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Continuous Cooling Transformation Behavior and Microstructure Control of Nb Microalloyed Reinforcing Bars

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Abstract: In this paper, CCT (continuous cooling transformation) diagrams are determined for Nb-containing reinforcing bars with different Nb, Mn additions, and initial austenite grain sizes by simulating industrial conditions via dilatometry tests. It was found that coarse austenite grain size, high Mn content and Nb remaining in solution all increase hardenability of Nb-containing rebars, namely lower A_{r3} for acicular phase transformation products, which leads to continuous yielding during tensile deformation when the volume fraction of acicular ferrite or bainite microstructure reaches a certain volume fraction. By coupling with actual cooling rates for different size rebars, it can be explained why bainitic structure is prone to form in the center of rebars, especially for small size rebars. In order to achieve required ferrite-pearlite microstructure, cooling strategy is optimized for industrial production.

Key words: Nb microalloying, hardenability, CCT diagram, continuous yielding.

1. Introduction

Reinforcing bars (abbreviated as rebars) have been widely used for reinforcement of concrete. In order to resolve the constraint of natural resources, and to realize carbon emission reduction, promotion of high strength hot rolled rebars, namely 400 MPa and above grades, has been proposed years ago, and big progress has been achieved ever since. In 2018, newly revised standard of GB1499.2 had come into effect to eliminate the low grade of 335 MPa, and to add 600 MPa grade. More importantly, tempered martensitic microstructure obtained through quenching and self-tempering process is strictly banned for building safety. According to the newly revised standard, the metallurgical structure is mainly composed of ferrite and pearlite, and no other items that affect the performance of rebars are allowed. During this promotion process, V microalloying with high nitrogen contents was found to be preferred by rebar makers due to a remarkable higher solubility and prominent precipitation strengthening effect. In addition, the V-containing rebars possess a clear yield point with a significant yield plateau in the typical stress-strain curve [1]. However, big fluctuation in the price of vanadium has triggered the development and application of Nb-containing rebars. Compared to V microalloyed rebars, one of the main issues affecting the promotion of Nb microalloyed rebars is the continuous yielding caused by large amounts of bainitic microstructure. The rebar without a yield point is of considerable concern to civil engineers [1]. In addition, the microstructure with large amounts of bainitic microstructure also manifests low maximum uniform elongation of A_{gt}, which is one important index for anti-seismic performance with minimum characteristic value of 9.0 percent for HRB400E and HRB500E.

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Typically, there are three kinds of microstructure for structural steels: ferrite-pearlite, bainitic and martensitic structure. Phase transformation behavior decides the final room temperature microstructures, which affects the yielding phenomenon. According to early works, yield point and yield plateau are the typical feature of ferrite-pearlite microstructure in low-carbon steels, which is caused by the interaction between the interstitial atmospheres and the dislocation motion in ferrite matrix [1]. Similarly, continuous yielding phenomenon is the typical feature of acicular ferrite or named bainitic structure, and yield point will disappear when the volume fraction of bainite reaches certain percentage. According to the standard of GB1499.2-2018, the characteristic value of yield strength is R_{eL}. As for those steels without yield point and yield plateau, the characteristic value of yield strength should apply the regulated non-proportionality elongation stress $R_{p0.2}$. Fig. 1 gives the typical stress-strain curves of two kinds of microstructures. It is seen that ferrite-pearlite microstructure possesses clear yield point and yield plateau with high yield strength and low tensile strength, but acicular ferrite microstructure with continuous yielding present low yield strength and high tensile strength.

For the HRB400E grade, yield strength is the main target considering cost factors, so bainitic microstructure with continuous yielding is not preferred by rebar makers. In this paper, we will focus on the transformation behavior and microstructure control of Nb-containing rebars, as well as the factors affecting the hardenability and optimization of cooling strategy.

To understand and control the transformation behavior in steels, it is essential to review the basic concept of hardenability. The concept of hardenability in steels was introduced more than 70 years ago, to correlate the integrated effects of austenite grain size, the quenching process, and the composition of the steel on the hardenability phenomenon. With years of studies, it has been recognized that hardenability is affected by the following factors: (1) the austenite size, (2) the carbon content, (3) the alloy content, and (4) the nonmetallic inclusions and/or undissolved carbides and nitrides. An increase in the austenite grain size, the carbon and alloy content tends to increase the hardenability by decreasing the nucleation and growth of diffusion-controlled transformation products. Factors which tend to decrease the austenite grain size and increase the number of nonmetallic inclusions and/or undissolved carbides and nitrides tend to decrease the hardenability of steel [2]. Regarding the effect of niobium on hardenability, it is closely linked with their existing state in each production step. Take low carbon Nb-containing plate as example, the high

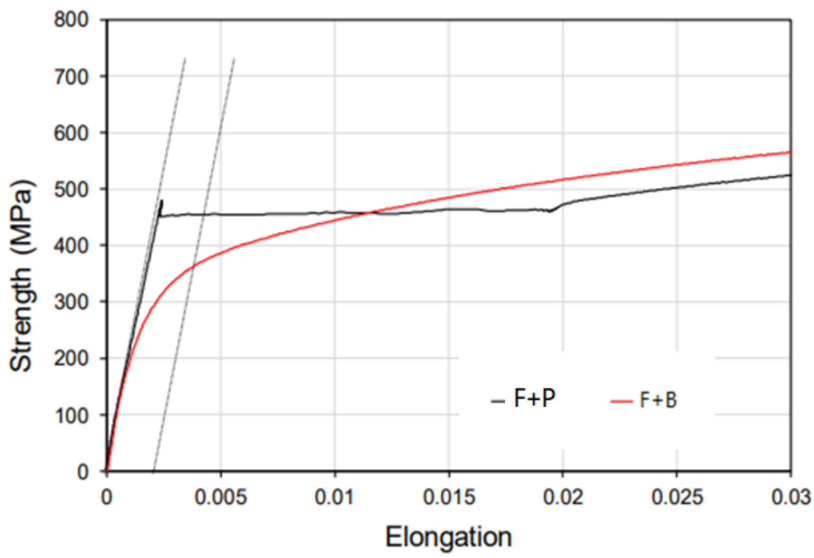


Fig. 1 Yielding behavior of two kinds of microstructure.

S_v resulted from controlled rolling by itself would lower the hardenability, namely increase of A_{r3}. In order to obtain lower transformation temperature and lower temperature transformation products, higher alloying with Mo and Mn and accelerated cooling are needed. When relatively large amounts of Nb are in solution in austenite during transformation, it often has an important effect on the CCT diagram and subsequent transformation products, such as acicular ferrite, Widmanstatten ferrite and even martensite, particular at higher cooling rates [4].

The purpose of this work is to elucidate the formation mechanism of bainitic microstructure for Nb-microalloyed rebars by thermal simulation tests of ferrite phase transformation, and then based on which cooling strategy have been optimized to obtain required ferrite and pearlite with yield point.

2. Experiment on the Effect of Bainitic Microstructure on Yielding Behavior

To understand the impact of the phase fractions on the mechanical strength and yielding behavior, thermal simulation experiments for a one Nb-containing rebar was conducted, whose chemical compositions are shown in Table 1.

The schematic diagram of two-step thermal cycles is shown in Fig. 2. All specimens were reheated to 1,250 °C for 120 min to dissolve added niobium as possible, and then quenched to room temperature in the first thermal cycle. In the second thermal cycle, all specimens were reheated to 980 °C for austenite conditioning, and then cooled at different cooling rates, ranging from 2.4 °C/s to 10 °C/s. The austenite grain sizes from quenched samples are about 11.8 μm, as shown in Fig. 3.

Table 2 shows the tensile properties at different cooling rates, respectively. As we can see from Table 2, the yield strengths decrease with increase of cooling rates, but on the other hand, the tensile strengths increase with the increase of cooling rates. For this metallurgical phenomenon, it can be explained by work hardening rate. With large amounts of bainitic microstructure, both grain boundary area and dislocation density are higher than only ferrite-pearlite microstructure, so work hardening rate is higher.

Fig. 4 shows the stress-strain curves of experimental steel. With the increase of cooling rates, the yield plateaus become short, and finally disappear when cooling rate is higher than 3.6 °C/s. Corresponding

Table 1 Chemical compositions of experiment steels.

Steel	C	Si	Mn	P	S	Nb	N
Nb	0.25	0.45	1.5	0.04	0.02	0.03	0.052

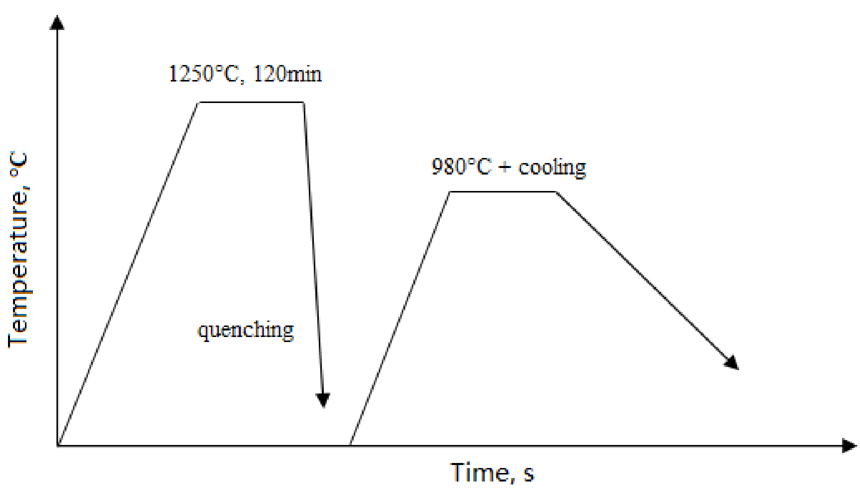


Fig. 2 Schematic diagram of two steps thermal cycles.

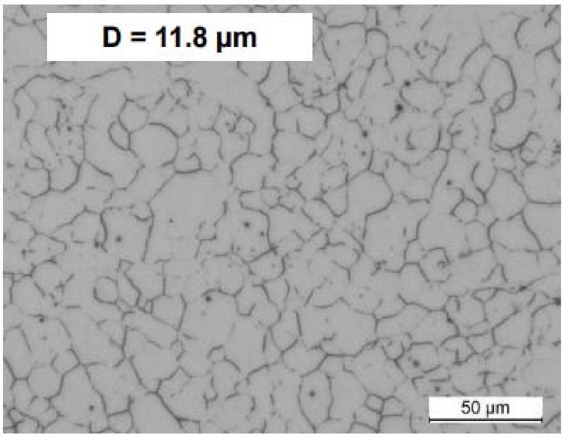


Fig. 3 Prior austenite grain before phase transformation.

Table 2 Test results of samples with different cooling rates.

Sample	R_{eL} or $R_{0.2}$ if no yield point, MPa	R_m, MPa	YPE (yield point elongation), %	A, %
2.4 °C/s	458	676	1.3	29
3.3 °C/s	431	682	0.36	30
3.4 °C/s	415	708	0	29
3.6 °C/s	390	724	0	28
5.3 °C/s	380	734	0	23

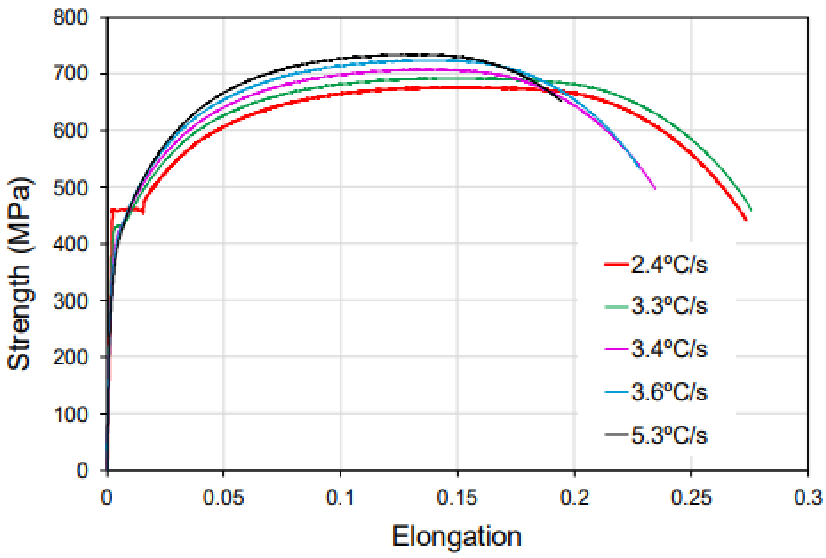


Fig. 4 Stress-strain curves with different cooling rates.

to the stress-strain curves, the yield strengths with high cooling rates are lower than required minimum 400 MPa.

Fig. 5 shows the phase transformation products, and low temperature phase transformation products will increase with increase of cooling rates. With further microstructure analyzing, it was found that room temperature is composed of ferrite, pearlite, bainite and small amounts of MA components when the cooling rates are higher than 3.4 °C/s. Through correlation, it was observed that yielding point would disappear when the volume fraction of bainitic microstructure is higher than 16.5 percent, as shown in Fig. 6. To obtain a YPE of around 1%, the fraction of non-ferrite-pearlite constituents should be kept below 10%.

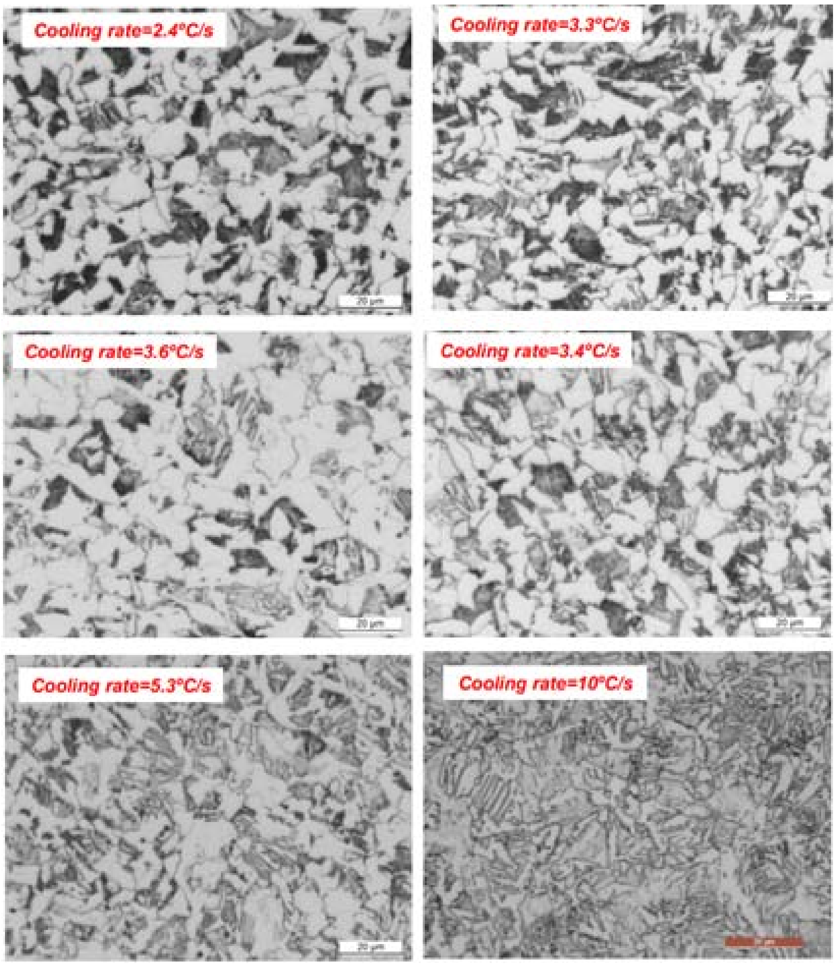


Fig. 5 Microstructures by applying different cooling rates.

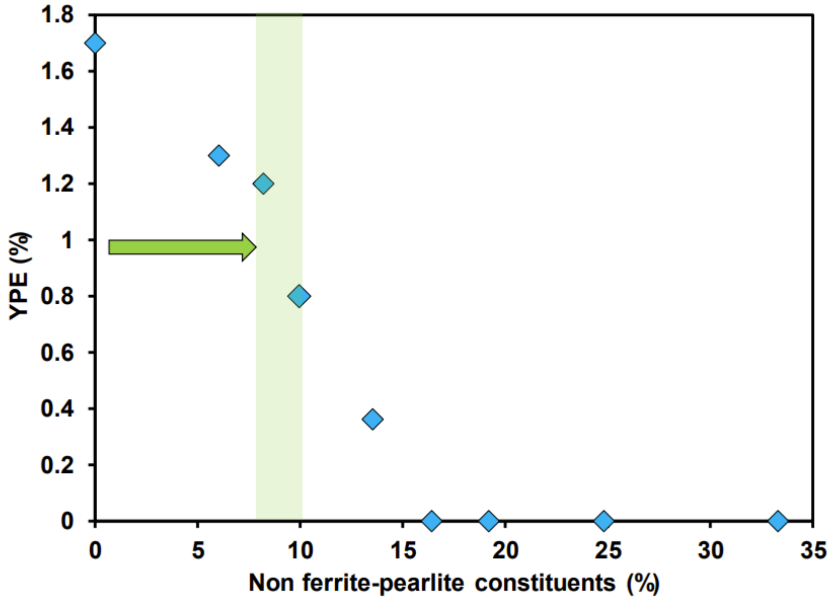


Fig. 6 Effect of non-ferrite-pearlite on the YPE.

3. CCT Curves and Phase Transformation Behavior

In this section, continuous cooling transformation diagrams via dilatometry tests were performed for three experimental steels, whose chemical compositions are shown in Table 3. The main difference between steel A and steel B is the additions of niobium, and the main difference between steel B and steel C is the content of Mn. Besides the effect of chemical compositions, the effect of prior austenite microstructure from hot working (reheating and rolling) on phase transformation behavior had been studied.

All dilatometry tests were carried out by Spain's Ceit research institute, and the whole thermal simulation tests were composed of two cycles, just like the description in Fig. 1. For the first cycle, the reheating temperature was set at 1,250 °C for 120 min, and then quenched to room temperature. Fig. 7 shows the schematic diagram of the second thermal simulation cycle. All specimens were reheated to given temperature, depending on the addition of Nb for complete dissolution, and then deformed with 0.3 in pass strain, and 1 s^{-1} in strain rate, and finally cooled at different cooling rates for three kinds of steel.

3.1 Effect of Austenite Grain Size on Phase Transformation and Product

As mentioned, prior austenite microstructure plays an important role in phase transformation. Fig. 8 shows the CCT curves of steel A with 6 μm and 20 μm in austenite grain size respectively. As we can see, ferrite transformation start temperature will decrease with the increase of prior austenite grain size, and the bainite transformation start temperature will move right and down. When the austenite grain size is 6 μm, no bainitic microstructure was found for steel A and B when cooling rate is less than 5 °C/s. In mass production, the cooling rates of 12 mm to 40 mm rebars are lower than 5 °C/s.

Figs. 9 and 10 show the ferrite transformation microstructures of steel A with 6 μm and 20 μm in austenite grain size respectively, which is in good agreement with simulation results of CCT curves.

Table 3 Chemical compositions of three experimental steels.

Steel	C	Si	Mn	Nb
A	0.20	0.36	1.28	0.015
B	0.24	0.50	1.25	0.030
C	0.26	0.44	1.50	0.030

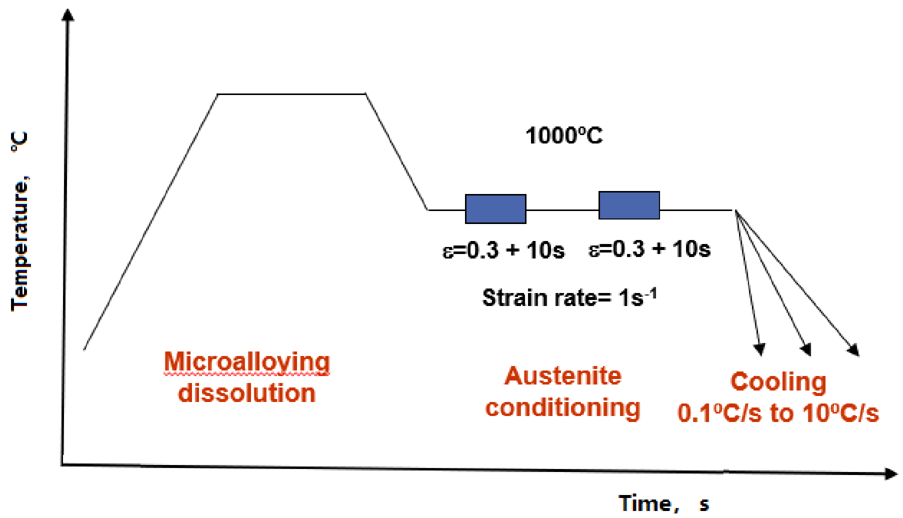


Fig. 7 Schematic diagram of the second thermal simulation cycle.

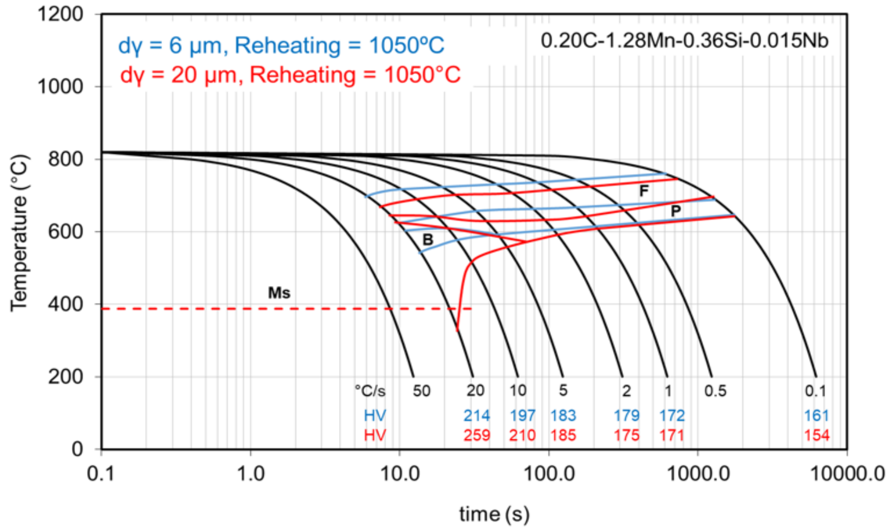


Fig. 8 CCT curves of steel A: 6 μm and 20 μm.

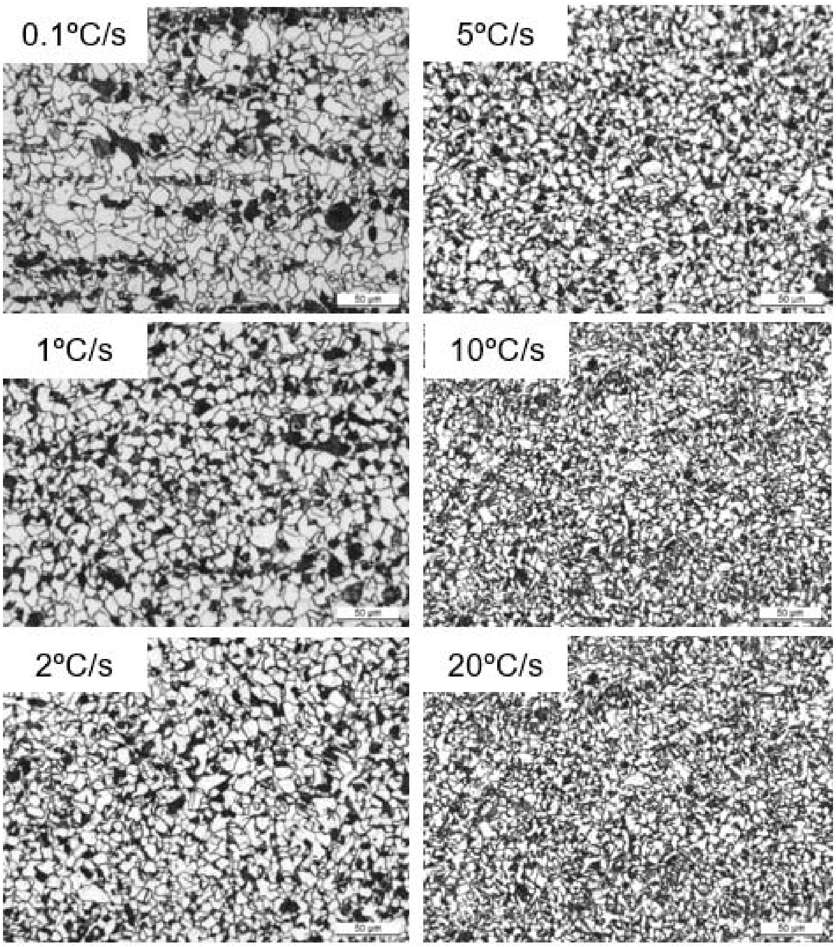


Fig. 9 Microstructures of steel A with 6 μm in grain size.

Figs. 11 and 12 show the CCT curves and transformation products of steel B with 6 μm and 20 μm in austenite grain size respectively. As we can see, the effect of prior austenite grain size is very prominent. For steel B, bainitic microstructure starts to appear even when cooling rate is 2 °C/s.

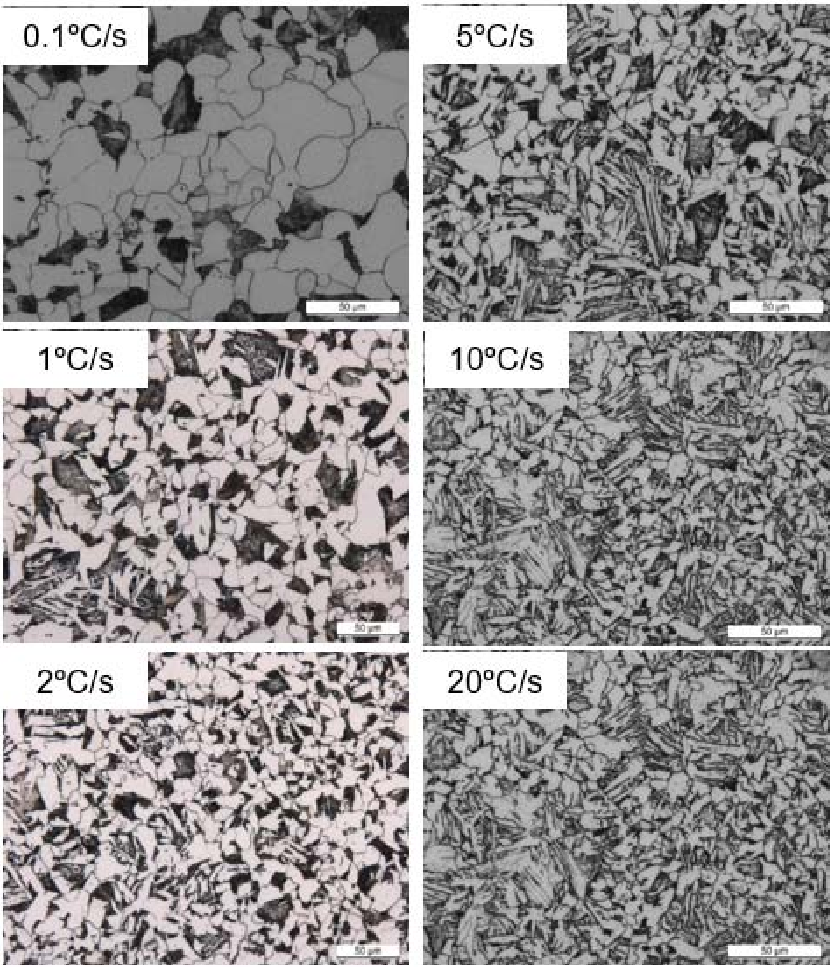


Fig. 10 Microstructures of steel A with 20 μm in grain size.

3.2 Effect of Nb Additions on Phase Transformation and Products

For low-carbon flat products, more attention was paid to the grain refinement resulted from TMP (thermomechanical processing), and recrystallization and grain growth can be inhibited through both solute drag effect and pinning effect of strain-induced precipitates that are the core concept of Nb microalloying. Due to low temperature and heavy reduction, more niobium contents exist in precipitation.

However, due to high carbon contents and exclusive processing conditions like high strain levels, high strain rates and short pass interval times, so the whole hot rolling temperatures are higher than recrystallization stop temperature. More importantly, the final rolling temperature for small size rebars is probably higher than reheating temperature, which means more niobium in solid solution and relatively high austenite grain sizes before phase transformation. Based on above introduction, both Nb in solution and big austenite grain size would increase the hardenability of steels. In addition, it was observed that high Mn contents have a big impact on phase transformation behavior. In this chapter, effect of Nb, Mn addition and austenite grain size on continuous cooling transformation will be carried out and presented.

Fig. 13 shows the CCT curves of steel A and steel B with an austenite size of 6 μm. As we can see, different amounts of Nb do not change the transformation behavior for small austenite grain size such as 6 μm.

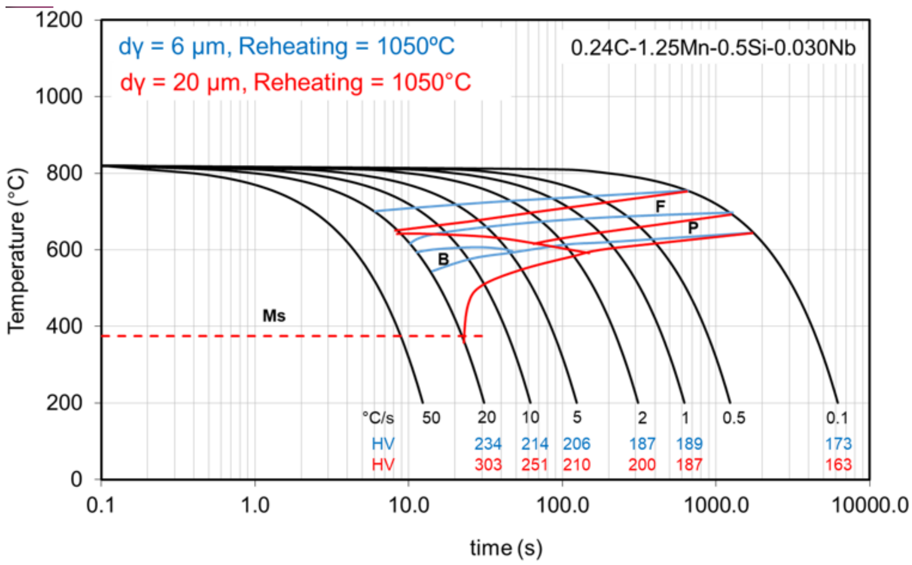
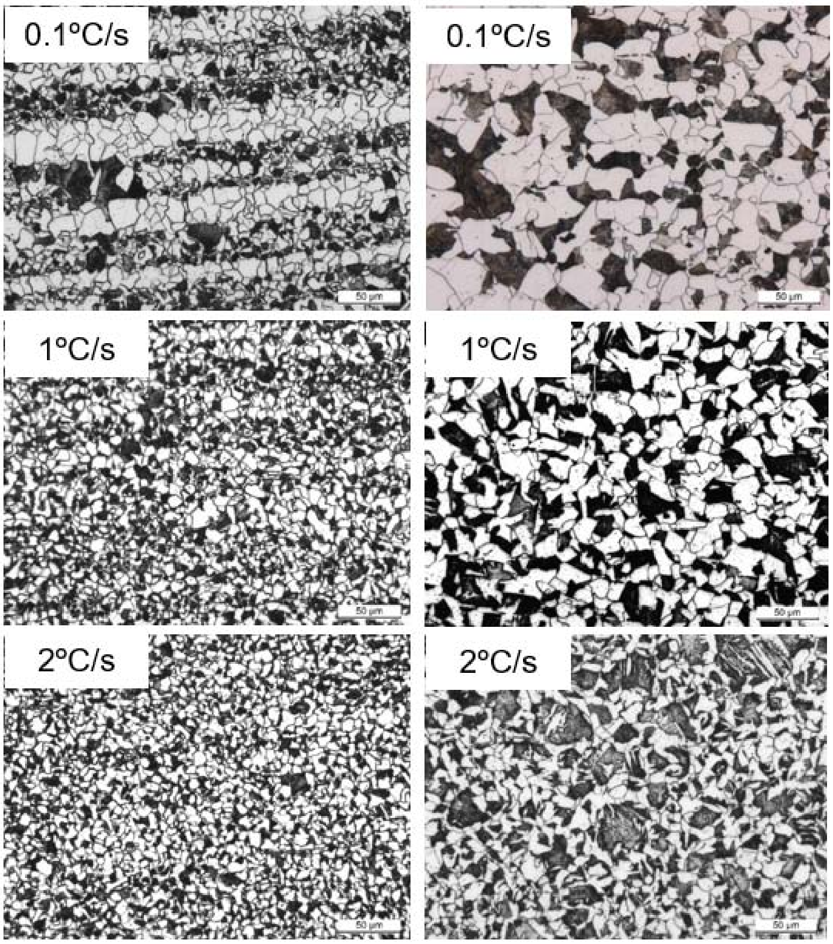


Fig. 11 CCT curve of steel B: 6 μm and 20 μm.



(a) 6 μm (b) 20 μm

Fig. 12 Comparison of phase products for steel B with 6 μm and 20 μm in austenite grain size.

Fig. 14 shows the corresponding phase microstructures at different cooling rates. All transformed microstructures are composed of fine ferrite and pearlite when cooling rates are not higher than 2 °C/s. Compared to the steel A, the pearlite percentage of steel B is clearly higher, regardless of cooling rates.

Fig. 15 shows the CCT curves of steel A and steel B with an austenite size of 20 μm. With the increase of austenite grain sizes, the effect of high Nb additions on ferrite transformation is more marked, and bainitic microstructures start to appear for steel B when cooling rate was set at 2 °C/s.

Fig. 16 presents the phase microstructures of steel A and steel B. As shown from the comparison results, ferrite grain sizes are more finer, and the percentage of pearlite volume fraction is higher than that of steel A.

3.3 Effect of High Mn Contents and High Reheating Temperature on Phase Transformation

It is widely recognized that additions of high manganese to rebars have a greater impact on the hardenability, especially together with big austenite grain size from high reheating temperatures. Fig. 17 shows the CCT curves of steel B and steel C with 20 μm and 38 μm in austenite grain size respectively. As we can see, bainitic microstructure can take place even at very slow cooling rate of 0.5 °C/s, so Mn additions would be controlled less than 1.5 percent. In addition, high reheating temperature is not preferred because Nb(C,N) particles undissolved can retard austenite grain coarsening at reheating and rolling stage.

Fig. 18 presents the final phase transformation microstructures of steel B and steel C. As we can see, large amounts of bainitic microstructure exist for steel C even when cooling rate is 1 °C/s. In industrial production, actual cooling rates for all size rebars are higher than 1 °C/s, so it is very challenging to get rid of bainite.

Based on thermal simulation results of CCT curves and phase transformation products, we can obtain following conclusions:

(1) Increase of austenite grain size advances transformation to low temperature phases. For 0.015% Nb, presence of bainite was observed at lower cooling rates for 20 μm in grain size.

(2) For steel B with 0.03% Nb, the increase of grain size advances transformation to low temperature phases considerably.

(3) Presence of high Mn addition and higher reheating temperature has a strong impact on the transformation behavior, considerably promoting transformation to low temperature phases.

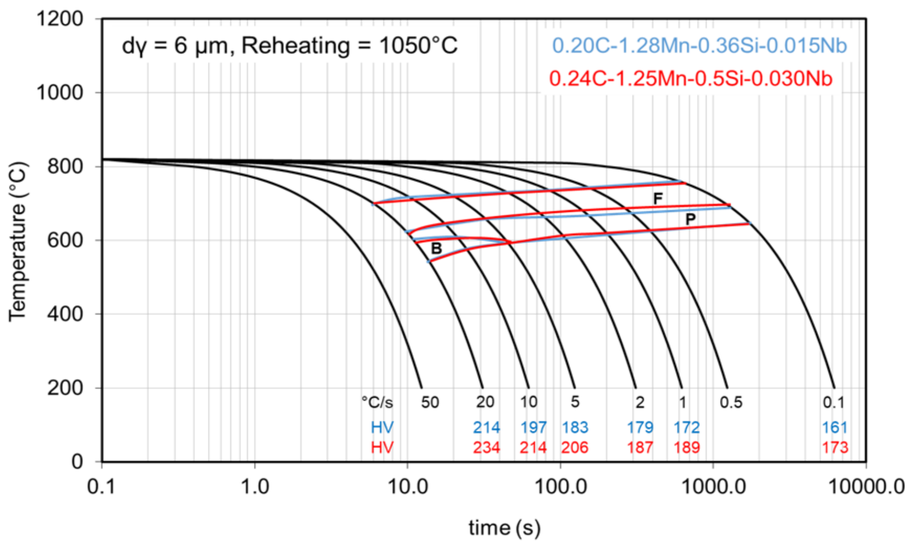
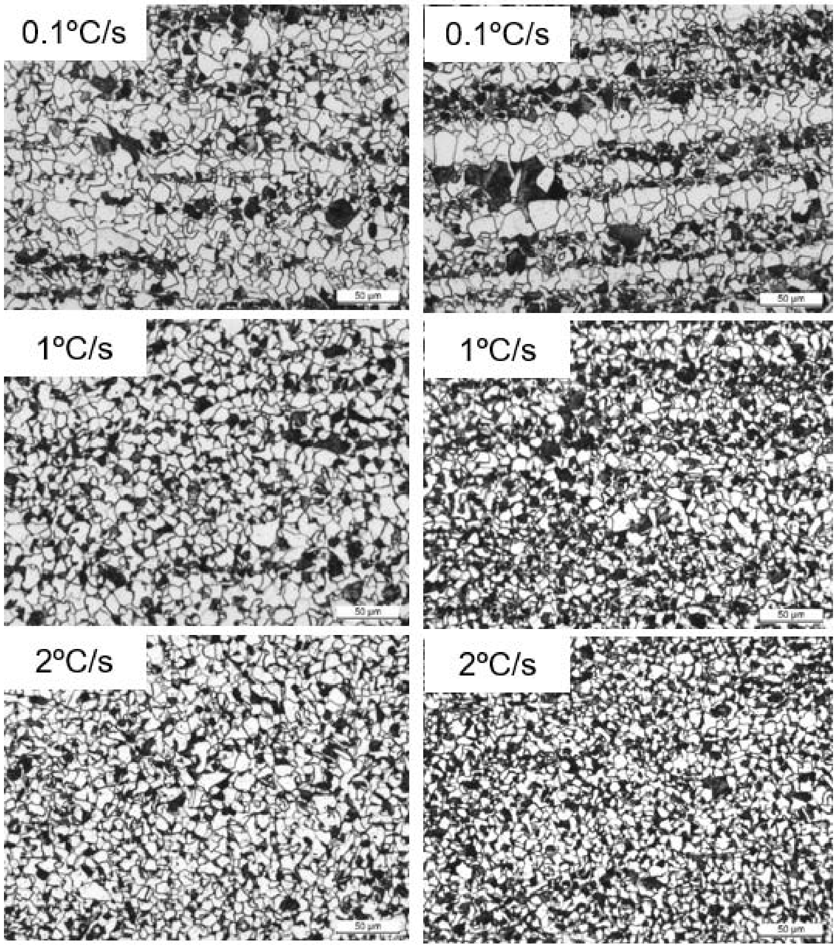


Fig. 13 Comparison of effect of Nb additions, 6 μm.



(a) Steel A (b) Steel B

Fig. 14 Phase transformation microstructure, 6 µm.

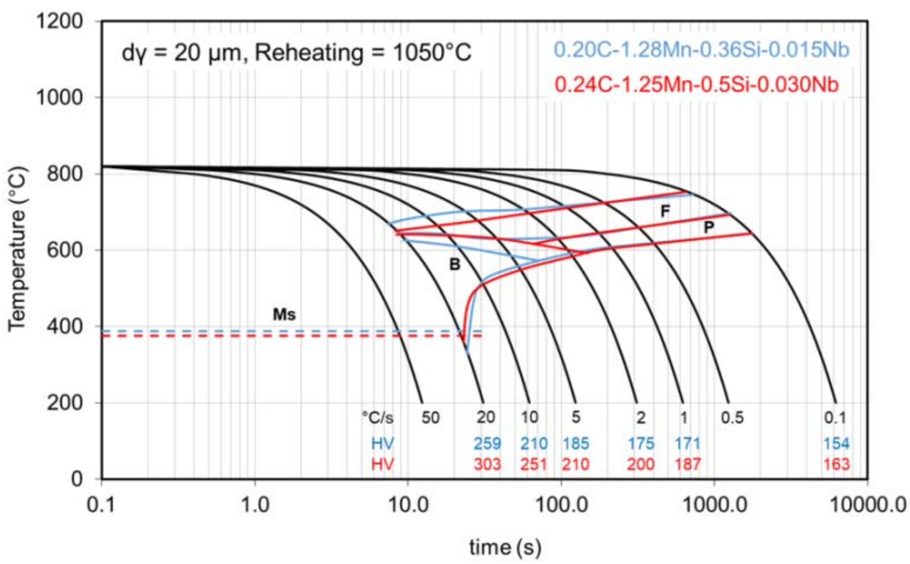
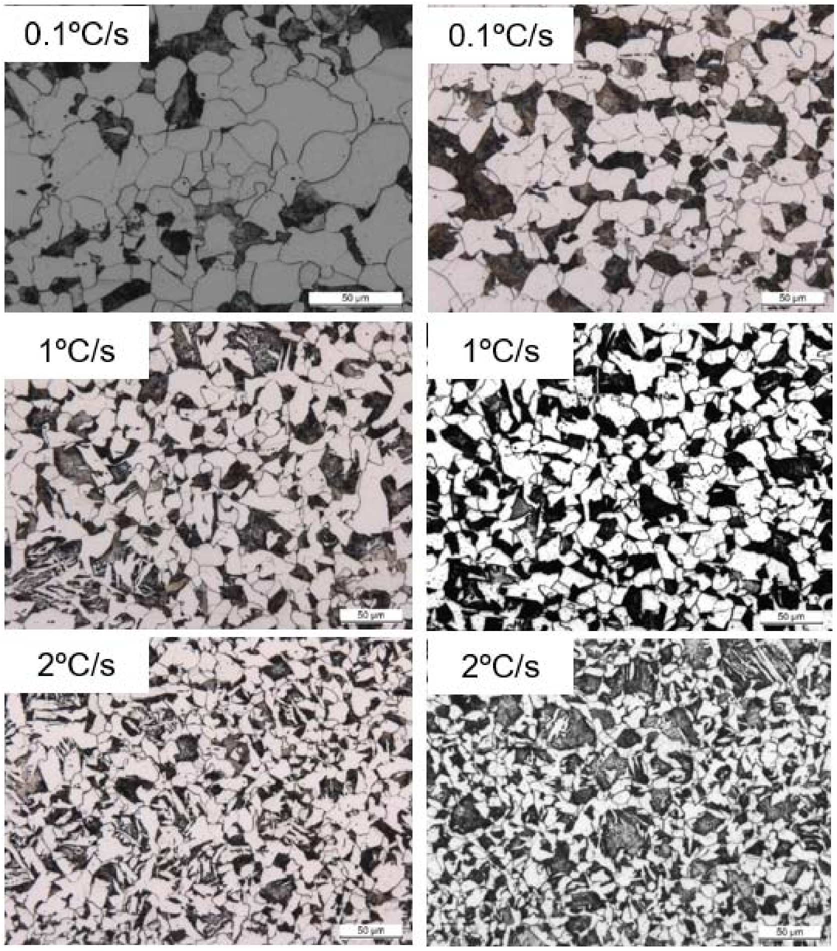


Fig. 15 Comparison of effect of Nb additions, 20 µm.



(a) Steel A (b) Steel B

Fig. 16 Phase transformation microstructure, 20 μm.

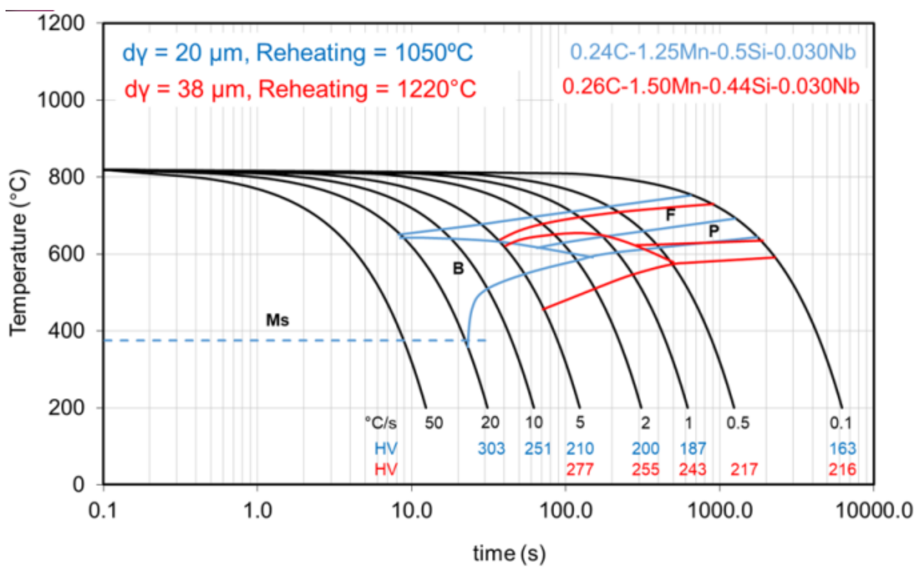
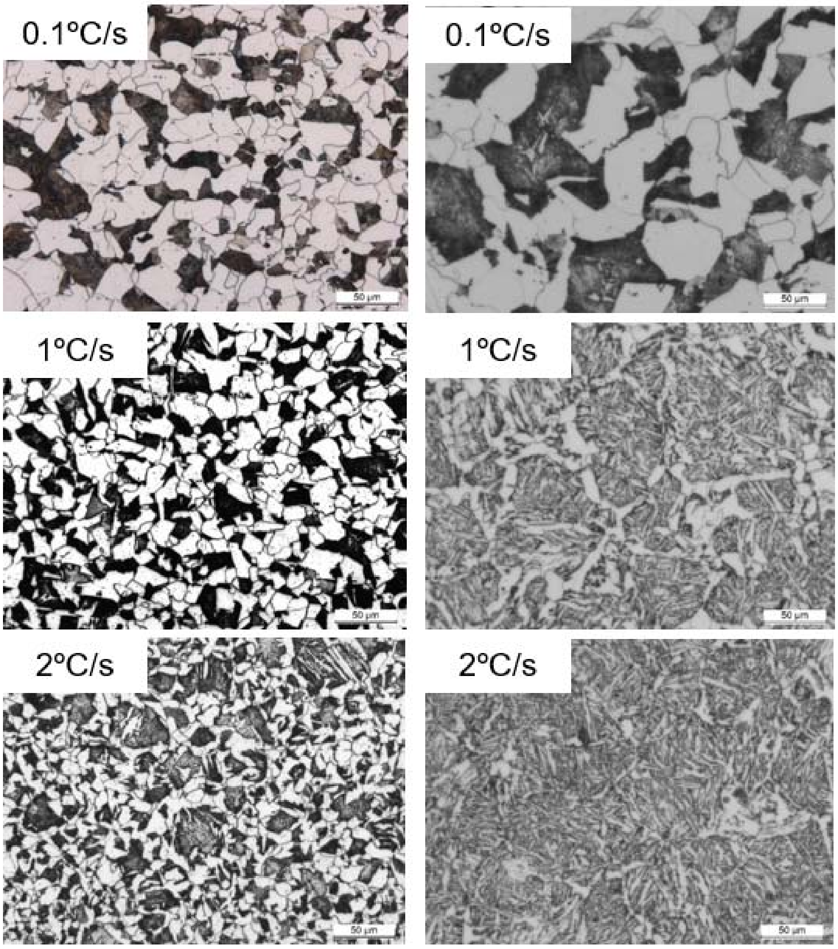


Fig. 17 CCT curves of steel B and steel C with different austenite grain sizes.



(a) Steel B, 20 μm (b) Steel C, 38 μm

Fig. 18 Effect of high Mn and high reheating temperature on phase transformation products.

4. Discussion and Optimization of Cooling Strategy

According to the standard of GB1499.2-2018, tempered microstructures, both martensite or sorbite, caused by quenching and self-tempering process, are strictly banned. On the other hand, bainitic microstructure with continuous yielding is not acceptable by rebar makers and end users. When the volume fraction of bainite is higher than 16.5 percent, continuous yield phenomenon takes place. During industrial trial process, it was observed that bainitic microstructure easily takes place for small sizes, like 14 mm in diameter. For this phenomenon, it can be explained by relatively fast cooling rates for small size rebars during phase transformation period, as shown in Fig. 19.

In addition, processing conditions of small size rebars, especially high final rolling temperatures resulted from high strain levels, high strain rates and short pass interval times, can lead to relatively large austenite grain sizes and high niobium in solution, both of which promote the formation of low temperature phase transformation products.

Based on thermal simulation results of CCT curves and phase transformation microstructures, it was found that large austenite grain sizes have a great impact on hardenability, which provide the possibility to counter the effect of solute Nb and Mn on hardenability. For most rebar production lines, there is no cooling equipment before finishing rolling stands for controlled rolling effect once used for hot rolled flat products, so controlled cooling after rolling

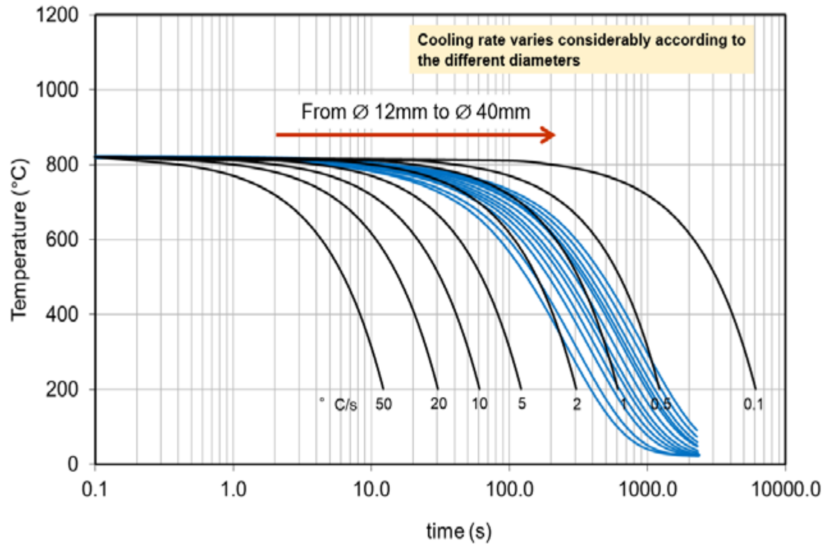


Fig. 19 Cooling profiles of rebars from 12 mm to 40 mm.

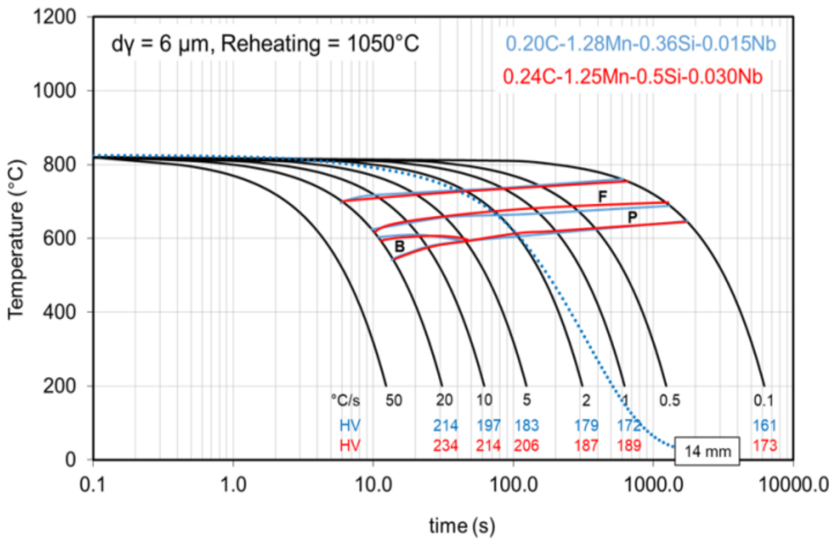


Fig. 20 Coupling the cooling of 14 mm with CCT curve of 6 μm for steel A and Steel B.

becomes the measure available to refine austenite grain size for compensating the effect of solute Nb and high Mn contents. It was proved by mass production that water cooling after rolling can decrease and eliminate bainitic microstructure effectively, as shown in Fig. 20.

Considering the requirement of ferrite-pearlite microstructure for hot rolled rebars, intelligent design for cooling strategy is needed for Nb-containing rebars. Firstly, water cooling after rolling is required to keep fine austenite grain size. Secondly, if the surface temperature of rebars at the exit of cooling equipment has to be higher than martensite zone, otherwise, tempered sorbite or tempered martensite would take place. Based on these considerations, layout with two or three cooling section was proposed for limited cooling.

Another wrong recognition about Nb-containing rebars is about reheating temperatures. Due to limited solubility of rebars with high carbon contents, high reheating temperatures were adopted, even up to 1,250 °C/s, which will lead to big austenite grain size and high solute Nb in austenite before phase, transformation.

5. Summary and Conclusions

Based on the thermal simulation tests, the following conclusions can be obtained:

Due to exclusive production processing with high strain levels and strain rates, the whole hot working takes place in high temperature recrystallization regime, so more niobium contents are left as solution before phase transformation, so niobium in solution would promote the formation of low temperature phase transformation products like acicular ferrite or bainitic microstructure.

Besides the solute niobium, effects of the prior austenite grain size on transformation behavior and final products are very marked, so keeping fine austenite grain sizes before ferrite phase transformation can decrease the hardenability to avoid the formation of bainitic microstructure.

For Nb-containing rebars, high reheating temperature will bring about coarse austenite grain size due to without water cooling for more rebar production line, which will promote the formation of bainitic microstructure. From the perspective of microstructure control, high reheating temperature is not preferred.

For Nb-containing rebars, addition of high Mn contents would strongly promote the formation of bainitic microstructure, so Mn additions will be less than 1.50 percent.

For Nb-containing rebars, bainitic microstructure can be controlled through intelligent design of cooling strategy.

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