ISIJ International, Vol. 46 (2006), No. 10, pp. 1510–1515

Effects of Microalloying Elements on Mechanical Properties of Reinforcing Bars

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(*Received on April 19, 2006; accepted on June 23, 2006*)

Reinforcing steel bars are an important material for construction. The strength level of rebar has been increased to as high as, for example, 345, 390 and 490 grade. In order to produce high-strength rebar, V microalloying technology has been successfully applied, while Nb application to reinforcing bars has been tried energetically recently. However, exact discussions about the effect of hot-rolling and cooling condition in Nb microalloyed steel on mechanical properties have not been reported exactly.

This paper reports on the experimental results of the effects of reheating temperature and cooling rate after hot-rolling on the microstructure and mechanical properties of 0.25C–0.5Si–1.2Mn steel and 0.25C–0.5Si–1.2Mn–0.05Nb(+0.05V) steel (mass%).

0.05 % Nb and 0.05 % Nb+0.05 % V additions to 0.25C–0.5Si–1.2Mn steel (mass%) led to an effective increase in strength, especially at high reheating temperature. This strengthening is caused by precipitation hardening and grain refinement hardening. Accelerated cooling after hot-rolling to 700°C was effective in increasing strength and yield point elongation.

KEY WORDS: bar; reinforcing bar; niobium; vanadium; carbonitride precipitates; grain refinement.

1. Introduction

Weldable reinforcing steel bar is one of the important steel products widely used in civil construction. In order to meet demands for lighter-weight products at lower carbon equivalent for weldability and lower price, higher-strength weldable steel bars have been developed by applying microalloying elements such as Nb, Ti and V[1–4)] or applying accelerated cooling—so called "Tempcore Process"[5)] or Tempcore Process with microalloying elements.[6)] Although V was the element most frequently used for this purpose, fluctuations in the V price have led bar makers to initiate the project to replace it with Nb.

The application of Nb to reinforcing bars as introduced in literatures[1–4)] has demonstrated that Nb addition is effective in increasing yield strength and tensile strength and is more effective than V addition in increasing both types of strength. However, the effects of processing parameters such as reheating temperature and cooling rate after hot-rolling on the mechanical properties have not been described precisely.

The experimental results concerning the effects of Nb addition and processing parameters such as reheating temperature and cooling rate after hot-rolling finishing on microstructure and mechanical properties of 0.25%C–0.5%Si–1.2%Mn–(0.05%Nb, 0.05%Nb+0.05%V) steels were extensively discussed in the paper.

2. Experimental Procedure

Steels shown in **Table 1** were melted in the air and were cast. 0NB is a base steel with 0.25%C–0.5%Si–1.2%Mn. 0.05% Nb and 0.05% Nb+0.05% V are added to the base steel, 0NB, and designated as 5NB and 5NV. The carbon equivalent (Ceq) of these steels is around 0.56.

The cast steels were hot-forged to $50^{t}\times 40^{w}$ mm and reheated. They were then hot-rolled in the laboratory rolling mill to 10 mm in thickness by two passes. The reduction of each pass was about 50%. The hot-rolling was carried out by using plate in this experiment.

The most important parameter in controlling the mechanical properties of microalloyed steel is the reheating temperature, which affects the solid solute Nb content and austenite grain size. As shown in **Fig. 1**(a), the RT (Reheating Temperature) was varied from 1 050 to 1 250°C to investigate its effects. The steels were kept for 30 min at each RT. In order to carry out the experiment precisely, the finishing temperature was controlled by the entry temperature of the second rolling. The entry temperature and delivery temperature of the second rolling were nearly the same, 900°C. The hot-rolled sheets were air-cooled to room temperature after hot rolling. Accelerated cooling after hot-

Table 1. Chemical compositions of steels (mass%).

	C	Si	Mn	P	S	Al	Nb	V	N	Ceq
0NB	0.249	0.47	1.19	0.023	0.002	0.040	–	–	0.0065	0.554
5NB	0.248	0.51	1.22	0.024	0.002	0.042	0.051	–	0.0079	0.565
5NV	0.244	0.51	1.26	0.026	0.003	0.036	0.050	0.045	0.0071	0.569

Ceq = C(%) + Si(%)/7 + Mn(%)/5 + Cr(%)/9

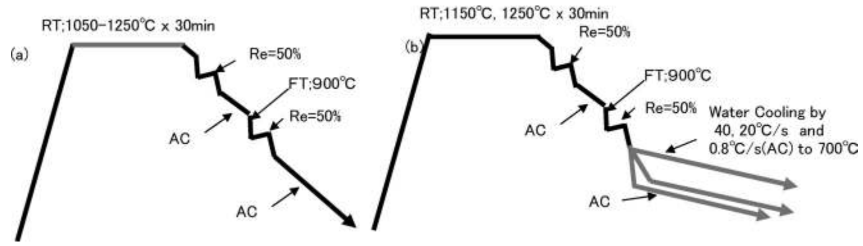

Fig. 1. Schematic illustration of hot rolling procedures to examine the effects of (a) RT (reheating temperature) and (b) CR (cooling rate) between 900°C and 700°C.

rolling is an important parameter in controlling microstructure. The effect of the cooling rate from 900 to 700°C was examined from 40 to 20°C/s by changing the water spray density. Air cooling with a cooling rate of 0.8°C/s was conducted for the purpose of comparison. The schematic hot-rolling and cooling condition is shown in Fig. 1(b).

Prior austenite grain was observed by water-quenched specimens from the necessary point. The procedure is explained in each section.

Tensile testing was conducted ten days after hot-rolling by using JIS 14 A, whose diameter and gauge length are 8 mm and 50 mm, respectively. The testing speed was 5 mm/min. The effect of aging was investigated by tensile-testing the specimens that had been kept for 56 d after hot-rolling.

The microstructures of the final product and prior austenite grain were observed by optical microscopy with nital etching and nitric acid solution (2% HNO_3) etching, respectively.

3. Results

3.1. Effect of RT (Reheating Temperature)

Figure 2 shows the effects of microalloyed elements and RT (Reheating Temperature) on LYP (Lower Yield Point Strength) and TS (Tensile Strength). LYP in 5NB increases as RT increases from 440 MPa at 1 050°C and 1 100°C to 485 MPa at 1 250°C. LYP of 5NV is about 30–60 MPa higher than 5NB. LYP increased from 470 MPa at 1 050°C to 535 MPa at 1 250°C. On the other hand, LYP of 0NB decreases with RT about 10 MPa. The difference in LYP between 0NB and 5NB is 20 MPa at low RT and 75 MPa at 1 250°C. The difference in LYP between 0NB and 5NV is 50 MPa at low RT and 130 MPa at 1 250°C. TS shows the same behaviour as LYP. The increase in TS with increase in RT from 1 050 to 1 250°C is about 40 MPa and 50 MPa in 5NB and 5NV, respectively, but close to 0 in 0NB.

Figure 3 shows the effects of microalloyed elements and RT on El (Total Elongation) and YPEl (Yield Point Elongation). Although YPEl is not defined in JIS, this value is the essential point in its application to concrete reinforcement, especially in seismic regions. El decreases with increase in RT, but El was higher than 28% except one point in all RT conditions. YPEl decreases slightly with increase in RT but is higher than 1.8% in microalloyed steels, which is a satisfactory value, judging from the existence of yield point is acceptable condition in the actual trading. Microalloyed steels show higher values than 0NB in the entire RT range.

Strength and El relationship is generally expressed by LYP×El. **Figure 4** shows the calculated LYP×El. 0NB shows the lowest value and 5NV shows the highest value. LYP×El of 5NB is half-way between them. These results mean that Nb and Nb+V added steel can show a better strength-elongation balance than Nb free steel.

The microstructure is important for understanding the behaviour of strength and YPEl. The effects of microalloyed elements on the optical microstructures reheated at 1 150°C are shown in **Fig. 5**. The microstructure consisted

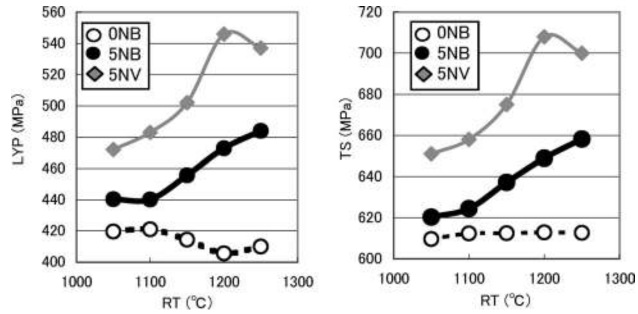

Fig. 2. Effects of microalloying elements and RT (reheating temperature) on LYP (lower yield point) and TS (tensile strength).

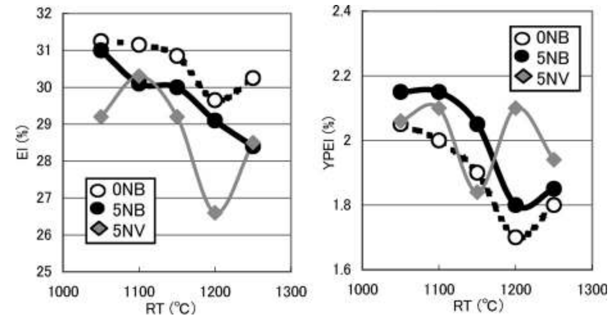

Fig. 3. Effects of microalloying elements and RT (reheating temperature) on El and YPEl (yield point elongation).

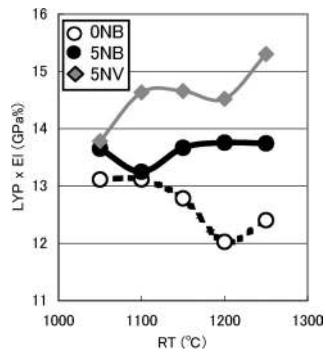

Fig. 4. Effects of microalloying elements and RT on strength-elongation balance expressed by LYP×El.

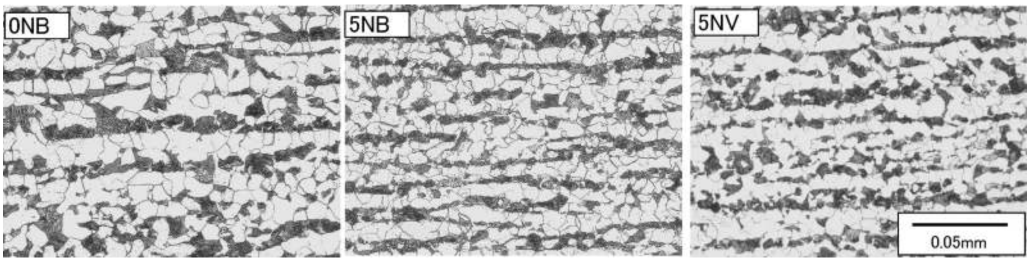

Fig. 5. Effect of microalloying elements on the microstructures of steels reheated at 1 150°C.

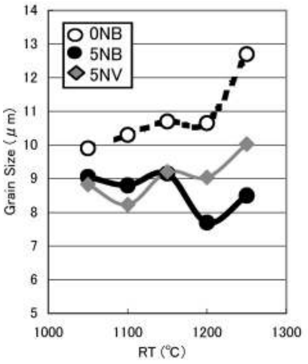

Fig. 6. Effects of microalloying elements and RT on grain size and volume fraction of pearlite.

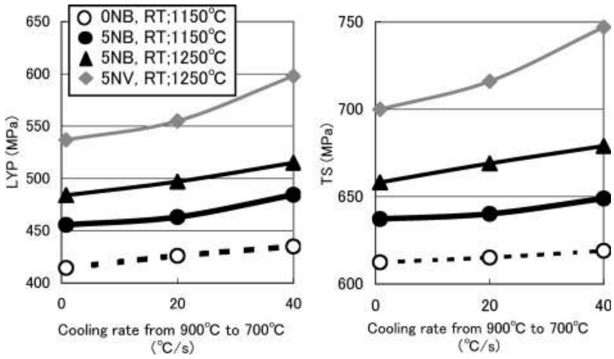

Fig. 7. Effects of microalloying elements, reheating temperature and CR (cooling rate) on LYP and TS.

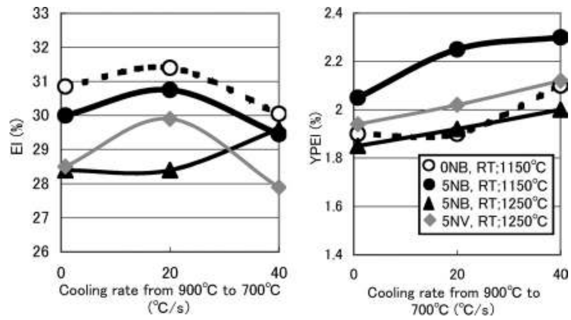

Fig. 8. Effects of microalloying elements, reheating temperature and CR (cooling rate) on El and YPEl.

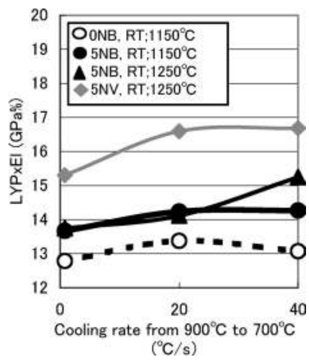

Fig. 9. Effects of microalloying elements, reheating temperature and CR (cooling rate) on strength and elongation balance expressed by LYP×El.

of ferrite and pearlite. Bainite or other low-transformation products were not observed. The ferrite grain size of steel 5NB and 5NV is obviously smaller than 0NB.

For the quantitative discussion, ferrite grain size and volume fraction of pearlite are observed by image analysis and the results are shown in **Fig. 6**. The volume fraction of pearlite was around 30% in all steels. The ferrite grain size increased from 10 to 13 mm with increase in RT from 1 050 to 1 250°C in steel 0NB. The coarse microstructure in 1 250°C in 0NB appears to be caused by the coarse austenite grain size. Microalloyed steels show smaller grain size in all RT range. 5NB shows a smaller grain size in the entire RT range and displays the opposite behaviour with increase in RT with 0NB.

3.2. Effect of CR (Cooling Rate)

Some advanced bar makers adopt water-cooling process after hot-rolling to attain grain refinement hardening. The effects of cooling rate from 900 to 700°C on the mechanical properties were examined by changing the water density. In this experiment the reheating temperatures were fixed at 1 150°C and 1 250°C. The effect of Nb addition on 0NB was compared at the RT of 1 150°C, and the effect of V addition on 5NB was compared at the RT of 1 250°C.

The results of LYP and TS are shown in **Fig. 7**. With an increase in the cooling rate from 0.8°C/s (no water-cooling, only air-cooling) to 40°C/s, LYP increased in all steels and all reheating temperatures. 0NB and 5NB steels showed an increase in LYP of 20–30 MPa with increase in CR. 5NV reheated at 1 250°C showed a 60 MPa increase. The maximum value obtained in 5NV was 600 MPa. An increase in TS with CR showed the same behaviour as LYP, but the increased value was smaller than those of LYP.

Figure 8 shows the effect of CR on El and YPEl. El does not show any remarkable change with CR, while YPEl increases remarkably with CR in all of steels and RT.

The LYP×El shown in **Fig. 9** increases with CR. 5NV shows the highest value and 0NB shows the lowest value. The effect of RT in 5NB was small in all CR. These results show clearly that accelerated cooling after hot-rolling is an effective way to increase LYP and to ensure YPEl.

The effects of Nb and cooling rate on microstructures are

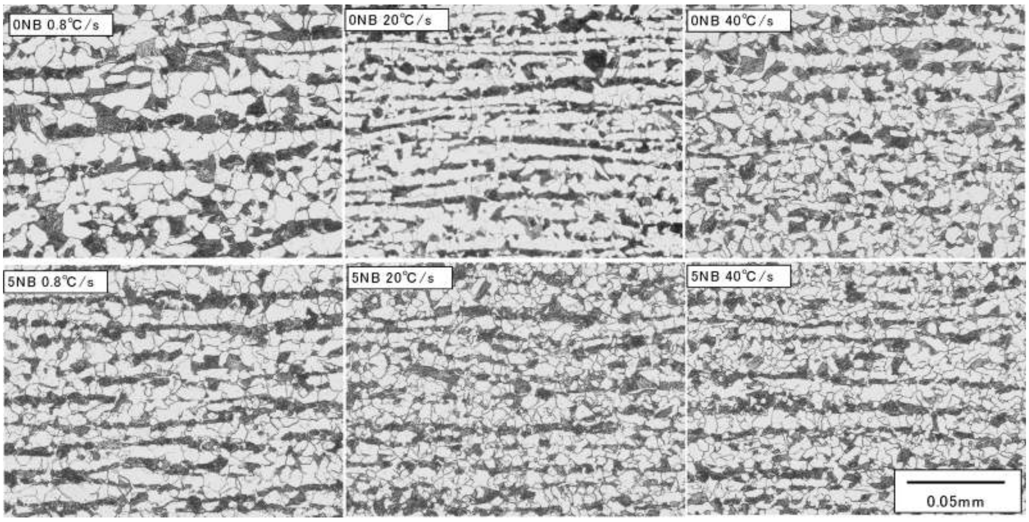

Fig. 10. Effects of Nb and CR on microstructures reheated at 1 150°C.

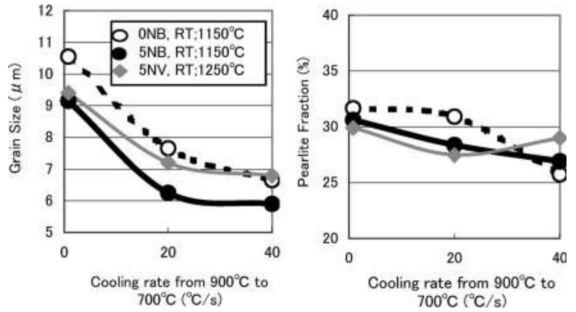

Fig. 11. Effects of microalloying elements and CR on grain size and volume fraction of pearlite.

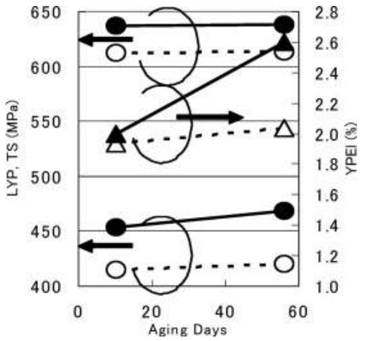

Fig. 12. Effect of aging on mechanical properties. Open mark; 0NB. Solid mark; 5NB.

shown in **Fig. 10**. Ferrite grain decreases with increase in CR and addition of Nb. All steels show ferrite and pearlite phases. No bainite or other low-transformation products were observed.

The ferrite grain size and volume fraction of pearlite observed by image analysis are shown in **Fig. 11**. Since the microstructures of 5NB reheated at 1 250°C were mixture of non-polygonal ferrite and pearlite, the data were omitted in Fig. 11. Ferrite grain size decreased with increase in CR from 0.8 to 40°C/s in all steels and all reheating temperatures. Especially the grain refinement was obvious between 0.8 to 20°C/s. In the case of 5NB, it decreased from 9 μm at 0.8°C/s to 6 μm at 20°C/s, while ferrite grain size of 5NV reheated at 1 250°C decreased from 9 μm at 0.8°C/s to 7 μm at 20°C/s. The volume fraction of pearlite decreased with increase in CR by about five points.

3.3. Effect of Aging on Mechanical Properties

Tensile-testing for rebar is generally conducted for the steels after aging. In order to understand the difference in mechanical properties after aging, the steels that had been kept for 56 d at room temperature were tensile-tested and compared with the steels processed for 10 d after hot-rolling as described in the above-mentioned results. The specimens used were 0NB and 5NB steels reheated to 1 150°C and air-cooled. Both steels show a slight increase of LYP and YPEl, but TS and El were not changed as shown in **Fig. 12**. The increase in YPEl of 5NB by aging was larger than that of 0NB. These results show that keeping the steel for a while after hot rolling is beneficial to higher LYP and YPEl. Although El was not changed in this result, it is shown that higher El is obtained after aging due to reduction of hydrogen.[7] The fact that the remarkable improvement was not shown in this experiment may be due to the smaller diameter of the specimen and that 10 d had already passed even for the compared specimen.

4. Discussions

4.1. Metallurgical Factors on LYP

The difference in LYP between 5NB and 0NB obtained in this experiment is shown in **Fig. 13**.

Pickering[7] proposed YS of ferrite–pearlite steel by Eq. (1).

$$YS=15.4\{f_\alpha^{1/3}[2.3+3.8Mn+1.13d^{-1/2}] +(1-f_\alpha^{1/3})[11.6+0.25S_0^{-1/2}]+4.1Si+27.6Nf^{1/2}\} \quad .....(1)$$

where,

f_α: Ferrite fraction
Mn, Si: Content (mass%)
d: Ferrite grain size (mm)
S_0: Pearlite lamellar spacing (mm), 0.0002 is inserted
N_0: Solid solute N (mass%), 0.001 is inserted

It is shown in this equation that YS is determined by f_α, Mn, Si, d, S_0 and N_0. Since Mn and Si contents are nearly the same, and S_0 and N_0 are inserted with the same value, 0.0002 mm and 0.001 mass% in both steels, respectively, the difference in YS is leaded by only the difference of grain size, d, and ferrite fraction, f_α. The difference in YS calculated by Eq. (1) is plotted by open mark in Fig. 13. As the difference of f_α in this experiment was not very big, YS is mostly determined by d. With increase in RT, ΔLYP by grain refinement increases from 20 to 40 MPa. This result means that in the low RT range, most of the increase in YP by addition of Nb is caused by grain refinement. The effect of precipitation hardening is not considered in Eq. (1) proposed by Pickering. However, in Nb containing steel, discussion on precipitation hardening is essential. As the base of discussion, solid solute Nb content in this chemical composition was calculated by Thermo-calc and is shown in **Fig. 14**. The solid solute Nb changes in the range of RT remarkably. Precipitation hardening is obtained most effectively by the coherent precipitates precipitated in ferrite, which relates closely with solid solute Nb in austenite.[9–11] The calculation result by Thermo-calc confirms the higher precipitation hardening effect in higher RT. Accordingly, in the high RT range, the precipitation hardening effect contributes to the increase in LYP in addition to the grain refinement effect. The estimated increase in LYP with RT by grain refinement and precipitation hardening was corresponded well with the experimental result.

Figure 13 also shows ΔLYP between 5NV and 0NB. It increases from 50 MPa at 1 050°C to 130 MPa at 1 250°C. The difference of ΔLYP between 5NB and 5NV is caused by the precipitation hardening of VCN. Accordingly the higher LYP obtained in 5NV is caused by the grain refinement and precipitation hardening of NbCN and VCN.

4.2. Metallurgical Factors on YPEl

It is known that decrease in ferrite grain size and decrease in ferrite volume fraction are effective in increasing YPEl.[12] The results shown in Fig. 8 support the metallurgical bases for the increase in YPEl with CR. Namely, increase in YPEl with increase in CR is explained by the refinement of ferrite grain size and increase in ferrite volume fraction with increase in CR.

4.3. Metallurgical Factors on Microstructures

The illustration in **Fig. 15** shows the role of accelerated cooling after hot rolling. When the cooling rate is low after hot rolling, ferrite transformation starts at high temperature. Therefore ferrite grain size is large and number of grain is small as shown at ① in Fig. 15. During slow cooling in high temperature ferrite transformation range, new ferrite at ①

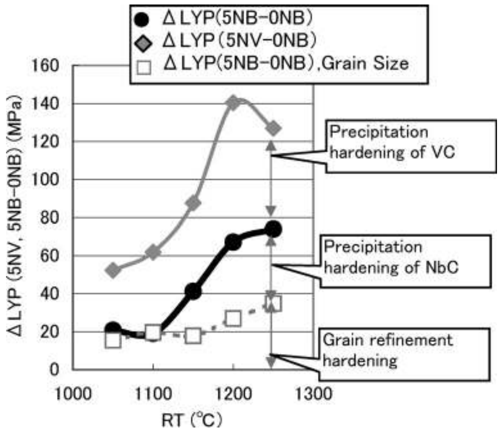

Fig. 13. Effects of grain refinement hardening and precipitation hardening by Nb and V addition on difference of LYP.

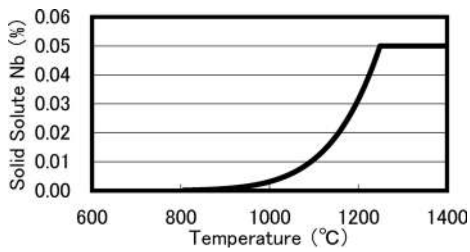

Fig. 14. Relationship between temperature and solid solute Nb of steel 5NB calculated by Thermo-calc.

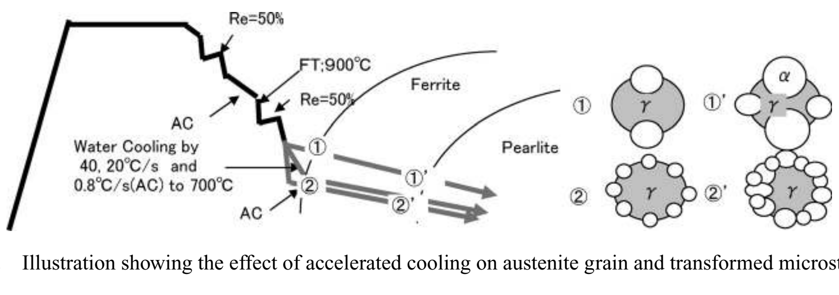

Fig. 15. Illustration showing the effect of accelerated cooling on austenite grain and transformed microstructure.

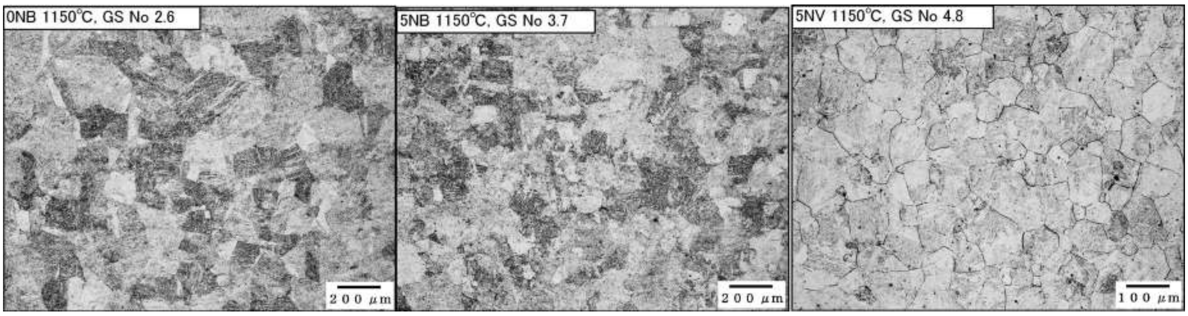

Fig. 16. Effects of microalloying elements on austenite microstructures.

grows and large transformed ferrite occurs as shown at ①′ in Fig. 15. On the other hand, accelerated cooling gives a small grain and large number of ferrite formation as shown at the point of ② in Fig. 15. As the steels are cooled at low temperature ferrite region, nucleated ferrites at the point of ② hardly grow and newly transformed ferrites in this region are small as illustrated at the point of ②′.

In addition, the prior austenite grain refinement in microalloyed steels contributes to the final grain refinement. The austenite microstructures were observed by water quenching from reheating temperature after keeping 30 min. Only the steels quenched from 1 150°C are shown in **Fig. 16**. The ASTM grain size number of 0NB, 5NB and 5NV is 2.8, 3.7 and 4.8 respectively.

5. Conclusions

(1) 0.05% Nb or 0.05% Nb+0.05% V addition to 0.25C–0.5Si–1.2Mn steel is effective to increase strength especially at high reheating temperature. The strengthening is caused by the precipitation hardening and grain refinement hardening.

(2) Accelerated cooling after hot rolling to 700°C is effective to increase in strength and yield point elongation.

(3) Microalloying addition is effective to improve strength–elongation relationship.

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