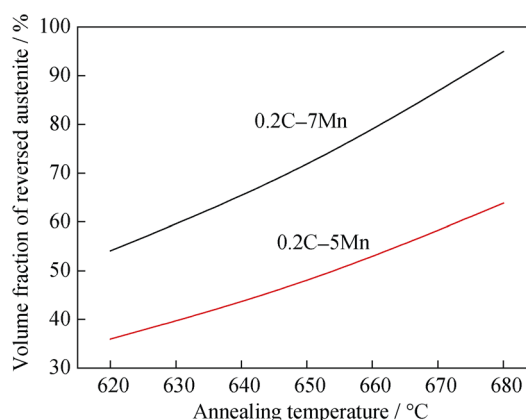
According to Eq. (1), the stability of reversed austenite is generally determined by the concentration of its alloying elements. When the concentration of alloying elements in reversed austenite increases, the  $M_s$  decreases, indicating a greater stability of the austenite. In contrast, a decrease in  $M_s$  would indicate a decrease in the stability of reversed austenite.

In the case of specimens annealed at 680°C,  $A_{e_3}$  is 685°C

( $Ae_3$  represents the austenite single-phase region); thus, these specimens were annealed at a temperature close to the austenite single-phase region. The results in Fig. 4 indicate that the equilibrium reversed austenite content in these specimens is approximately 95.0vol%, approaching to full austenite. Thus, these specimens after water quenching are similar to those quenched from the austenite single-phase region. Consequently, the final austenite content approaches the initial retained austenite content of 7.5vol%. In addition, because the formation of reversed austenite is a growth process, the volume fraction of reversed austenite increases gradually and approaches the equilibrium fraction with increasing annealing time. The alloying-element concentration in reversed austenite decreases with increasing time [21], which may lead to a decrease in the stability of reversed austenite according to Eq. (1). In the case of water-quenched specimens, more reversed austenite transforms into fresh martensite with increasing time; thus, the retained austenite fraction gradually decreases with increasing annealing time at 680°C. According to Fig. 4, the volume fraction of reversed austenite gradually increases with annealing temperature and the austenite content in 0.2C–7Mn steel is substantially greater than that in 0.2C–5Mn steel.

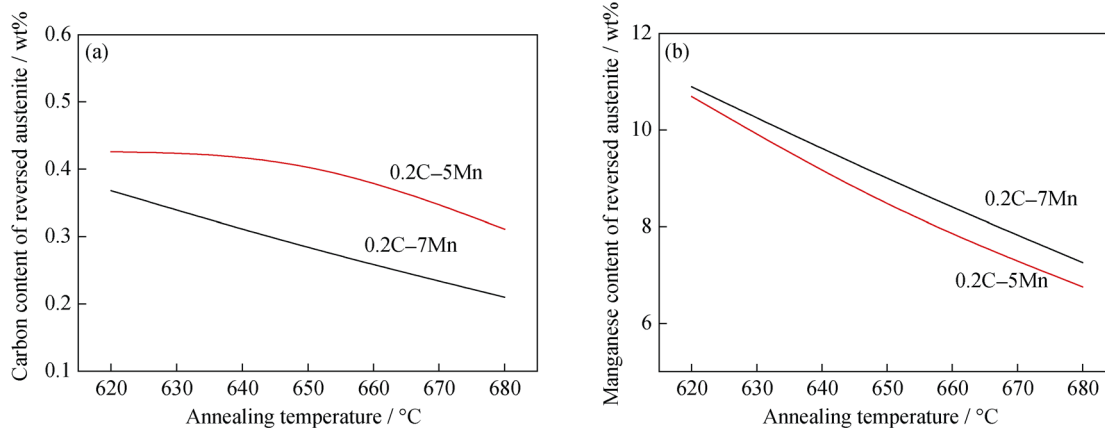
The equilibrium volume fractions of carbon and manganese in reversed austenite were calculated by Thermo-Calc software and TCFE6 database, the results are shown in Fig. 5. Both of the carbon and the manganese contents in reversed austenite decrease with increasing annealing temperature. Compared with the 0.2C–5Mn steel, the manganese content in the reversed austenite of 0.2C–7Mn steel is substantially greater; in contrast, the opposite is observed in case of the carbon content in reversed austenite of 0.2C–7Mn steel. Thus, the calculation through Eq. (1) enables an assessment of steel stability. The calculation results are shown in Fig. 6; they indicate that the  $M_s$  of 0.2C–5Mn

steel is slightly lower than that of 0.2C–7Mn steel, which means that 0.2C–5Mn steel is slightly more stable than 0.2C–7Mn steel. However, because the equilibrium volume fraction of reversed austenite (shown in Fig. 4) in 0.2C–7Mn steel is substantially greater than that in 0.2C–5Mn steel, the maximum retained austenite fraction in 0.2C–7Mn steel is still higher than that in 0.2C–5Mn steel, as shown in Fig. 3. The maximum contents of retained austenite obtained under these heat-treatment conditions are 46.6vol% at 620°C, 53.1vol% at 650°C, and 24.7vol% at 680°C in 0.2C–7Mn steel, whereas the corresponding contents in 0.2C–5Mn steel are 26.6vol% at 620°C, 33.0vol% at 650°C, and 36.5vol% at 680°C [21].



**Fig. 4.** Variation in equilibrium volume fraction of reversed austenite with annealing temperature predicted by Thermo-Calc in 0.2C–7Mn and 0.2C–5Mn steel [21] for comparison.

Fig. 6 also shows that the  $M_s$  for 0.2C–7Mn steel and 0.2C–5Mn steel increase with increasing annealing temperature, which means that the stability of the reversed austenite decreases with increasing temperature. Thus, specimens annealed at 650 and 620°C retain more austenite than that annealed at 680°C. In addition, the retained austenite



**Fig. 5.** Variation in carbon (a) and manganese contents (b) in reversed austenite with annealing temperature by Thermo-Calc in 0.2C–7Mn steel and 0.2C–5Mn steel [21] for comparison.

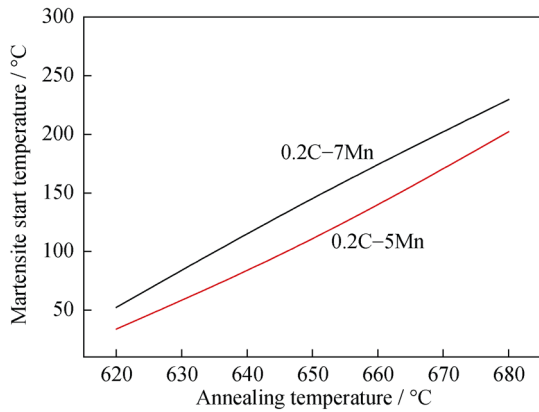


Fig. 6. Martensite transformation starting temperature as a function of the annealing temperature.

fraction slightly decreases after reaching the maximum value in the case of the specimens annealed at 650°C; in contrast, in the case of specimens annealed at 620°C, the fraction of retained austenite increases over the full range of investigated annealing times, without exhibiting a decrease.

### 3.2. Effect of annealing time and temperature on the mechanical properties of 0.2C–7Mn steel

After the heat treatments, the mechanical properties of selected samples were characterized by tensile tests. The results are shown in Fig. 7 to Fig. 11.

Fig. 7 shows the effects of annealing time (i.e., 10, 60, and 360 min) at 650°C on the mechanical properties of 0.2C–7Mn steel, including the tensile strength ( $R_m$ ), the 0.2% yield strength ( $R_{p0.2}$ ), and the elongation ( $A_T$ ). These results indicate that with increasing annealing time,  $R_m$  increases and the rate of increase gradually decreases. In contrast, both  $R_{p0.2}$  and  $A_T$  decrease with increasing annealing time and their rate of decrease also gradually decreases. Correspondently, Fig. 8 shows that at annealing times ranging from 10 min to 360 min, the austenite fraction increases and the rate of increase gradually decreases with increasing annealing time. Fig. 8 also shows that the product of tensile strength and total elongation ( $R_m \cdot A_T$ ) as a function of annealing time for 0.2C–7Mn steel annealed at 650°C; this product decreases with the increasing annealing time, which indicates that a long annealing time does not favor the enhancement of mechanical properties of 0.2C–7Mn steel.

Fig. 9 shows the effect of annealing temperature on the properties of 0.2C–7Mn steel, as indicated by the variations of  $R_m$ ,  $R_{p0.2}$ , and  $A_T$  with annealing temperature (620, 650, and 680°C) at a constant annealing time of 1 h. These results indicate that with increasing annealing temperature,  $R_m$  also increases and the rate of increase gradually decreases. In contrast,  $A_T$  decreases with time,  $R_{p0.2}$  first decreases and

then increases. Correspondently, Fig. 10 indicates that at the annealing temperatures from 620 to 680°C and an annealing time of 1 h, the austenite fraction first increases with increasing temperature and then decreases.

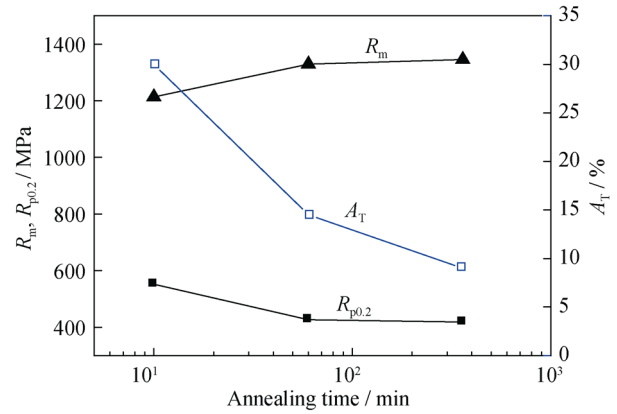


Fig. 7. Variation in mechanical properties with annealing time at 650°C for 0.2C–7Mn steel.

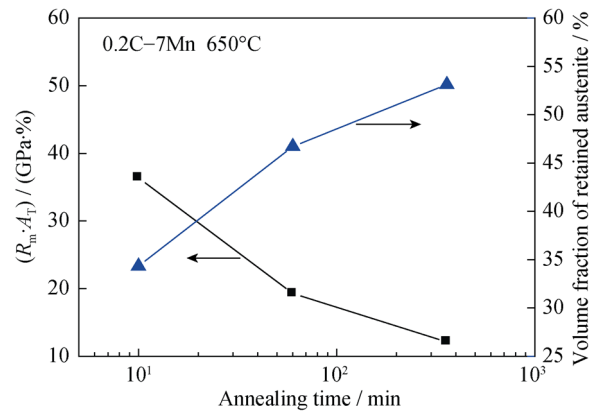


Fig. 8. Product of tensile strength and total elongation ( $R_m \cdot A_T$ ) and retained austenite content as functions of annealing time for 0.2C–7Mn steel annealed at 650°C.

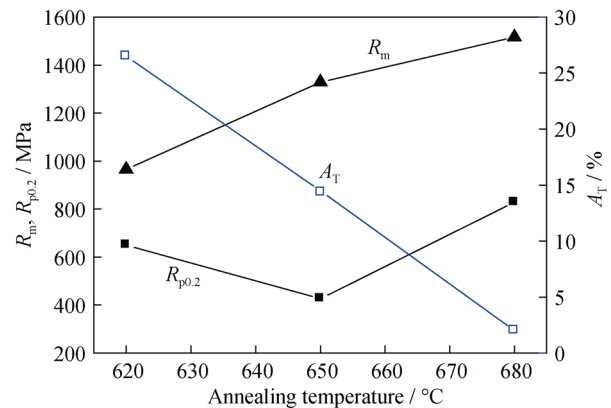
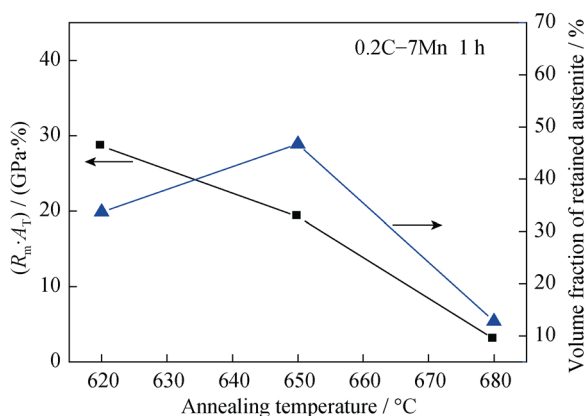


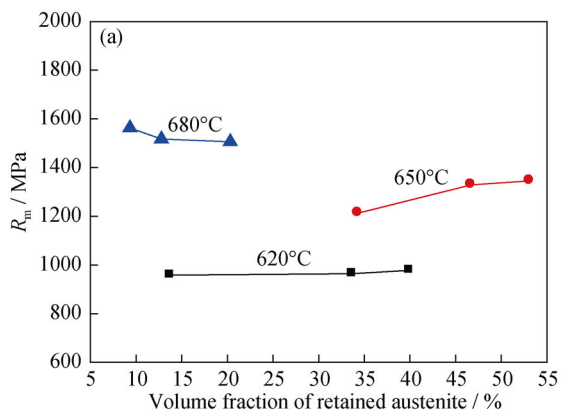
Fig. 9. Variation in mechanical properties with increasing annealing temperature for 0.2C–7Mn steel annealed for 1 h.

Fig. 10 also shows that the product of tensile strength and total elongation ( $R_m \cdot A_T$ ) of 0.2C–7Mn steel after 1 h of annealing as a function of annealing temperature; the product decreases with increasing annealing temperature. This result indicates that similar to long annealing times, high annealing temperatures also do not favor the enhancement of mechanical properties of 0.2C–7Mn steel.



**Fig. 10.** Product of tensile strength and total elongation ( $R_m \cdot A_T$ ) and retained austenite content as functions of annealing temperature for 0.2C–7Mn steel annealed for 1 h.

Fig. 11 shows the relationship between the retained austenite content and mechanical properties in 0.2C–7Mn steel. Results in Fig. 11(a) indicate that the variation in tensile strength comprises three different stages in which the strength decreases, remains the same, and increases with in-



**Fig. 11.** Dependence of mechanical properties on the volume fraction of retained austenite in 0.2C–7Mn steel: (a) tensile strength; (b) yield strength.

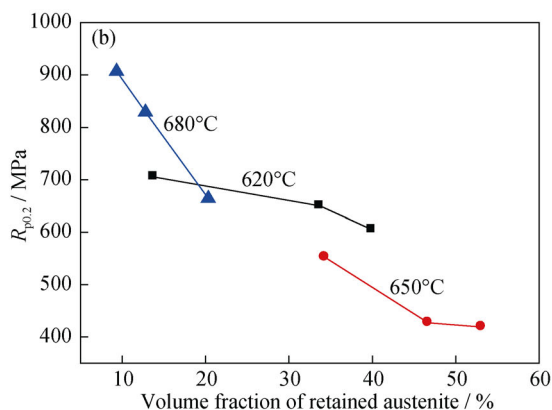
#### 4. Conclusions

Intercritical annealing was applied to 0.2C–7Mn steel. The effect of annealing time and temperature on the content of retained austenite and on the mechanical properties of 0.2C–7Mn steel were studied.

(1) After 0.5 h austenitization at 850°C and water quenching, approximately 7.5vol% austenite is retained in

creasing austenite fraction. Small amounts of austenite (less than 15vol%) correspond to an annealing temperature of 680°C; in these specimens, the tensile strength decreases with increasing austenite amount, as shown in Fig. 11(a). The results in Fig. 3 indicate that when the annealing time (10, 60, or 360 min) exceeds the time needed for achieving the peak austenite content (1 min), the decrease of austenite (from 10 to 360 min at 680°C in Fig. 3) should be accompanied by an increase in the content of fresh martensite [21]. In contrast, an increase of austenite (from 360 to 10 min at 680°C in Fig. 3) is accompanied by a decrease in the content of fresh martensite. Therefore, the observed decrease of tensile strength is attributed to the decreased content of fresh martensite, which means that the martensite would dominate the tensile strength when the content of austenite is low.

An intermediate austenite content (from 15vol% to 40vol% in Fig. 11(a)) corresponds to an annealing temperature of 620°C, which indicates that the tensile strength increases only slightly and is nearly independent of the austenite content. The obtained results may reflect the combined effects of retained austenite and fresh martensite. Large amounts of retained austenite (greater than 40vol% in Fig. 11(a)) correspond to 650°C; the tensile strength increases with increasing austenite content. Fig. 11(b) shows that  $R_{p0.2}$  linearly decreases with increasing austenite volume fraction, demonstrating a strong effect of the austenite amount on  $R_{p0.2}$ .



0.2C–7Mn steel. After the intercritical annealing and water quenching procedure, 0.2C–7Mn steel exhibits the same duplex ultrafine lath structure as 0.2C–5Mn steel.

(2) The effects of annealing time and temperature on the content of retained austenite in 0.2C–7Mn steel are generally similar to that in 0.2C–5Mn steel. However, in detail, they differ substantially. The retained austenite content in 0.2C–7Mn steel increases faster than that in 0.2C–5Mn steel.

Although the stability of 0.2C–7Mn steel is slightly lower than that of 0.2C–5Mn steel, 0.2C–7Mn steel is also retained a large amount of austenite because of the large content of equilibrium reversed austenite.

(3) In the case of specimens annealed at 680°C, the retained austenite content first increases and then gradually decreases with increasing annealing time. In the case of specimens annealed at 650°C, the volume fraction of retained austenite gradually increases and then slightly decreases. In the case of specimens annealed at 620°C, the volume fraction of retained austenite slowly increases and does not decrease. The maximum content of retained austenite in 0.2C–7Mn steel under different annealing conditions is obtained as 46.6vol% at 620°C, 53.1vol% at 650°C, and 24.7 vol% at 680°C, respectively.

(4) Long annealing times and high annealing temperatures may not favor the enhancement of mechanical properties of 0.2C–7Mn steel. The effect of austenite on  $R_m$  depends on the retained austenite content. With increasing content of retained austenite, the tensile strength first decreases, then remains steady, and eventually increases. In contrast,  $R_{p0.2}$  decreases linearly with increasing content of retained austenite.

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