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Materials

Effect of Continuous Cooling Conditions on Microstructure and Mechanical Properties of High Carbon Steel Rod

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Abstract: The effect of cooling rate and austenitizing condition on the mechanical properties of high carbon steel (SWRH82B) has been investigated. Specimens were made of high carbon steel rod and heat-treated by Gleeble-2000 to produce a wide variation in prior austenite size. Different cooling rates were carried out, and then pearlite interlaminar spacing and mechanical properties were measured and tested respectively. According to the results, it could be found that under the continuous cooling with the increase of cooling rate, tensile strength greatly increases and reduction in area exhibits a slightly increase for an equivalent value of prior austenite grain size. When prior austenite size increases, reduction in area decreases, and tensile strength increases slightly for an equivalent value of pearlite interlaminar spacing. It is concluded that prior austenite size primarily controls ductility and pearlite interlaminar spacing controls tensile strength. Mathematical formulae are given for these relations.

Key words: high carbon steel; continuous cooling; interlaminar spacing of pearlite, austenite grain size.

1 Introduction

Eutectoid steel has a fully pearlitic microstructure. From direct observation and indirect deduction in early stage, the forming of pearlite territory is a process of α and Fe_3C nucleation and growth alternately [1–2]. Since prior austenite grain size is one of the features that control the nucleation rate of pearlite, it is expected that pearlite nodule size should be related to prior austenite grain size. This has been shown the case [1].

Although the microstructure and mechanical properties of pearlite have been studied for many years, the mechanism of pearlite deforming has not been clearly made. A number of papers have reviewed the microstructural effects on the deformation and fracture of fully pearlitic materials [2–5]. As observed by Takahashi, *et al.*[6] and Porter, *et al.*[7], the process of pearlite deforming is as follows. At the beginning, the density of dislocations increase preferentially at the interface between ferrite and cementite and the slip after sufficient extension eventually gives rise to the transverse shear of cementite. Furthermore, the sites where the shear of cementite occurs are occasionally apart from the intersection with slip bands, creating an easy path for further deformation. The intense shear in the adjoining ferrite along the slip band follows fracturing adjacent cementite lamellae. Eventually, the voids form in the ferrite at the fractured end(s) of the cementite lamellae. Local stresses are concurrently elevated by work hardening, even during void growth, eventually producing rapid brittle (*i. e.*, catastrophic) fracture in a tensile specimen when the local critical stress for cleavage is reached.

Room temperature tensile ductility is dependent on both prior austenite grain size and pearlite interlaminar spacing. For an equivalent value of austenite grain size, finer pearlite generally exhibits a slightly higher ductility. However, the prior austenite grain size exhibits a comparatively greater influence on ductility (*i.e.*, for an equivalent value) than it does in the former case. Lewandowski and Thompson [4] have reviewed the mechanism of effects of the prior austenite grain size on the ductility of fully pearlitic eutectoid steel: the prior austenite grain size can control the distances over which flow localizes in fully pearlitic specimens. Large grain size enable flow to localize over comparatively larger distances than do fine grained specimens. Thus, it is reasonable to conclude that the pearlite interlaminar spacing and the prior austenite grain size are all important factors influencing the mechanical properties of pearlite. In spite of many studies from different aspects, all studies were concentrated on the pearlite from isothermal transformation. The mechanical properties of pearlite obtained by continue cooling had not been touched. In this study, in order to clarify the effect of cooling conditions on high carbon steel rod which are on Stelmor conveyor, different continuous cooling rates are carried out on different prior austenite grain size. The aim of this work is to obtain a better understanding of the effect of microstructural variables on the behavior of the steel at continuous cooling and thereby control the heat treatment conditions associated with optimum performance.

2 Experimental

(1) Equipment

The heat treatment equipment is built around a closed loop servo-hydraulic system, Gleelble-2000 thermomechanical simulator. Temperature and time can be precisely given and controlled. Tensile test is made under MTS810 at room temperature at an initial strain rate of $5\times10^{-4}\,s^{-1}$. Metallography is observed in XL-30 scanning electron microscopy and IBAS image analyzing system.

(2) Material

The material used was a high carbon steel (SWRH82B) rod which is processed by open furnace, LF/VD (EMS) furnace and high speed hot rolling. The chemical composition is C, 0.83%; Si, 0.27%; Mn, 0.78%; S, 0.012%; P, 0.019% and Cr, 0.17% in mass fraction. The specimens were sampled from ϕ12.5 mm wire rod and machined to the standard dimension for testing.

(3) Procedure

The heat treatment sequences are given in **table 1**. From the series A of specimens, it is observed that different cooling rates affect on pearlite interlaminar spacing and mechanical properties while maintaining a constant value of austenite grain size. The series B of specimens were designed to produce a wide variation in austenite grain size, in order to compare the effects of prior austenite grain size on pearlite interlaminar spacing and mechanical properties, while the same continuous cooling rate is performed. Then directly quenching is carried out to freeze the austenite grain structure, which are quenched in brine, resulting in the cooling rates of approximately 500℃/s. All quenching samples were sectioned, mounted, polished and etched before measured by IBAS image analysis system. The etchant used was saturated picric acid, with Teepol added, and heated to 50℃. A method described by Chen [9] to measure pearlite interlaminar spacing is performed, from which samples were sectioned, mounted, polished and etched. After that, at least 20 photos were observed and taken by XL-30 scanning electron microscopy at random visual field, and analyzed by IBAS image-analyzing system with linear intercept technique. **Figures 1 and 2** show the pearlite structure of A2 and A5 specimens respectively

3 Results

The effects of various heat treatment conditions on the microstructural parameters and mechanical properties are given in **figures 3 and 4**. For the series A of specimens, it is of note that the increase in cooling rate is accompanied by a decrease in pearlite interlaminar

Table 1 Heat treatment sequences.

Specimen	Austenitizing condition	Cooling condition
A1	1 000℃ for 5 min	quenching
A2	1 000℃ for 5 min	drop to 870℃ within 2 s, to 400℃ at 0.2℃/s and air cooling
A3	1 000℃ for 5 min	drop to 870℃ within 2 s, to 400℃ at 0.5℃/s and air cooling
A4	1 000℃ for 5 min	drop to 870℃ within 2 s, to 400℃ at 1.0℃/s and air cooling
A5	1 000℃ for 5 min	drop to 870℃ within 2 s, to 400℃ at 2.0℃/s and air cooling
A6	1 000℃ for 5 min	drop to 870℃ within 2 s, to 400℃ at 5.0℃/s and air cooling
A7	1 000℃ for 5 min	drop to 870℃ within 2 s, to 400℃ at 8.0℃/s and air cooling
A8	1 000℃ for 5 min	drop to 870℃ within 2 s, to 400℃ at 10.0℃/s and air cooling
A9	1 000℃ for 5 min	drop to 870℃ within 2 s, to 400℃ at 15.0℃/s and air cooling
A10	1 000℃ for 5 min	drop to 870℃ within 2 s, to 400℃ at 20.0℃/s and air cooling
B1	1 000℃ for 2 min	quenching
B2	1 000℃ for 5 min	quenching
B3	1 000℃ for 10 min	quenching
B4	1 000℃ for 20 min	quenching
B5	1 000℃ for 30 min	quenching
B6	1 000℃ for 2 min	drop to 870℃ within 2 s, to 400℃ at 8.0℃/s and air cooling
B7	1 000℃ for 5 min	drop to 870℃ within 2 s, to 400℃ at 8.0℃/s and air cooling
B8	1 000℃ for 10 min	drop to 870℃ within 2 s, to 400℃ at 8.0℃/s and air cooling
B9	1 000℃ for 20 min	drop to 870℃ within 2 s, to 400℃ at 8.0℃/s and air cooling
B10	1 000℃ for 30 min	drop to 870℃ within 2 s, to 400℃ at 8.0℃/s and air cooling

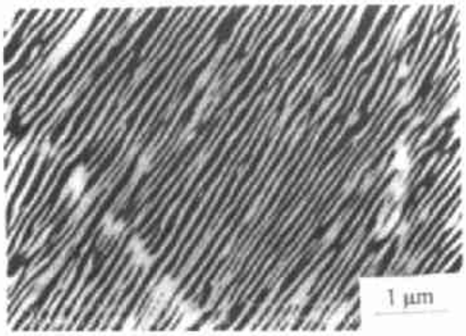

Figure 1 Pearlite structure of specimen A2.

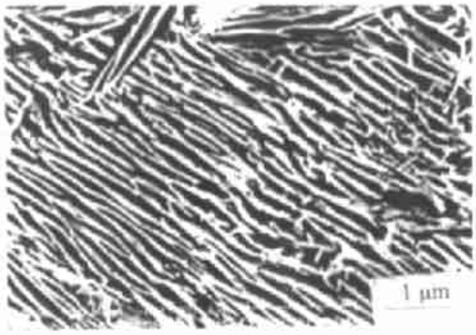

Figure 2 Pearlite structure of specimen A5.

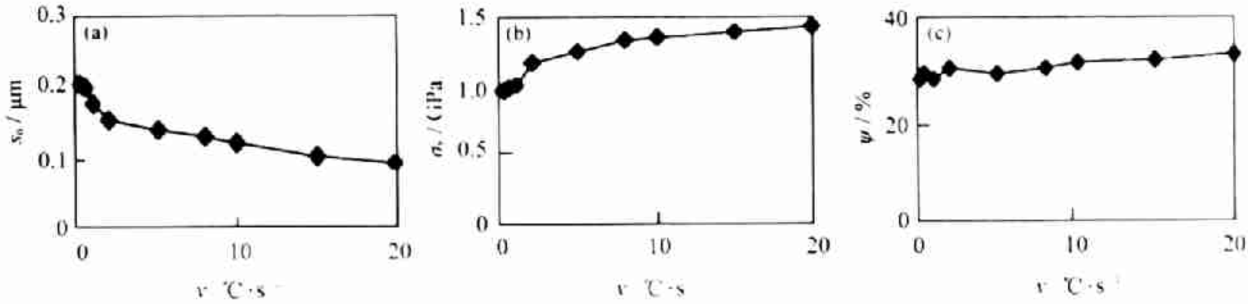

Figure 3 Effect of air cooling rate (v) on interlaminar spacing (s_0), tensile strength (σ_t) and reduction in area (ψ).

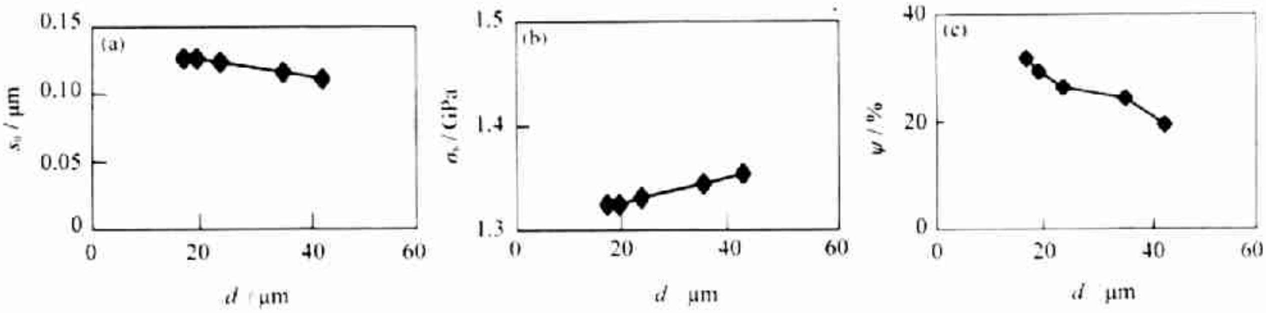

Figure 4 Effect of prior austenite grain size (d) on interlaminar spacing (s_0), tensile strength (σ_t) and reduction in area (ψ).

spacing and the associated increase in tensile strength. Meanwhile the reduction in area shows a slight increase. From the series B, the reduction in area decreases with the prior austenite grain size increasing, while the tensile strength presents a slight increase.

The effects of the cooling rate on the pearlite interlaminar spacing, tensile strength and reduction in area are shown in figure 3. These data were obtained from the series A with an equivalent value of prior austenite grain size. The result from figure 3 shows an obvious feature as follows. When the cooling rate speeds up, the pearlite interlaminar spacing decreases and the tensile strength increases intensely while the reduction in area show a narrow variable in width. The relation of the austenite grain size to the microstructure and mechanical properties is shown in figure 4. With the prior austenite grain size growing up, the reduction in area showed steep decrease and tensile strength showed little increase.

4 Discussion

4.1 Relation of cooling rate and pearlite interlaminar spacing

The relation of the continuous cooling rate and the interlaminar spacing is shown as figure 3(a). As the cooling rate increased, the interlaminar spacing presented nonlinear decreased. It can be contributed to that the over-cooling degree is increased with the cooling rate increasing. Based on the theory of metallography [1], transformation temperature primarily controlled the pearlite interlaminar spacing. Therefore raising transformation temperatures could increase the interlaminar spacing. As the cooling rate increase, the transformation temperature decreases, which resulted in interlaminar spacing decrease.

4.2 Relation of tensile strength and pearlite interlaminar spacing

The tensile and compressive yielding tests show that the yield stress of pearlite increases as the interlaminar spacing decreases as many investigations have shown [2,10]. As in the other studies, the yielding strength σ_y can be fitted to either an s^{-1} or $s^{-1/2}$ relation:

$$\sigma_y = \sigma_0 + ks^{-1} \quad (1)$$

or

$$\sigma_y = \sigma'_0 + k's^{-1/2} \quad (2)$$

where σ_0, σ'_0, k, and k' are constants. For the tensile strength, as observed by Shi [11] and Alexander, *et al.* [12], the cleavage fracture stress σ_b increases as the interlaminar spacing decreases, which is same as that the yield strength does. The tensile strength data obtained against the inverse of the true interlaminar spacing s_0^{-1} in the present work are shown in **figure 5**. The result

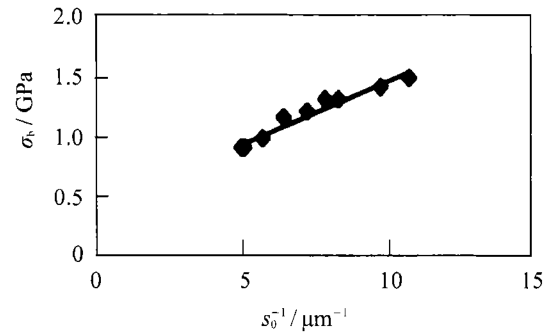

Figure 5 Dependence of tensile strength on inverse of interlaminar spacing.

agrees well with the linear relation, the similar equation with equation (1) and where σ_0= 469.7 MPa and k = 0.102 N/mm. This relationship (shown in figure 5) can predict the effect of interlaminar spacing on tensile strength.

4.3 Effects of cooling rate and prior austenite grain size on mechanical properties

From figures 3 and 4, for the equivalent value of prior austenite grain size, the tensile strength σ_b shows increase progressively and the reduction in area ψ presents slightly increase with the cooling rate increasing. For the same cooling rate, ψ decreases and σ_b exhibits nearly constant with the prior austenite grain size increase. It could be summarized that cooling rate primarily effects the tensile strength while prior austenite grain size primarily effects the ductility of fully pearlite steel. These results are similar to the works of pearlite from isothermal transformation by others [2–4,6–8]. In order to control the product quality conveniently in practice manufacturing, the tensile strength is simplified as a function of cooling rate and the reduction in area as a function of prior austenite grain size only. The mathematical formulas are given as following, respectively.

$$\sigma_b = 110.46 \ln v + 1\,088.8 \quad (3)$$

$$\psi = -11.468 \ln d_\gamma + 63.993 \quad (4)$$

where v and d_γ are the cooling rate and prior austenite grain size respectively. These relations can been used to predict the on-line product mechanical properties.

5 Conclusions

(1) Pearlite interlaminar spacing decreases nonlinear with continuous cooling rate increasing.

(2) Prior austenite grain size and pearlite interlaminar spacing are two important microstructure parameters on mechanical properties of pearlite obtained by continuous cooling. With the range of this paper, varying the prior austenitic grain size has a much greater effect on the subsequent reduction in area of pearlitic steel, and varying the continuous cooling rate has a much greater effect on the tensile strength. The mathematical formula could be used to control process parameters in practice manufacturing.

(3) Finer prior austenite grain size accompanied high cooling rate can obtain good mechanical properties in actual manufacturing.

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