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Materials

Effect of continuous annealing parameters on the mechanical properties and microstructures of a cold rolled dual phase steel

Shuang Kuang[1)], *Yong-lin Kang*[1)], *Hao Yu*[1)], *and Ren-dong Liu*[2)]

1) School of Materials Science and Engineering, University of Science and Technology Beijing, Beijing 100083, China
2) Technology Center, Anshan Iron & Steel Group Corporation, Anshan 114001, China
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Abstract: A cold rolled dual phase (DP) steel with the C-Si-Mn alloy system was trial-produced in the laboratory, utilizing a Gleeble-3800 thermal simulator. The effects of continuous annealing parameters on the mechanical properties and microstructures of the DP steel were investigated by mechanical testing and microstructure observation. The results show that soaking between 760 and 820°C for more than 80 s, rapid cooling at the rate of more than 30°C/s from the quenching temperature between 620 and 680°C, and overaging lower than 300°C are beneficial for the mechanical properties of DP steels. An appropriate proportion of the two phases is one of the key factors for the favorable properties of DP steels. If the volume fraction of martensite and, thereby, free dislocations are deficient, the tensile strength and *n* value of DP steels will decrease, whereas, the yield strength will increase. But if the volume fraction of martensite is excessive to make it become a dominant phase, the yield and tensile strength will increase, whereas, the elongation will decrease obviously. When rapid cooling rate is not fast enough, pearlite or cementite will appear, which will degrade the mechanical properties. Even though martensite is sufficient, if it is decomposed in high temperature tempering, the properties will be unsatisfied.

Key words: austenization; intercritical annealing; dual phase steel; cold rolling; diffusion

1. Introduction

Fuel economy and, thereby, weight reduction are extremely important factors for the automotive industry. The development of lightweight vehicles with high safety has been accomplished through the use of high strength steels, like multiphase steels [1]. Because of the unique properties of low yield strength, high tensile strength, continuous yielding, and good uniform elongation, dual phase (DP) steels have become an excellent new class of high strength low alloy steels used for lightweight vehicles [2]. Their microstructures mainly consist of about 20vol% of hard martensite islands dispersed in a soft and ductile ferrite matrix [3]. These steels are usually produced by annealing low-carbon cold rolled sheets in an intercritical temperature range to produce the ferrite-austenite mixture followed by rapid cooling to transform austenite into martensite [4].

In the present industrial process, continuous annealing lines are widely used to produce high quality DP steels [5]. This process includes the following stages (Fig. 1): heating to the intercritical temperature region, soaking in order to allow austenite to nucleate and grow, slow cooling to the quench temperature to make redundant austenite transform into epitaxial ferrite, rapid cooling to transform austenite into martensite, and overaging to temper martensite slightly.

In the present study, the effects of different continous annealing parameters on the mechanical properties and microstructures of a cold rolled DP steel with the C-Si-Mn alloy system were investigated through simulated annealing, mechanical test, and microstructural analysis.

2. Experimental procedure

The tested steel was melted using a vacuum smelter and cast into a slab of 90 mm in thickness. The composition (wt%) is 0.07 C, 0.25 Si, 1.65 Mn, <0.015 P, <0.01 S, 0.04 Als, 0.004 N, and balanced Fe. The slab was reheated to 1250°C and hot rolled to 5 mm through ten passes on a single stand experimental mill. The finishing temperature was kept above 880°C, and the coiling temperature was 690°C. After pickling in hydrochloric acid, the sheet was cold rolled to the final thickness of 1.2 mm.

Corresponding author: Shuang Kuang, **E-mail:** steelwarrior@126.com

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Continuous annealing was conducted on a Gleeble-3800 thermal simulator, which needs machining the cold rolled sheet into the samples of 200 mm×50 mm. According to the practical case of industry, heating rate, slow cooling rate, and overaging time mainly depend on the strip speed, and have a little change. Therefore, the effects of soaking, rapid cooling parameters, and overaging temperatures were investigated.

As shown in Fig. 1, the samples were first reheated to the intercritical temperature at the rate of 5°C/s. After soaking at this temperature for several seconds, the specimens were slowly cooled at the rate of 10°C/s to the quenching temperature, and rapidly cooled to the overaging temperature at different rates.

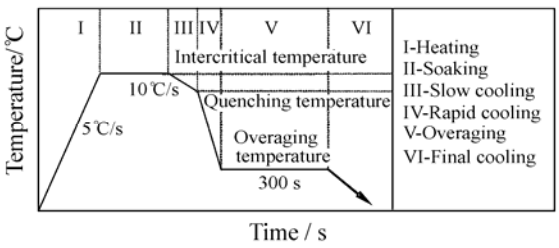

Fig. 1. Schematic diagram of continuous annealing for DP steel.

As shown in Table 1, a sample was annealed with the basic values of parameters first, then the value of one parameter was adjusted each time, while other parameters were equal to the basic values.

Table 1. Processing parameters of continuous annealing

Parameter	Basic value	Values for adjusting
Soaking temperature /°C	800	720, 740, 760, 780, 800, 820, 840
Soaking time / s	80	40, 60, 80, 100, 120, 150
Rapid cooling temperature /°C	680	580, 600, 620, 640, 660, 680, 700
Rapid cooling rate / (°C·s^{-1})	30	15, 20, 25, 30, 35, 40, 45
Overaging temperature /°C	280	100, 200, 250, 280, 300, 350, 400

The samples of 50 mm in gauge length were used for the mechanical test. The microstructures of the samples were observed by optical microscope (OM) and scanning electron microscope (SEM) after etching in 2vol% nital. Two jet thinning samples were prepared for the transmission electron microscope (TEM) observation.

3. Results

3.1. Mechanical properties and microstructures of the trial steel annealed with basic parameters

The mechanical properties and microstructures of the hot rolled steel and DP steel annealed with the basic values of annealing parameters are shown in Table 2 and Fig. 2, respectively. Compared to the hot rolled steel, the yield stress of DP steel decreases 105 MPa, whereas, the tensile strength increases 103 MPa. The yield ratio reaches 0.47, and the *n* value is up to 0.277, which is beneficial to stamping.

Table 2. Mechanical properties of the trial steel

Microstructural state	R_e / MPa	R_m / MPa	A_{50} / %	Yield ratio	n
Hot rolled	360	442	31.0	0.81	0.167
Annealed	255	545	28.7	0.47	0.277

Note: R_e and R_m are the yield and tensile strength, respectively; A_{50} is the elongation.

The hot rolled microstructure of the tested steel is composed of polygonal ferrite and pearlite, whereas, the DP steel mainly consists of martensite islands dispersed in the ferrite matrix. There are lots of high density dislocations in the ferrite matrix observed by TEM, which, as reported by many reseachers, are induced by volume expansion (about 2%-3%) from austensite-to-martensite transformation.

3.2. Effects of annealing parameters on mechanical properties

Fig. 3 shows the influences of soaking parameters on the mechanical properties of DP steels. It can be seen that the tensile strength and *n* value increase with the rise of soaking temperature, whereas, the elongation decreases slightly. The yield strength decreases when the soaking temperature is lower than 800°C, but increases when it exceeds 800°C. The properties of DP steels are deteriorated when the soaking temperarture is lower than 760°C. Soaking time has little effect on the yield and tensile strength, but the elongation and *n* value go up with the increase of it.

The effects of rapid cooling parameters on the mechanical properties of DP steels are shown in Fig. 4. The tensile strength increases with the increase in quenching temperature. The yield strength, yield ratio, and *n* value maintain a satisfying level when the quenching temperature is between 620 and 680°C.

The change tendency of elongation is not obvious.

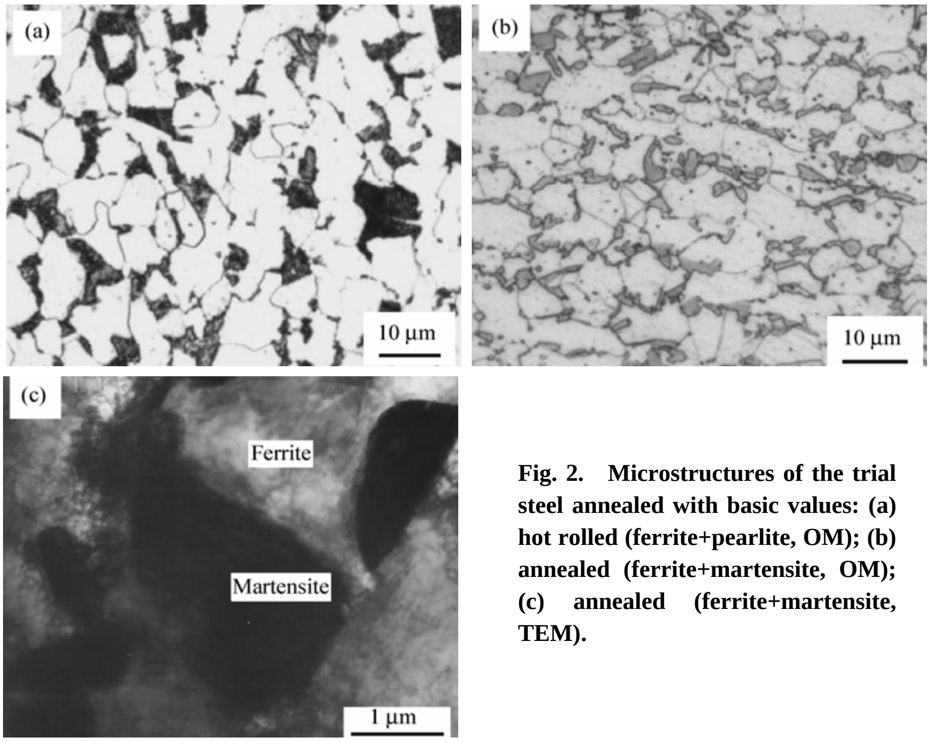

Fig. 2. Microstructures of the trial steel annealed with basic values: (a) hot rolled (ferrite+pearlite, OM); (b) annealed (ferrite+martensite, OM); (c) annealed (ferrite+martensite, TEM).

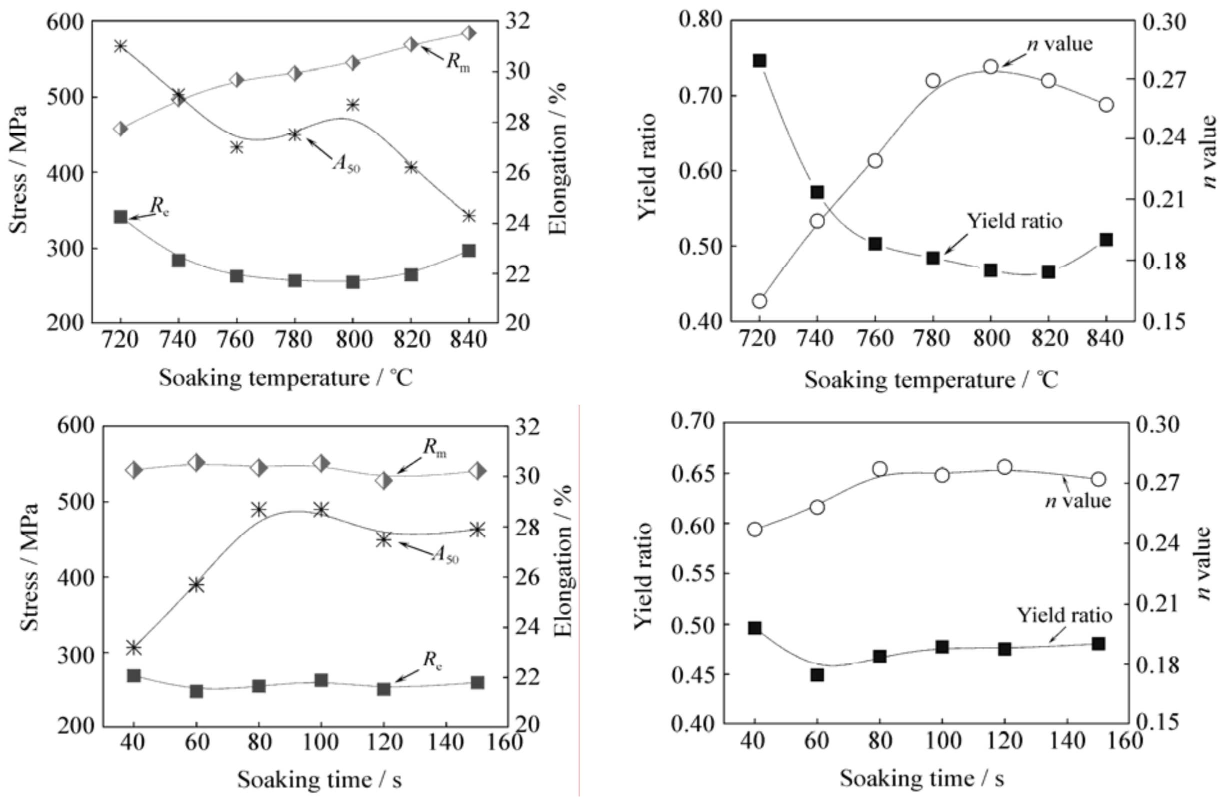

Fig. 3. Effects of soaking parameters on the mechanical properties of the tested DP steels.

Rapid cooling rate has a greater effect on the mechanical properties of DP steels. When the cooling rate is less than 25°C/s, the tensile strength does not reach 500 MPa, but the yield stress is higher than 250 MPa; the yield ratio and *n* value are deteriorated. From the experimental data, it is necessary that the rapid cooling rate is bigger than 30°C/s, which is benefical to the properties of DP steels.

Fig. 5 shows the effects of overaging temperature on the mechanical properties of DP steels. It can be seen that there are few changes in mechanical properties except elongation when overaged below 300°C. When the overaging temperature is higher than 300°C, the tensile strength and *n* value decrease strongly, whereas, the yield strength and yield ratio increase obviously.

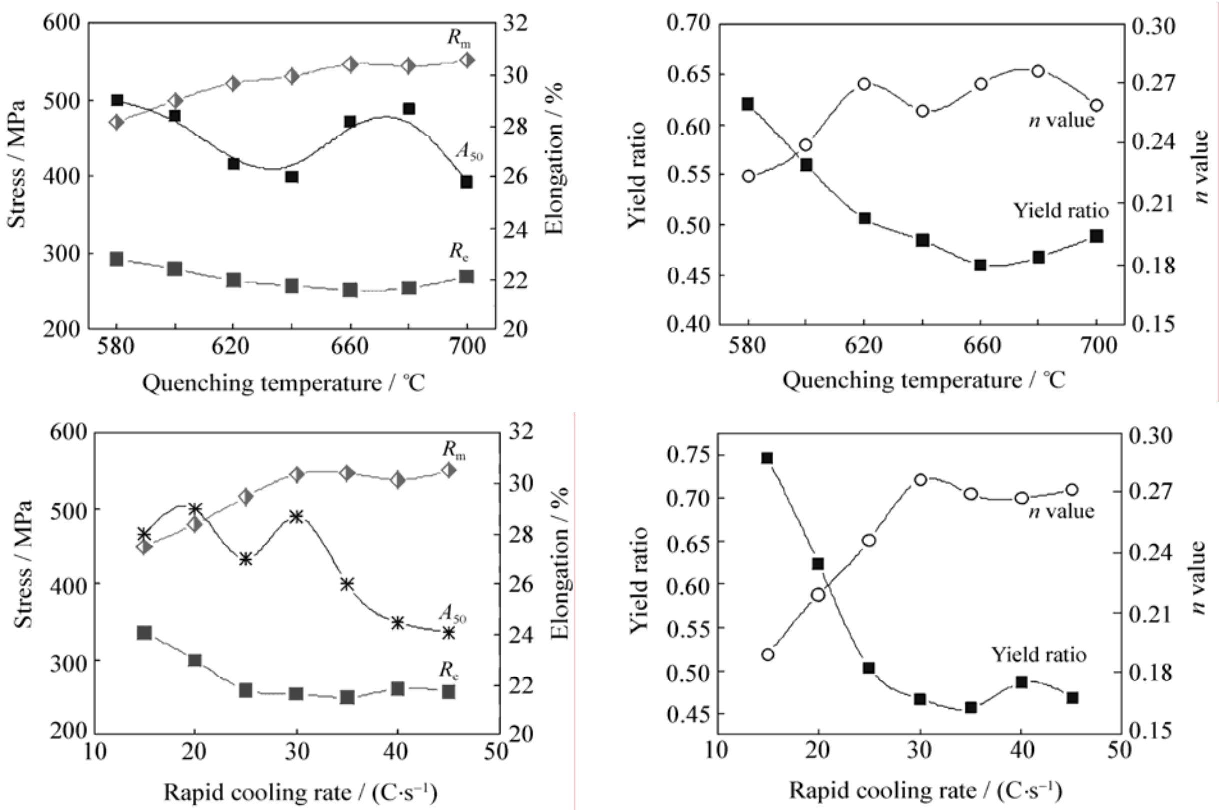

Fig. 4. Effects of cooling parameters on the mechanical properties of the tested DP steels.

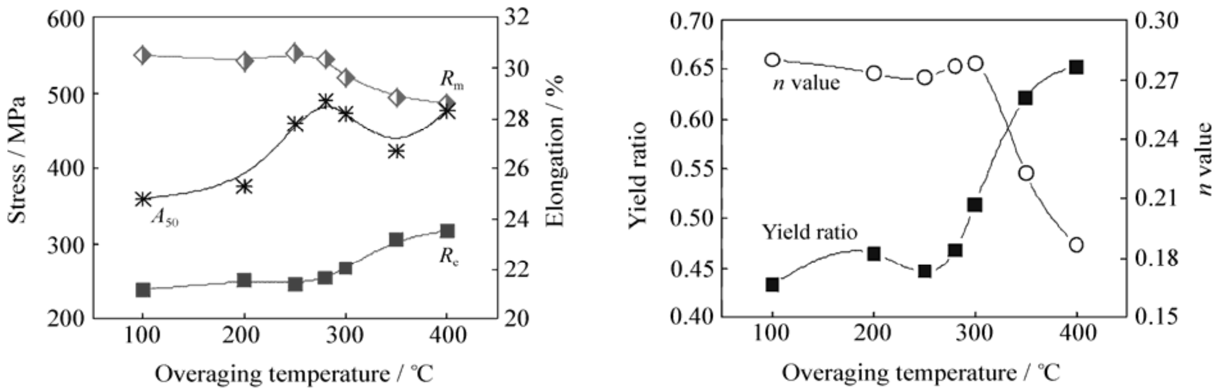

Fig. 5. Effects of overaging temperature on the mechanical properties of the tested DP steels.

4. Discussion

Favorable mechanical properties of DP steels such as low yield ratio, high tensile strength, and high *n* value are determined by appropriate microstructures. The enhancing mechanism of DP steels is phase transformation strengthening. Martensite provides the strength, and ferrite provides plasticity. When annealed in the intercritical temperature range, the solubility of carbon and manganese in the ferrite of the tested steels decreases, therefore those atoms transfer from ferrite to austenite [6-8]. Meanwhile, lots of carbide and nitride dissolve at high temperture, and they cannot reprecipitate in the subsequent rapid cooling process [9]. Those reasons make the ferrite in DP steels purer than that in as-received steels. As the volume expands during the transformation of austenite to martensite in the rapid cooling process [10], ferrite must plastically deform to accommodate it, which induces the generation of geometrically necessary dislocations in the ferrite around matensite phase. Those dislocations could keep mobility because no precipitates pin them. When an external stress is given to DP steels, plastic yield first occurs in ferrite. This will make lots of free dislocations drive, so DP steels exhibit low yield stress and continuous yield behavior [11]. With the increase in stress, dislocations will entangle each other and pile up at the phase interface, which makes the incompatibility of two phases increase, and then the external stress must have a greater increase in order to make the plastic deformation of martensite take place. Therefore, DP steels have high work-hardening value and tensile strength.

If the rapid cooling rate is sufficient to make austensite transform into martensite completely, the volume fraction of martensite is decided by soaking temperatrue, soaking time, and quenching temperature. When the soaking and quenching temperatures are too low to obtain enough martensite and free dislocations, the tensile strength and *n* value of DP steels will decrease, whereas, the yield strength and yield ratio will increase [12]. But if the volume fraction of marensite is excessive to be a dominant phase, the yield and tensile strength will increase, whereas, the elongation will decrease obviously.

Fig. 6 shows the microstructures which are processed at different soaking temperatures. It can be seen that only some martensite particles disperse on the ferrite maxtrix when soaked at 720°C. In this case, the yield ratio of the trial steel is up to 0.75, but the *n* value is only 0.16. On the other hand, when the soaking temperature reaches 840°C, the volume fraction of martensite exceeds that of ferrite, therefore the elongation of the trial steel decreases to 24%. From the experimental results, favorable comprehensive mechanical properties of DP steels can be obtained when soaked between 760 and 820°C.

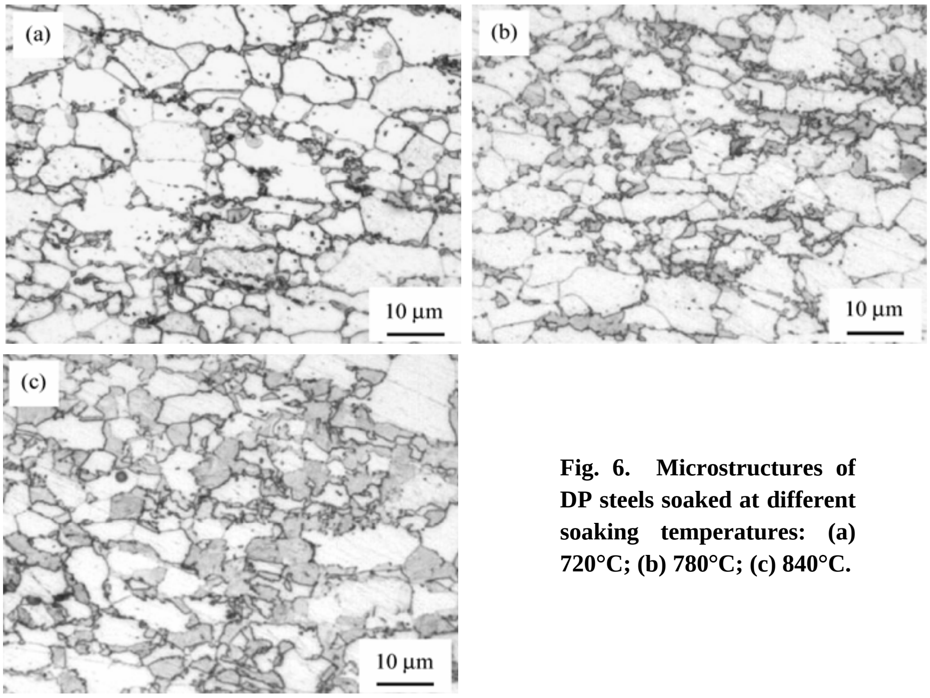

Fig. 6. Microstructures of DP steels soaked at different soaking temperatures: (a) 720°C; (b) 780°C; (c) 840°C.

As the austenization course is rapid at 800°C, the proportion of the two phases will not change obviously when the soaking time is more than 40 s, but C and Mn atoms can diffuse into austensite more sufficiently, which makes ferrite become purer. So the increase in soaking time will improve the elongation of DP steels.

Rapid cooling rate mainly influences the transformation ratio of martensite from austenite. When the cooling rate is too slow to avoid pearlite or cementite transformation, some unstable austenite will transform into cementite or carbide, which will degrade the mechanical properties of DP steels. Fig. 7 shows the microstructures after rapid cooling from 680°C at different rates. It can be seen that there are lots of cementite particles coexisting with martensite after cooling at the rate of 15°C/s. But the case after cooling at the rate of 35°C/s is different, with only martensite islands existing in the ferrite maxtrix.

The purpose of overaging is to improve the quench-hardening and, thereby, the comprehensive mechanical properties of DP steel [13]. As shown in Fig. 8, when overaged at 280°C, the fine structure of martensite islands has few changes. But when the overaging temperature is up to 400°C, martensite has decomposed violently, and lots of carbide particles precipitate. The results indicate that it is necessary to overage below 300°C.

5. Conclusions

(1) The experimental results show that soaking between 760 and 820°C for more than 80 s, rapid cooling at the rate of more than 30°C/s from the quenching temperature between 620 and 680°C, and overaging at less than 300°C are beneficial for the mechanical properties of DP steels.

(2) An appropriate proportion of the two phases is one of the key factors for the favorable properties of DP steels. If martensite and, thereby, free dislocations

are deficient, the tensile strength and n value of DP steels will decrease, while yield strength will increase. But if the volume fraction of martensite is excessive to make martensite become a dominant phase, the yield and tensile strength will increase, whereas, elongation will decrease obviously.

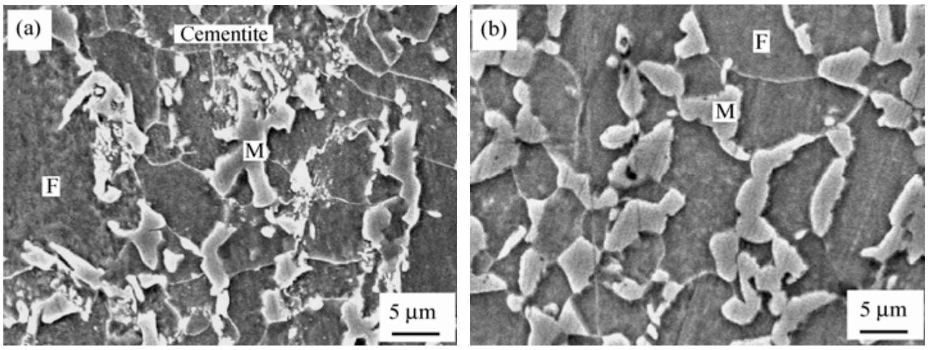

Fig. 7. Microstructures processed at different cooling rates: (a) 15°C/s (ferrite+martensite+cementite); (b) 35°C/s (ferrite+martensite).

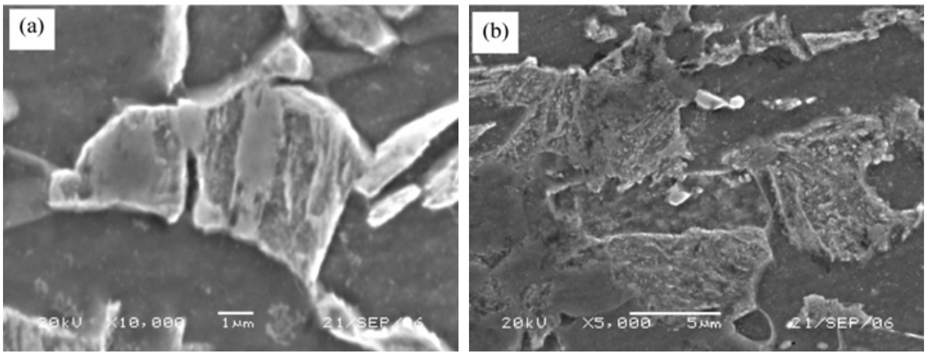

Fig. 8. Microstructures after overaging at different temperatures: (a) 280°C; (b) 400°C.

(3) When rapid cooling rate is not fast enough, pearlite or cementite will appear in DP steels, which are detrimental to mechanical properties. Even though martensite is sufficient, if it has decomposed in high temperature tempering, the properties of DP steels will be deteriorated.

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