PRODUCTION AND PROCESSING OPTIMIZATION OF HOT ROLLED REBARS FOR NEWLY REVISED STANDARD IN CHINA*

Zhang Weiqiang[1]
Zhang Yongqing[2]
Felipe Bastos[3]
Leonardo Silvestre[3]
Marcelo Rebellato[4]
Guo Aimin[2]

Abstract

This work reviews the new version of GB1499.2-2018 Chinese national standard and specification, which governs the production of high-strength reinforcing hot rolled ribbed bars in China. In addition, it discusses the main concerns from Chinese rebar makers that might affect production and application of Nb-bearing rebars, like reheating temperature required to dissolve given niobium additions, the promotion of bainite microstructure and continuous yielding, as well as Nb strengthening effects. Through extensive investigation involving both thermomechanical laboratory simulations and industrial trial, the existing state and effects of Niobium along the reheating, rolling and cooling are illustrated. At the end, optimum processing conditions have been established to produce high strength rebars for the specified requirements. The adoption of new process conditions reflected in an amount of about 20.0 million tons of Nb-bearing rebar being produced in China in 2018 with required tensile properties and microstructure, and helped rebar makers to reduce production costs considerably. Based on production data, Niobium demonstrated positive strengthening effect for high strength rebars, in particular for small diameter rebars with earthquake resistant performance. What is more, the results of the research enrich the knowledge of the application of Niobium in steels when TMCP rolling is not used.

Keywords: Nb-bearing rebar; Bainite microstructure; Precipitation strengthening

[1] *Kunming Iron and Steel Group Co., Ltd. Anning District, Kunming, China, 650302*
[2] *CITIC Metal Co., Ltd Capital Mansion, Chaoyang District, Beijing, China, 100004*
[3] *CBMM, Av. Brg. Faria Lima, 4285, São Paulo-SP, Brazil, 04538-133*
[4] *Eurosport – RMS, R. Dr. Diogo de Faria, 1202, 5a, São Paulo, SP, Brazil, 04037-004*

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1 INTRODUCTION

Within progressive urbanization and industrialization taking place in China over the last two decades, the demand for steel used for concrete reinforcement with improved strength level and earthquake resistance has increased considerably. In 2013, for its first time the production output of hot rolled reinforcing bars, or rebars, has reached 206 million tons and have kept for five consecutive years. Furthermore, China's government and related departments have established coordinated group in 2012, aiming the promotion of high strength and earthquake resistant rebars for environmental constraint and safety. In China, rebars with 400MPa and above in minimum yield strength are defined as high strength rebars, and rebars with 335MPa and below are classified into low-strength grades. Based on latest statistical data, it is estimated that the percentage of high-strength rebars have reached 95 percent in 2018.

In China, rebar makers have organized production and delivery of HRB400E and above based on national standard of GB1499.2-2007, corresponding to the international standard ISO 6935-2:1991 "Steel for Reinforcement of Concrete - part 2: Ribbed Bars". In order to match with national policy, big changes took place for new version of rebar standard, namely GB1499.2 -2018. Compared with GB1499.2-2017, there are some significant changes in the new version, as follows:

- Removal of HRB335 grade;
- HRB600 was added;
- Increase of "E" grade for highlighting earthquake resistant rebars;
- Increase of clauses for microstructure testing and hardness arbitration to limit QST (quenching and self-tempering) rebars with tempered sorbite or martensite.

Before GB1499.2-2018 taking effect, two production processes were widely adopted by rebar makers: a majority of rebar makers employed VN microalloying process and QST process to produce HRB400E and HRB500E, and a few rebar makers used niobium microalloying to produce HRB400E and HRB500E. With adoption of the standard and restriction of the microstructure to mostly ferrite pearlite, microalloying addition of elements such as such as vanadium, niobium or their combination, became necessary for producing HRB400E grade. For this reason, VN price has increased from 200,000 RMB to 800,000 RMB per ton, which promoted the development and production of Nb-bearing high strength rebars.

Although niobium microalloying has been widely used for hot rolled plates and strips, less information is reported about the application and promotion of niobium microalloying for reinforcing bars. Some technical concerns that have affected the promotion of Nb-bearing reinforcing bars include:

- Solution of added niobium content before rolling for middle-carbon steel;
- Bainite microstructure and resulted in continuous yielding effect;

Besides the concerns above, Nb demonstrates totally different strength effects compared with low carbon plate and strip products with TMCP. Nb-bearing HRB400E shows higher tensile-to-yield ratio than V-bearing HRB400E given equal additions and production processing, which is inconsistent with grain refinement effect of Nb in low carbon flat product.

In this paper, we will first introduce the new version of GB1499.2-2018, and then simply review the physical metallurgy of niobium, production equipment and processing of reinforcing bars. Based on above information, emphasis will be placed on specific technical issues like reheating and solution of niobium by phase analysis, formation of bainite microstructure by CCT simulation, as well as strengthening effects of niobium in reinforcing bars. By processing optimization and validation, we will set up the best way for HRB400E and HRB500E. In addition, we will introduce some promising results of HRB600E by adding small amount niobium to achieve required earthquake resistant performance.

2 INTERPRETATION OF GB1499.2 – 2018

Although GB 1499.2-2007 "Steel for the Reinforcement of Concrete-Part 2: Hot Rolled ribbed Bars" is corresponding to the international standard ISO 6935-2:1991 "Steel for Reinforcement of Concrete–Part 2: Ribbed Bars", it has own characteristics, for example, requirements on microstructure and earthquake resistant performance besides tensile properties. Table 1 gives the basic requirements for chemical compositions. If required, vanadium, niobium and titanium or other elements can be added to achieve strength level.

Table 1. Basic requirements for chemical compositions, wt% in max

Grade	C	Si	Mn	P	S	Ceq
HRB400, HRB400E	0.25	0.8	1.6	0.045	0.045	0.54
HRB500, HRB500E	0.25	0.8	1.6	0.045	0.045	0.55
HRB600	0.28	0.8	1.6	0.045	0.045	0.58

Table 2 shows the requirements of tensile test. As we can see, earthquake resistant reinforcing bars require higher Agt (%) value. Here we will focus on earthquake resistant reinforcing bars because most areas in China are seismic prone areas. For earthquake resistant reinforcing bars, following three requirements should be conformed: 1) The ratio of actual tensile strength to actual yield strength should not be less than 1.25; 2) The ratio between actual measured yield strength and minimum specified yield strength value should not be higher than 1.30; 3) The general maximum force extensibility rate, Agt (%) should not be less than 9%. Among above three requirements, the yield-to-tensile ratio of 1.25 is the most difficult for 500MPa and 600MPa grade in yield strength. That is the reason why newly added 600MPa grade requires no earthquake resistant performance.

Table 2. Requirement of tensile test

Grade	Rel, MPa	Rm, MPa	A, %	Agt, %
HRB400	400	540	16	7.5
HRB400E	400	540	---	9
HRB500	500	630	15	7.5
HRB500E	500	630		9
HRB600	600	730	14	7.5

Another important change is specification of microstructure testing and micro-hardness arbitration. In the old version, although reinforcing bars are required to deliver on hot rolling condition, which metallurgical structure is mainly composed of ferrite plus pearlite, old version of standard specified no mandatory requirement on testing and arbitration. In order to reduce alloy costs, some rebar makers employ QST process to produce HRB400E with tempered martensite on the surface. For safety and fair competition, new version adds items to limit tempered structure on the surface by microstructure testing. Figure 1 shows picture for microstructures requirement. Figure 1(a) shows microstructure of ferrite plus pearlite along the section, that is required. Microstructures in Figures 1(b) and 1(c), for instance, are strictly forbidden. If it is hard to differentiate microstructure, hardness testing and arbitration would be performed. If hardness gap between surface and center (H_v-H_{v0}) is higher than 40 in Vickers hardness, it is unacceptable, as in Figure 1(d).

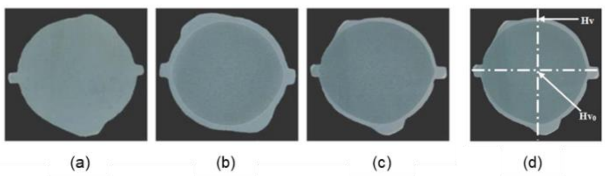


Figure 1. Metallography picture of the cross-section of a rebar

3 PHYSICAL METALLURGY OF NIOBIUM IN STEELS

Since Microalloying '75 conference held on October 1-3, 1975 in Washington, D. C., considerable development in high-strength and low-alloy (HSLA) steels and fundamental metallurgical principle have been made and further validated with simulation research and mass industrial production. Grain refinement and dispersion precipitation strengthening through TMCP (Thermo-Mechanical Processing) have been regarded the two basic strengthening approaches for modern microalloyed steels to obtain desired mechanical properties [1,2]. Among microalloying elements niobium has been widely used for low-carbon flat products due to strong grain refinement effect. Vanadium, on the other hand, has been employed for middle and high carbon long products due to strong precipitation dispersion strengthening effect. Derived from Hall-Patch equation, semi-empirical relationships for yield strength and tensile strength had been established by early forerunners like Gladman and Pickering [3,4], and following semi-empirical equations, as equations (1) and (2), have been widely quoted. As we can see, grain refinement contributes more to yield strength than tensile strength. For Nb-bearing reinforcing bars, if main strengthening effect of Nb in reinforcing bars is grain refinement, tensile-to-yield ratio would be lower, but actual test results of Nb-bearing HRB400E and above is higher than V-bearing HRB400E and above given equal additions and production processing.

$\sigma_y(MPa) = 53.9 + 32.3 (\%Mn) + 83.2(\%Si) + 354(\%N_{free})^{0.5} + 17.4.d^{-1/2} + \sigma_p$	(1)
$R_T(MPa) = 294 + 27.7(\%Mn) + 83.2(\%Si) + 3.8(\%pearlite) + 7.7.d^{-1/2} + \sigma_p$	(2)

Compared with other two microalloying elements vanadium and titanium, the strengthening effects of niobium are multiple and more flexible depending on processing conditions, and following five strengthening effects are listed as follows [5,6,7]:

- Grain refinement effect;
- Retard recrystallization during conditioning of austenite;
- Precipitation dispersion strengthening;
- As a stabilizing element with Ti, as for IF steel;
- Transformation hardening by niobium remaining in solution before transformation

Although the benefits and metallurgical conception of niobium additions is well known to low-carbon steels, the application and study of niobium additions for middle and high carbon are not complete because of limited solubility in austenite and processing conditions of long products. In order to clarify specific strengthening effects of Nb on high-strength reinforcing bar, it is necessary to distinguish the difference of production equipment and processing conditions between flat product and long product. Figure 3 shows typical layout of hot rolling strip, and alloy design and rolling temperatures. Firstly, carbon contents of hot rolling are less than 0.15%, and most products are less than 0.10% for Auto and pipeline products. Secondly, rolling temperatures are lower than Tnr, so most pass reductions happen under Tnr.

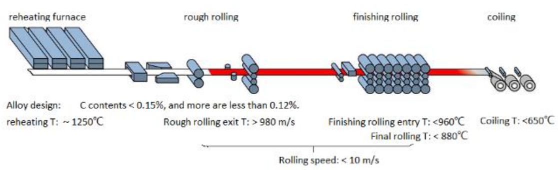


Figure 3. Typical layout of hot rolling strip and key temperature parameters

Figure 4 shows typical layout of bar production line and key processing parameters. Compared with hot rolled strip rolling, carbon contents of reinforcing bars are about 0.25 %, and limited solubility for given niobium additions. In addition, all pass rolling temperatures are higher than Tnr, and dynamic recrystallization takes place considering high strain speed and short interval time in finishing rolling passes.

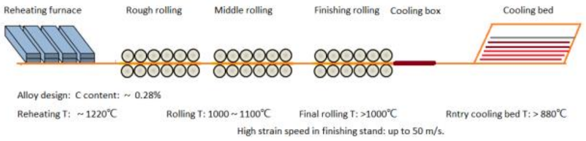


Figure 4. Typical layout of bar production line and key temperature parameters

Another particularity is that TMCP is not a common practice in rebar production, due to process constraints commented before. What is more, with high final rolling temperatures, usually above Tnr, Niobium exists in solution, which may increase hardenability and promote low temperature transformation microstructure.

4 INDUSTRIAL PRODUCTION

4.1 – Industrial results for HRB400E

In China, the basic alloy design for 335MPa is 20MnSi, based on which 400MPa and above grades were produced by adding microalloying elements such V, Nb and their combination. Table 3 gives the chemical compositions and tensile test results for plain C-Mn steel, 335MPa grade.

Table 3. Chemical compositions and test results for plain C-Mn 335 MPa

Size, mm	Num. of sample	C	Si	Mn	YS, MPa	TS, MPa	TS/YS	A, %
14	2689	0.21	0.52	1.39	406	564	1.39	26.5
16	4367	0.21	0.52	1.39	402	562	1.40	26.5
20	115	0.21	0.52	1.39	398	560	1.41	26.4
22	3790	0.21	0.52	1.39	391	559	1.43	25.3
25	5130	0.21	0.52	1.39	385	557	1.45	25.4
28	1460	0.21	0.52	1.39	386	558	1.45	24.7
32	1060	0.21	0.52	1.39	388	559	1.44	22.7
36	165	0.21	0.52	1.39	384	560	1.46	23.0
40	50	0.21	0.52	1.39	383	549	1.43	22.3

Because of high solubility in reheating furnace and practices, that commonly does not concern TMCP, VN has been the prior choice to produce HRB400E. According to regression of mass production, 0.01%V contributes to 20MPa in yield strength. In order to reduce production costs, more and more rebar makers started to replace vanadium with niobium for HRB400E, and industrial trials with different Nb additions are conducted. Table 4 gives the trial results. as we can see, no visible contribution to yield strength when Nb addition is higher than 0.03%. Another important point is the influence of reheating temperature, normally, reheating temperature of billets are 50℃ higher than starting rolling temperature in the first pass. According to calculation result of Irvine equation, only about 0.01%Nb is in solid solution, which mean undissolved Nb contents before rolling also contribute to yield strength increase. In fact, we can also see that for same particular conditions, 0.016% Nb is enough to achieve the minimum margin of 430MPa, which is industrially required for quality reasons for HRB400. Compared with test results of V-bearing HRB400E, tensile-to-yield ratio of Nb-bearing HRB400E are higher, which illustrates other strengthening effects exert influence in addition to grain refinement strengthening effect.

Table 4. Industrial trial of Nb-bearing HRB400E

Size, mm	Alloy design, wt%				Processing		Mechanical properties		
	C	Si	Mn	Nb	Starting rolling T, ℃	Entry cooling bed T, ℃	YS, MPa	TS, MPa	A,%
25	0.22	0.45	1.40	0.016	1050	900	430	608	25.9
				0.026	1050	900	446	622	27.0
				0.030	1050	900	452	623	26.3
				0.060	1050	900	452	621	24.2

For Nb-bearing HRB400E, two technical concerns need further explanation: one is effect of reheating temperature on yield strength; another is formation of low temperature microstructure. We will discuss them in the later chapter.

4.2 – Industrial trial of HRB500E and HRB600

Originally, China's rebar makers added high V contents for HRB500E, but found it is difficult to balance the tensile-to-yield ratio and yield strength for different sizes. As mentioned before, the new version of GB1499.2-2018 also considers HRB600, but no requirement for earthquake resistant performance. As Table 5 shows, TS/YS of small sizes cannot meet the required 1.25 in HRB500E and HRB600 with only vanadium microalloying, and margin of yield strength of big sizes HRB500E are not enough for delivery.

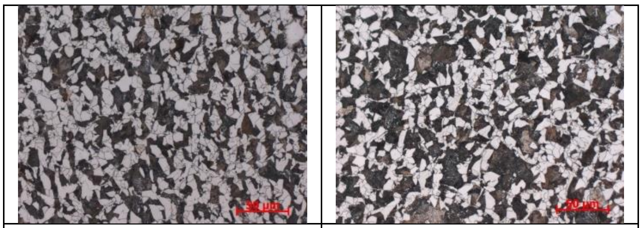
Table 5. Trial results of V-bearing HRB500E

Grade	V, %	Size, mm	YS, MPa	TS, MPa	A, %	Agt, %	TS/YS
HRB500E	0.08	12	548	668	26.2	15.8	1.22
		14	545	666	26.0	15.2	1.22
		16	544	669	25.5	14.9	1.23
		20	538	661	24.9	15.9	1.23
		22	528	656	24.1	15.0	1.24
		25	510	656	22.0	15.4	1.29
		28	502	651	24.4	17.3	1.30
		32	512	644	23.1	16.4	1.26
HRB600	0.13	14	655	802	19.2	13.0	1.22
		16	642	790	19.5	13.5	1.23

For this dilemma, addition of small amount of niobium showed positive effect on tensile-to-yield ratio of HRB400E, in this case compensating equal amount of vanadium. Table 6 shows the test results of HRB500E with V and Nb alloy design. Figure 5 gives the optical microstructure of HRB600 with V and V plus Nb. Optical microstructures shows slightly finer microstructure and more amount of pearlite, with 0.10%V plus 0.015%Nb composition than with 0.13%V.

Table 6. Trial results of HRB500E with V plus Nb

Grade	V, %	Nb, %	Size, mm	YS, MPa	TS, MPa	A, %	Agt, %	TS/YS
HRB500E	0.065	0.015	12	535	676	24.2	14.8	1.26
			14	532	678	24.0	14.2	1.27
			16	540	682	23.5	14.0	1.26
HRB600	0.10	0.015	14	622	786	19.0	12.5	1.26
			16	630	800	19.0	12.5	1.27



a. HRB600 with 0.13%V. b. HRB600 with 0.10%V and 0.015%Nb.

Figure 5. Optical microstructure and HRB600

5 RESEARCH AND DISCUSSIONS ON KEY TECHNICAL ISSUES

For Nb-containing steels, control of the solution and precipitation of carbide and carbonitride is the basic building block of HSLA technology. In order to maximize the effect of added niobium, reheating temperature is required to dissolve as much niobium additions as possible. According to Irvine equation of $\log[Nb][C+12/14N]=-6770/T+2.16$, more than 1250℃ in billet is required to fully dissolve 0.03%Nb for reinforcing bar with 0.22%C and 0.005%N. Obviously, actual reheating temperature of reinforcing bar is far less than required full solution temperature, so one interesting issue is if we waste some niobium additions? If it is true, we can reduce niobium addition for high competitiveness. However, we found yield strengths decrease production practice is not consistent with this assumption. Two hypothesis come in hand: Irvine equation is not applicable to middle-carbon steels, or Nb(C,N) particles undissolved in reheating furnace also make contribution to strength level. In order to verify the possibilities, two thermo-simulation tests were performed.

Firstly, simulated samples were reheated to 950℃, 1000℃, 1050℃, 1100℃, 1150℃ and 1200℃ for holding 30 minutes, and then quenched to room temperature to observe austenite grain size. As Figure 6 shows, when reheating temperature is 1150℃ and more, austenite grain size starts to coarsen and individual grain sizes become non-uniform.

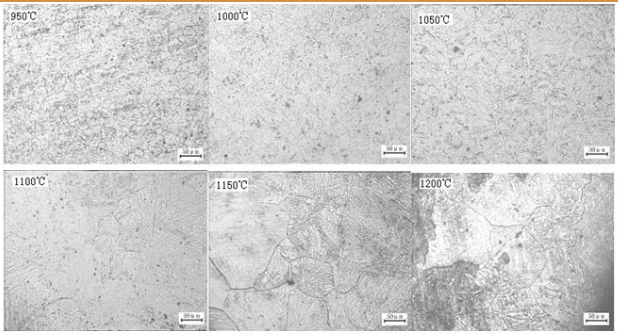


Figure 6. Austenite microstructure with different reheating temperature and holding 30 °C

From the perspective of maximizing solution of added contents, machined billet samples were reheated to 1000℃, 1050℃, 1100℃, 1150℃, 1200℃ to 1250℃ for holding 30 minutes, and then quenched to room temperature to quantifying the existing state of added niobium by chemical extraction technique. The chemical compositions of experimental steels include 0.23%C, 0.42%Si, 1.32%Mn, 0.028%Nb, 0.0056%N. Table 7 gives the analysis results of chemical extraction experiment, as we can see, when reheating temperature is 1100℃, only about 0.014%Nb is dissolved, and about 0.016%Nb exists in precipitation. Figure 7 compares the calculation results and analysis results. A good agreement is achieved. The research results confirm that undissolved Nb precipitates also exert positive effects to yield strength by refine austenite grain size before and during rolling. For small sizes HRB400E with very high strain rate in finishing strands, if final rolling temperature is up to 1100℃, undissolved and precipitated niobium can have still more contribution in avoiding abnormal grain growth.

Table 7. Analysis results of NbC phase by chemical extraction technique

Type	Reheating Tem. ℃	Holding time, m	Nb in precipitation, %	Nb in solution, %
1	1000	30	0.022	0.006
2	1050	30	0.018	0.010
3	1100	30	0.016	0.012
4	1150	30	0.011	0.017
5	1200	30	0.0077	0.020
6	1250	30	0.0023	0.025

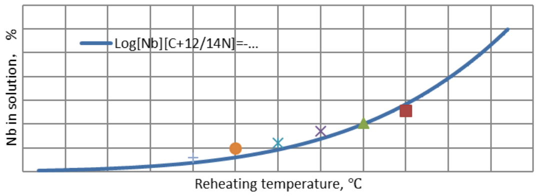


Figure 7. Solubility of Irvine calculation equation and analysis results of Nb in solution

5.1 – Thermo-simulation of CCT and measure to control bainite microstructure

For Nb-bearing reinforcing bars, bainite microstructure and continuous yielding is one of barrier for promotion. While bainite microstructure is not clearly forbidden in the new version of standard, continuous yielding would appear when bainite microstructure accounts for certain amount, like 30 percent or more. Most end users refuse to accept this kind reinforcing bar for the sake of safety concern. For this opinion, argument exists, but it is confirmed that large amount bainite microstructure would decrease Agt value.

In order to clarify the effects of niobium and reheating temperature, three sets of CCT simulation tests were carried out for Nb-free and Nb-bearing steels with different reheating temperature and equal deformation and cooling parameter. Chemical compositions of experimental steels and reheating temperature are shown in Table 8, and schematic of thermo-simulation test is suggested as Figure 8.

Table 8. Chemical compositions of experimental steels

	Reheating T, ℃	C	Si	Mn	Nb	N
One	1100	0.23	0.48	1.36	0	0.0052
two	1100	0.23	0.48	1.36	0.03	0.0056
two	1200	0.23	0.48	1.36	0.03	0.0056

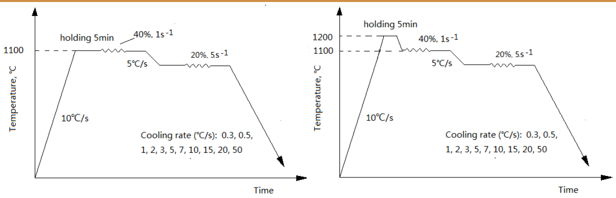


Figure 8. Schematic of CCT simulation tests

Figure 9 shows simulated CCT curves. Results shows niobium additions promote low ferrite transformation temperature, and at the same time bainite regime moves right, which make bainite microstructure more easy to happen when cooling rate is 3 ℃/s from 5℃/s . By comparison between CCT curve two and CCT curve three, we can find reheating temperature means bigger austenite grain sizes and more solute niobium, both promote formation of bainitic microstructure.

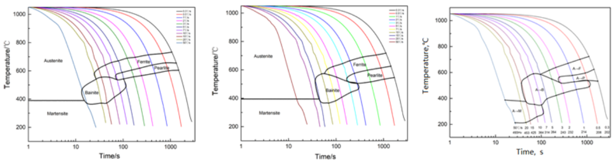


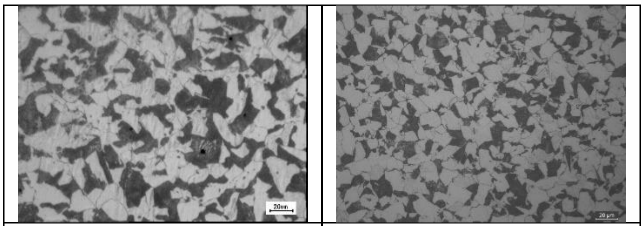
Figure 9. CCT curve of three sets simulation experiments

How to control bainite microstructure by processing optimization? Because no TMCP is available for most bar production line, the theory that low-temperature rolling and heavy reduction can induce ferrite transformation become invalid for Nb-bearing reinforcing bar production. However, most bar production lines have water cooling equipment after rolling, we can adopt weak cooling processing for minimize the austenite grain size, which can offset the effect of solute niobium on ferrite transformation. Besides niobium, it should be noted that too much manganese contents will depress ferrite transformation so much that bainite is formed. Normally, Manganese additions are round 1.40%.

6 STRENGTHENING EFFECTS OF NB IN REBARS AND PROCESS OPTIMIZATION

6.1 – Grain refinement effect

First, based on phase analysis results, it is confirmed that undissolved Nb in reheating stage can inhibit coarsening of austenite and retards recovery and grain growth during rolling. Figure 10 shows comparison of optical microstructures between 20MnSi and 20MnSiNb in equal processing conditions that does not imply TMCP. Ferrite grain size of Nb-bearing reinforcing bar is finer and more uniform.



(a) 20MnSi (b) 20MnSiNb

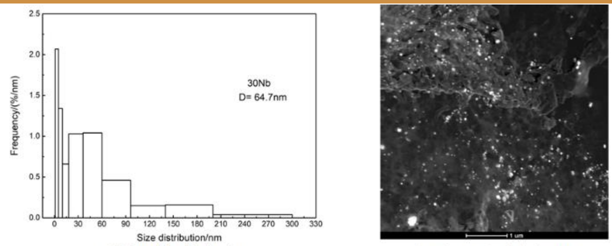
Figure 10. Comparison of optical microstructure between 20MnSi and 20MnSiNb

6.2 – Precipitation dispersion strengthening effect

For Nb-bearing hot rolled rebars, phase analysis experiments were carried out by TEM and chemical extraction methods. Table 9 shows phase analysis result of Nb(C,N) particles. About 0.022% of Nb exist in precipitation, accounting for about 70 percent of total addition, which is very similar with precipitation of VN of V-bearing HRB400E. Figure 11 gives particle distribution and analysis result by TEM respectively. The results show that a large amount and finer Nb(C,N) particles existed, of which Nb(C,N) particle number of less than 60nm accounts for 63.7 percent. It is clear precipitation dispersion strengthening effect of niobium is marked. Considering rest of niobium additions in ferrite is only 0.008%, solid solution hardening effect can be ignorable.

Table 9. Phases analysis results of Nb-bearing hot rolled HRB400E

Each element fraction among M(CN) phase, wt%				Phase structure
Nb	N	C*	Σ	
0.022	0.0022	0.0010	0.025	Nb ($C_{0.35}N_{0.65}$)



a. NbC particles distribution b. Analysis result of NbC by TEM

Figure 11. Analysis result of Nb-bearing reinforcing bar with TEM

6.3 – Phase transformation strengthening effect

As shown from trial results of HRB500E and HRB600, and CCT simulation experiments, it is confirmed solute niobium contents in austenite before transformation would increase hardenability. About the influence of Nb on tensile-to-yield ratio, it seems reasonable that promotion of small amounts of low transformation temperature constituents, in volume fractions lower than 10%, may be contributing to this behavior. This aspect needs further research.

Based on above analyses, precipitation dispersion strengthening, grain refinement strengthening and phase transformation strengthening all bring positive effects to strength level in turn in magnitude. Compared with 20 MPa in yield strength per 0.01% V, 0.01% Nb also contributes to 20 MPa for reinforcing bar of HRB400E. In addition, niobium demonstrates more positive effect on tensile-to-yield ratio, in particularly higher grades like HRB500E and HRB600E.

6.4 – Process optimization

Compared with low carbon flat production, adjustable parameters for production processing of reinforcing bar are limited to reheating temperature and entry cooling bed temperature. Considering the integrated effects of austenite grain size and solution of added niobium, it is not advisable to require higher reheating temperature. From the perspective of elimination of bainitic microstructure and continuous yielding effect, immediate cooling is strongly recommended for minimizing austenite grain size, which would offset the effect of solute niobium additions for hardenability. Considering actual contribution to yield strength by niobium additions, TMCP is not essential for production of hot rolled reinforcing bars.

7 CONCLUSION

New phenomenon regarding microalloying with Nb plain C-Mn steel for rebars have been found through production practice. In the early literature, some recommended higher reheating temperature for more dissolution niobium, and some thought water-cooling after rolling would promote formation of bainite. New lab research and mass production validation indicated that the integrated strengthening effects of Niobium additions is similar to that of vanadium additions, about 20 MPa in yield strength per 0.01% Nb or V. For reheating temperature, while better agreement is achieved between calculation results of Irvine equation and phase analysis results, reheating temperature higher than 1150 ℃ in Nb-bearing billet is not recommended for energy saving. Regarding practices for the exit of rolling, adoption of water-cooling right after exit of rolling mill showed as and strategy to control bainite formation. Application of water should stop in temperatures about 60 to 100 ℃ above Ar3, to avoid tempered microstructure on the surface, as prohibited by new standard.

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