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Metallurgical Design, Development and Strengthening Mechanisms for HRB600E Reinforcing Bar

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Abstract: High-strength, anti-seismic requirements represent the development tendency to hot-rolled ribbed bar used for the reinforcement of concrete. In this paper, metallurgical design, development and strengthening mechanisms for 600 MPa reinforcing bar with anti-seismic requirements have been studied and presented based on the production practice of 335 MPa, 400 MPa and 500 MPa grades. Through trial and error, it was found that alloy design with niobium plus vanadium is the best way to achieve the optimum combination of yield strength and anti-seismic properties, especially, small amount niobium addition can improve upon tensile-to-yield ratio. In order to clarify the underlying theoretical principles for the strengthening effects, qualitative and quantitative analysis for microstructure had been conducted with the aid of optical microscopy, scanning electron microscopy, transmission electron microscopy and chemical extraction technique, together with the solution and precipitation behavior of niobium and vanadium during the hot-rolling and cooling processes. Based on analysis results, it was found strengthening effects of both niobium and vanadium demonstrate some additional strengthening effects apart from predominated precipitation strengthening and grain refinement strengthening respectively. Although adding high vanadium contents is indispensable to achieve needed yield strength through precipitation strengthening effects, but fine VN particles precipitated in relatively high temperature also bring grain refinement effects for austenite and ferrite. Equally, grain refinement is not overall to describe the effects of niobium in long products, small amount of niobium contents is marked to improve upon tensile-to-yield ratio due to transformation strengthening resulted from the niobium contents in solution. Through the development of HRB600E, strengthening mechanisms of vanadium and niobium in medium carbon long products had been enriched.

Key words: HRB600E, anti-seismic, tensile-to-yield ratio, transformation strengthening.

1. Introduction

In China, hot-rolled reinforcing bars used for the reinforcement of concrete have been the largest single field among all application segments, and total annual output has reached and surpassed 200 million tons in crude steel output since 2013, and expected to reach 266.39 million tons in 2020. In order to reduce energy constraint and improve safety and reliability for both civil and public buildings, promotion and application high-strength and anti-seismic reinforcing bars have been the priority work since 1990's, and significant advances have been made since then, in particular elimination of low-strength grade of 335 MPa in 2013. In 2018, the newly revised reinforcing bars standard of GB1499.2-2018 had taken effect to replace the old version of 2007, and some significant changes had been listed as follows [2]:

- removed low-strength grade of 335 MPa;
- added high-strength grade of 600 MPa, but no requirement on anti-seismic property;
- added "E" grade in seismic prone areas for 400 MPa and 500 MPa;
- added the clauses for microstructure testing and

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hardness arbitration to limit quenched and self-tempered QST bars produced through quenching and self-tempering processing with tempered sorbite or martensite.

According to the newly revised standard, required microstructure of 600 MPa is composed of ferrite and pearlite, which is very challenging to balance required yield strength level and tensile-to-yield ratio simultaneously. In the following sections, standardization, metallurgical design, industrial trial and strengthening mechanism studies will be presented and discussed in turn.

2. Standardization

In 2018, the new version of GB1499.2 came into force, but 600 MPa with "E" grade was not added because some experts were uncertain to develop anti-seismic 600 MPa with the microstructure of ferrite and pearlite. Considering more than half of big cities in China locate in earthquake prone areas, it is not significant to add 600 MPa without anti-seismic requirements for promotion and application. For this reason, large amount research works had been done to develop anti-seismic 600 MPa reinforcing bar, and then organized industrial mass production for providing evidence for setting up industry standard of T/CISA 026-2020 for HRB600E anti-earthquake hot rolled ribbed bar for the reinforcement of concreate.

The technical specifications on chemical compositions and mechanical properties for HRB600 and HRB600E in GB1499.2-2018 and T/CISA 026-2020 are presented in Tables 1 and 2. To achieve required strength levels and anti-seismic properties, metallurgical designs with alone vanadium, vanadium plus niobium had been studied, and found that the combination of high vanadium and small amount niobium is the best way for successful development of 600 MPa grade with earthquake resistant requirements. What is more, transformation strengthening resulted from the niobium contents in solution is regarded the key to ensure required tensile-to-yield ratio, especially for small-size reinforcing bars.

3. Metallurgical Designs

Since Microalloying 75 International Conference, physical metallurgy of high-strength, low-alloy (HSLA) steels had been well established like Brain Pickering, Lutz Meyer and Isao Kozasu and so on, based on the microstructure-property relationship, of which grain refinement and precipitation strengthening have been regarded the two most important strengthening approaches for microalloyed steels, as shown in Eq. (1) for the case of mainly ferritic microstructure [1] and [5].

$$\sigma_y = \sigma_0 + \sigma_{ss} + k.d^{-1/2} + \sigma_{prec} + \sigma_d \ldots\ldots \quad (1)$$

where σ_0 is the friction lattice stress, σ_{ss} is the solution effect, d is the ferrite grain size, σ_{prec} is the contribution of precipitation and σ_d is the dislocation hardening.

Control of the solution and precipitation of carbides, nitrides and carbonitrides is the building block for microalloyed steels [3], so optimum combination of mechanical properties can be obtained by optimizing the solution and precipitation along production steps such as reheating, hot-rolling and cooling. For the successful development of 600-MPa grade with

Table 1 Technical requirements on chemical compositions (in wt.%).

Standard	Grade	C	Si	Mn	P	S	Ceq	Others
GB1499.2-2018 T/CISA-2020	HRB600 HRB600E	0.28	0.80	1.60	0.045	0.045	0.58	Free to add V, Nb, Ti and other elements or their combination.

Table 2 Requirements of tensile properties and anti-seismic properties.

Standard	Grade	R_{el}, MPa	R_m, MPa	A, %	A_{gt}, %	R_m^o/R_{eL}^0	R_{eL}^0/R_{eL}
GB1499.2-2018	HRB600	≥ 600	≥ 730	≥ 14	≥ 7.5	-	-
T/CISA-2020	HRB600E	≥ 600	≥ 750	-	≥ 9.0	≥ 1.25	≤ 1.30

Table 3 Statistics results of 335 MPa, 400 MPa and 500 MPa.

Grade, MPa	Size, mm	Chemical compositions, wt.%					Tensile properties			
		C	Si	Mn	V	Nb	YS, MPa	TS, MPa	A, %	TS/YS
335	12	0.21	0.50	1.40	-	-	410	564	26.5	1.40
	25	0.21	0.50	1.40	-	-	385	557	25.4	1.45
400	12	0.21	0.50	1.40	0.025	-	461	612	28.0	1.33
	25	0.21	0.50	1.40	0.030	-	451	606	24.0	1.34
400	12	0.21	0.50	1.40	-	0.025	464	624	26.0	1.34
	25	0.21	0.50	1.40	-	0.030	453	606	22.5	1.34
500	12	0.21	0.50	1.50	0.07	-	544	669	26.0	1.23
	12	0.23	0.50	1.50	0.06	0.015	530	671	24.0	1.27
	25	0.21	0.50	1.50	0.07	-	510	656	24.0	1.29

anti-seismic properties, it is very essential to review some production experiences of HRB400E, HRB500E, as well as the basic matrix of 20MnSi for 335-MPa grade, as shown in Table 3. For the HRB400E grade, vanadium and niobium can be used alone to achieve required combination of mechanical properties, and the strengthening effects of per 0.01% of vanadium and per 0.01% niobium are almost equal, but relatively tight control is needed for niobium. According to regression, 0.01% vanadium and niobium alone contribute to 20 MPa for yield strength increment. As proved through industrial trials, there is one plateau when niobium contents are higher than 0.03 percent, which can be explained by the relatively lower solid solubility of niobium in austenite compared to vanadium, so for higher yield strengths like 500 MPa or 600 MPa, it is almost impossible to achieve required yield strength with required ferrite plus pearlite.

For the production of 500 MPa grade, vanadium microalloying was firstly used, but it is difficult to meet required tensile-to-yield ratio for small diameters like 12 mm with vanadium alone. Interestingly, it was found that small amount of niobium addition is effective to improve upon tensile-to-yield ratio, which can not be explained by conventional grain refinement strengthening mechanism.

According to the regression calculation of vanadium additions, the yield strength of minimum 600 MPa can be achieved by adding 0.12% and 0.15% vanadium for typical sizes of 12 mm and 25 mm respectively. The difficulty of HRB600E was finally reduced to meet the required tensile-to-yield ratio of 1.25. Based on early research results by Pickering in the regression Eqs. (2) and (3) used for ferrite-pearlite structure, high pearlite volume is positive to increase tensile strength, which is favorable to improve upon tensile-to-yield ratio. For the effects of grain refinement, fine ferrite grain size should contribute to increment of both yield strength and tensile strength, but too fine ferrite grain size would increase difficulty to ensure minimum tensile-to-yield ratio requirement. For the effects of nitrogen, higher nitrogen contents are needed to make good use of added vanadium, but more free nitrogen would bring some negative effect to ductility, and cause marked natural aging, so the use of free nitrogen for controlling of tensile-to-yield ratio was not considered [1] , [6] and [7].

$$\sigma_y = 53.9 + 32.3(\%\mathrm{Mn}) + 83.2(\%\mathrm{Si}) + 17.4.d^{-1/2} + \sigma_p \quad (2)$$

$$R_m = 294 + 27.7(\%\mathrm{Mn}) + 83.2(\%\mathrm{Si}) + 354(Nf)^{1/2} + 3.8(\mathrm{pearlite}) + 7.7.d^{-1/2} + \sigma_p \quad (3)$$

To sum up, metallurgical designs for HRB600E are as follows: (1) Adding 0.12% and 0.15% vanadium with appropriate nitrogen contents according to stoichiomtric ratio for required yield strength based on 20MnSi matrix; (2) High carbon contents are preferred for high pearlite volume, but limited to upper limit of carbon equivalent; (3) Chromium maybe effective to increase tensile-to-yield ratio, but no big room due to limitation of carbon equivalent; (4)

For the microalloying element of niobium, there are some speculations, as demonstrated by production practice of HRB500E, in particular the effects of niobium remaining in solution before $\gamma \rightarrow \alpha$ transformation.

4. Industrial Trials and Simulation Tests

In this section, industrial trials had been carried out to validate the effects of bar sizes, vanadium additions, as well as chromium, copper and small amount niobium additions on microstructure and properties. Besides, the influences of production processing including the analysis of the effects of reheating temperature, rolling temperatures and cooling after rolling had been studied to provide reference for processing optimization.

4.1 Effects of Product Sizes on Tensile Properties

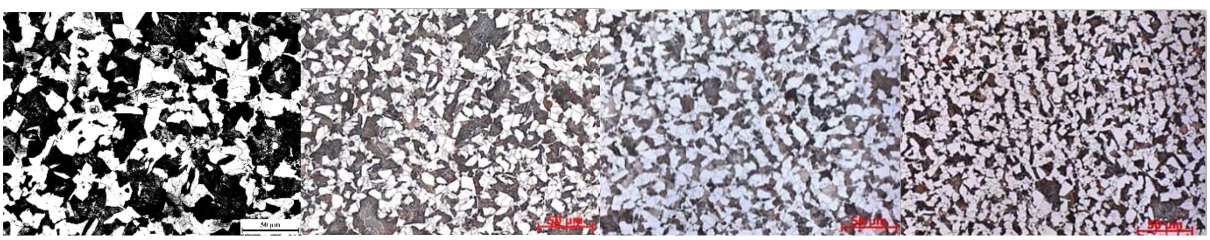
As stated above, bar sizes play one important role in tensile properties due to different strain parameters and cooling rates, in particular rolling and cooling penetration for small sizes, which will affect austenite recrystallization, grain growth and subsequent ferrite transformation. Table 4 shows the trial results of HRB600E with the same chemical compositions for different bar sizes. All mechanical properties meet the requirements of GB1499.2-2018, but the test results of tensile-to-yield ratios of 25mm and below are less than required characteristics value of 1.25 for earthquake resistant requirements. Fig. 1 shows the microstructures corresponding to four sizes. As shown, all microstructures are composed of ferrite and pearlite, but both ferrite grain size and pearlite volume fraction vary regularly.

4.2 Effects of Vanadium Additions on Tensile Properties

Table 5 shows the trial results of 25 mm 600 MPa grade and it was found that vanadium additions contribute to both yield strength and tensile strength in almost linear relationship, but tensile-to-yield ratio values decrease with the increase of vanadium additions, as shown in Fig. 2. For this phenomenon, it can be explained from the precipitation behavior of the nitrides of vanadium. Compared to the other precipitates of vanadium and niobium, the nitrides of vanadium can precipitate in relatively high temperature, but can keep stable and fine, which present the similar effects to retard austenite grain growth, just like the grain refinement of induced precipitated Nb(C,N) in flat products under two-stage rolling. In addition, precipitated particles before transformation can provide nucleation sites for ferrite formation, and ferrite grain refinement can come true. For the grain

Table 4 Trial results of HRB600E with given chemical compositions for different sizes.

	Chemical compositions				Tensile properties					Microstructure analysis	
Size, mm	C	Si	Mn	V	YS, MPa	TS, MPa	A, %	A_{gt}, %	TS/YS	Grain size, um	Pearlite volume, %
28	0.26	0.65	1.48	0.15	632	794	18.0	12.0	1.256	18.2	65.2
25					641	796	18.2	13.5	1.241	12.6	52.6
16					647	801	19.0	13.6	1.238	10.7	46.7
14					656	806	19.2	14.0	1.228	8.5	42.2



28 mm 25 mm 16 mm 14 mm

Fig. 1 Microstructures of HRB600E of different sizes of 28 mm, 25 mm, 16 mm and 14 mm.

Table 5 Trial result of 25 mm HRB600E with different vanadium additions.

No.	C	Si	Mn	V	YS, MPa	TS, MPa	A, %	A_{gt}, %	TS/YS
1	0.26	0.71	1.48	0.09	569	732	20.3	12.90	1.286
2	0.25	0.69	1.46	0.12	612	768	21.3	11.60	1.255
3	0.26	0.67	1.51	0.14	640	792	20.3	11.20	1.238
4	0.26	0.67	1.52	0.15	648	800	20.3	11.20	1.235
5	0.27	0.71	1.52	0.16	654	805	20.4	12.10	1.231
6	0.27	0.72	1.54	0.17	673	822	22.9	11.40	1.221
7	0.27	0.71	1.56	0.18	677	823	22.1	12.70	1.216

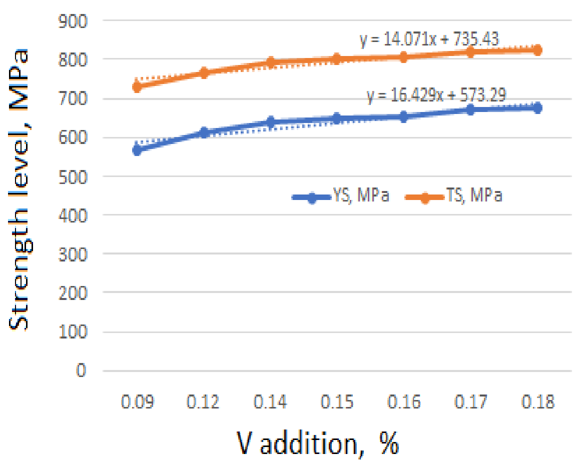


Fig. 2 Strength levels of different V additions of 25 mm.

refinement effect by fine VN particle, it was verified that strengthening effects are the integrated functions of characterization and processing parameters, so when processing parameters change, the effects will change accordingly [4].

4.3 Effects of Cr, Cu and Small Amount of Nb

According to the standard requirements, it could be possible to increase the solid solution strengthening by adding elements like Cr and Cu metallurgical worker can be free to add any solid solution elements like Cr and Cu, but there is a limit because they increase the carbon equivalent value that is limited to a maximum of 0.58. Based on this limitation, niobium was selected as microalloying addition for two reasons: (1) Firstly, niobium is not considered in calculation equation of carbon equivalent; (2) Secondly, small amount of niobium increases the tensile-to-yield ratio of HRB500E, as shown in the results of Table 3. For the effect of niobium on the tensile-to-yield ratio of HRB500E, preliminary explanation is that niobium in solution increases hardenability during transformation, which contribute to formation of low temperature microstructures like bainitic structure or/and pearlite.

Table 6 shows the trial results with Cr, Cu and small amount of niobium for the size of 14 mm in diameter, and Fig. 3 shows the microstructures and analysis results.

As we can see from Table 6, it is very challenging with only vanadium microalloying to achieve required tensile-to-yield ratio for anti-seismic 600 MPa grade. Chromium and copper maybe effective to increase tensile-to-yield ratio, but also limited to their maximum amount. Finally, the addition of 0.015% Nb increases the tensile-to-yield ratio to levels higher than the standard requirements. Fig. 3 shows how the different additions are affecting the room temperature microstructure without modifying the rolling process parameters. Comparing these microstructures with the

Table 6 Trail results of 14 mm HRB600E with Cr, Cu and Nb.

Steel No.	C	Si	Mn	V	Cr	Cu	Nb	Ceq	YS, MPa	TS, MPa	A, %	Agt, %	TS/YS
1	0.27	0.70	1.54	0.125	-	-		0.578	642	800	20.5	12.0	1.246
2	0.27	0.68	1.40	0.126	0.20	-		0.583	630	789	22.0	10.4	1.252
3	0.28	0.70	1.42	0.105	-	0.20		0.577	620	782	23.3	12.0	1.261
4	0.27	0.72	1.52	0.106	-	-	0.015	0.574	653	830	22.5	13.0	1.271

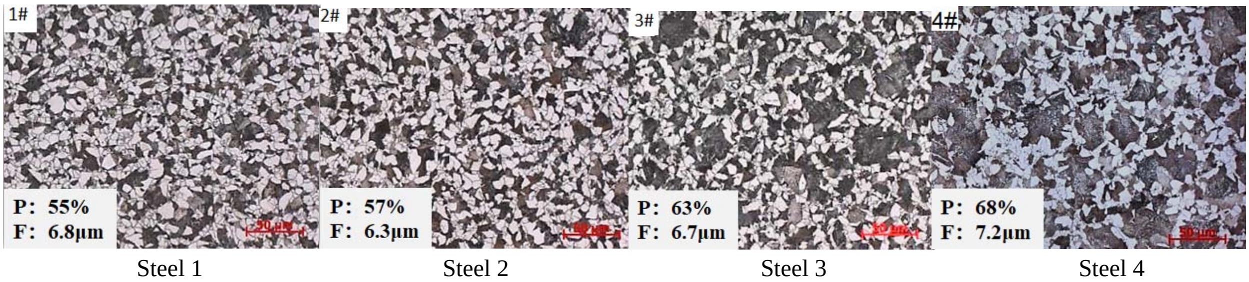


Fig. 3 Microstructures of four alloy designs.

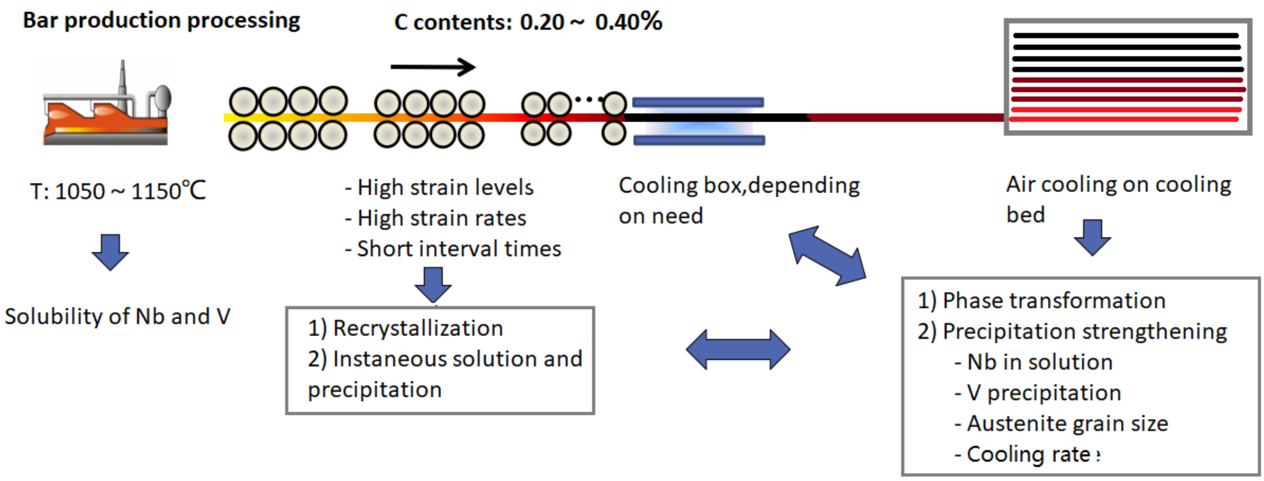


Fig. 4 Production processing features of reinforcing bar.

tensile test results of Table 6, it can be observed that an increase of pearlite volume fraction and moderate ferrite grain size help to obtain the minimum required tensile-to-yield ratios.

4.4 Effects of Production Processing Parameters

Compared to the flat products, long products have their features in production processing, as shown from Fig. 4. Firstly, carbon contents of long products are higher than that of flat products, so the solubility of niobium is limited. Secondly, conventional controlled rolling is hard to implement due to high strain levels, higher strain rates and short interval times per pass. Contrary to the grain refinement effects resulted from strain-induced precipitation of Nb(C,N), during hot rolling, higher final rolling temperatures should bring coarser austenite grain and higher amount of Nb in solution, both factors increasing hardenability during transformation to room temperature. Finally, controlled cooling after hot rolling can be used as a procedure to properly adjust austenite grain size before transformation.

In order to consider all these variables, different process conditions were analyzed in laboratory. Considering the effects of reheating temperature before hot rolling, specimens with 0.26% C, 0.67% Si, 1.48% Mn and 0.12% V were reheated to 1,000 °C, 1,050 °C, 1,100 °C, 1,150 °C and 1,200 °C, holding 30 min. Fig. 5 shows the results of tensile test results as a function of reheating temperature. As it can be observed, both yield strength and tensile strength increase before 1,100 °C, and then yield strength starts to decrease, but tensile strength continues to increase until 1,150 °C, and then starts to decrease. For these variations, it can be explained from the interplay of austenite grain sizes and niobium contents in solid solution and/or precipitation, as shown in Fig. 6. When reheating temperature is higher than 1,150 °C, austenite grains start to coarsen resulted from unpinning due to complete dissolution of added niobium. Because of structure inheritance, coarse austenite grains mean coarse ferrite grains, and even non-polygonal ferrite. In addition, the positive effects of high reheating temperatures are both coarse austenite grain and niobium in solution would promote formation of pearlite structure.

For most bar production lines, there are no cooling facilities before finishing rolling stands, so higher reheating temperature implies higher finishing rolling temperatures. Fig. 7 shows the microstructures of simulation tests with different rolling temperatures, given 60 percent strain and strain rate of 10/s in single pass. As observed in the microstructure, the application of deformation at lower temperature favors the microstructure refinement and increase of the total amount of ferrite. In order to achieve the anti-seismic requirement of 600 MPa grade and considering the microstructural results shown in Fig. 3, the previous results confirm that high rolling temperatures are favorable. For the influences of cooling after rolling, higher cooling rates should inhibit austenite grain growth, which is the reason why increasing difficulty is observed for small bar sizes to meet the requirement of tensile-to-yield ratio. From the perspective of controlling tensile-to-yield ratio, cooling after rolling should be moderate or avoided, but depending on the need of strength levels.

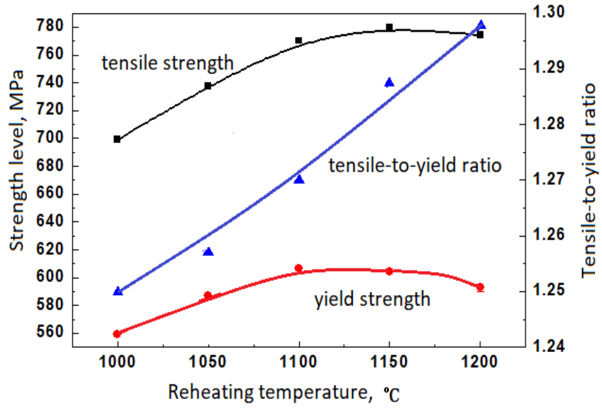
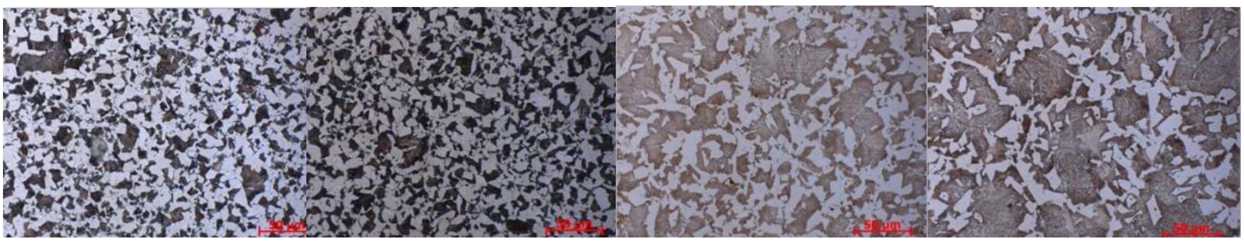
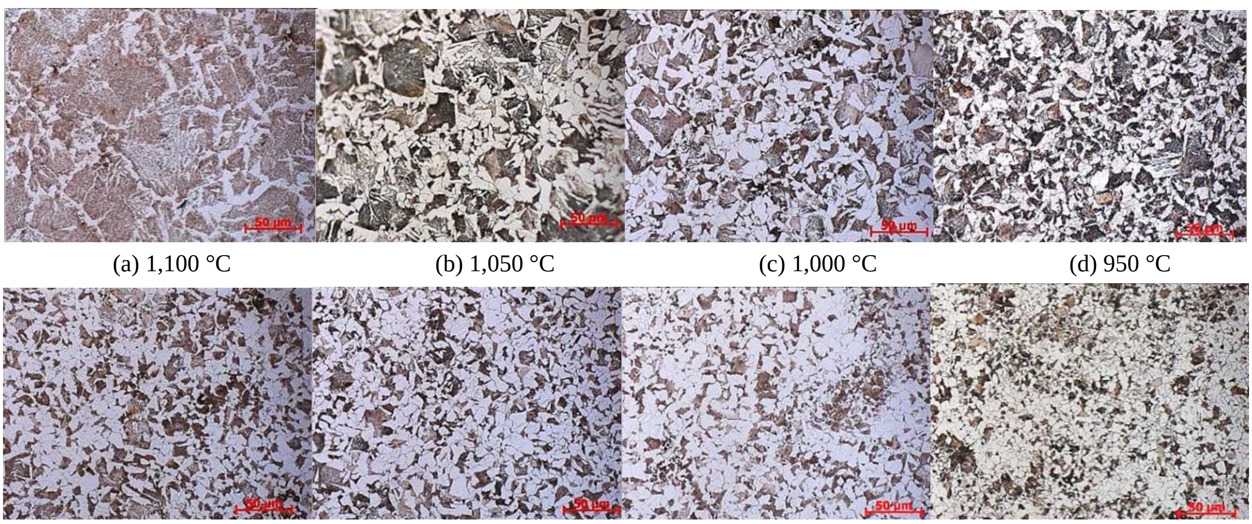


Fig. 5 Effects of reheating temperatures on tensile properties.



(a) 1,000 °C (b) 1,050 °C (c) 1,100 °C (d) 1,150 °C

Fig. 6 Effects of reheating temperatures on ferrite-pearlite microstructures.



(a) 1,100 °C (b) 1,050 °C (c) 1,000 °C (d) 950 °C

(e) 900 °C (f) 850 °C (g) 800 °C (i) 750°C

Fig. 7 Effects of rolling temperatures on ferrite-pearlite microstructures.

Based on industrial trial results and laboratory simulation tests, following practices are useful to develop HRB600E:

- Alloy design with high vanadium and small amount niobium is the best way to balance the yield strength and required tensile-to-yield ratio.
- Within 1,150 °C, high reheating temperatures and corresponding finishing rolling temperatures are preferred. Here 1,150 °C is the temperature of billets, not the temperatures of furnace atmosphere.
- Cooling after rolling should be moderate or avoided for the maximizing of tensile-to-yield ratio.

5. Mass Production and Strengthening Mechanisms

Based on above metallurgical designs, industrial trial results and simulation tests, 600 MPa grade with anti-seismic requirements had been produced on commercial scale. Up to now, about 500,000 tons HRB600E had been produced by two China's steel mills. Table 7 shows the statistics results of tensile tests as a function of rolled bar diameter. As we can see, all test results meet the requirements of anti-seismic 600 MPa reinforcing bar, which provided production records for setting up industry standard of T/CISA-2020: HRB600E anti-earthquake hot-rolled ribbed bar for the reinforcement of concrete. Fig. 8 shows the analysis results of microstructures of 12 mm, 18 mm, 25 mm and 32 mm. As we can see, besides high pearlite volume, pearlite interlamellar can be obtained due to lower transformation temperatures.

According to early reports, it is possible to achieve 600 MPa in yield strength, but thought impossible to reach 1.25 in tensile-to-yield ratio for ferrite-pearlite structure. In this regard, it is one technology breakthrough to develop anti-seismic 600 MPa reinforcing bar. In addition, based on production practice, it is necessary to recommend concerted effects of niobium and vanadium for optimum combination of mechanical properties in medium carbon steels. Table 8 gives the phase analysis results by chemical extraction technique. Due to relatively high nitrogen contents, about 75 percent of vanadium additions precipitate as nitrides of vanadium. In addition, about 72 percent of added niobium also exists in the form of precipitation. Both precipitations of vanadium and niobium should contribute to precipitation strengthening.

Fig. 9 shows the distribution of particle sizes for two steels. As observed, the particle sizes of 1-5 nm account for about 27.9% and 24.2% respectively, and they will contribute to the total strengths of the steel. Figs. 10 and 11 correspond to examples of precipitation of vanadium and niobium respectively. According to the calculation results of Irvine [8], it is assumed that added 0.015% niobium contents are in complete solution at reheating stage of 1,150 °C. Due to temperature increment resulted from high strain levels, strain rates and short interval time in finishing rolling for splitting rolling of small sizes, final rolling temperature is almost equal or even higher than

Table 7 Tensile test results of HRB600E on mass production.

Size, mm	V, %	Nb, %	R_{eL}, MPa	R_m, MPa	A, %	A_g, %	R_m/R_{eL}
φ32	0.17	-	632-665	831-852	15.1-16.2	9.8-11.5	1.285-1.326
φ28	0.15	-	632-665	831-852	15.1-16.2	9.8-11.5	1.272-1.315
φ25	0.15	0.015	656-673	859-867	15.2 -16.9	10.0-11.3	1.260-1.312
φ20	0.14	0.015	639-654	799-827	16.9-21.0	9.5-11.8	1.252-1.270
φ18	0.13	0.015	643-667	835-849	18.8-19.4	10.9-13.2	1.274-1.300
φ16	0.12	0.015	630-653	796-814	17.5-22.3	10.4-12.6	1.253-1.280
φ14	0.12	0.015	629-674	794-846	20.7-24.4	10.4-14.4	1.253-1.285
φ12	0.12	0.015	625-675	792-826	20.2-24.6	10.5-14.5	1.252-1.284

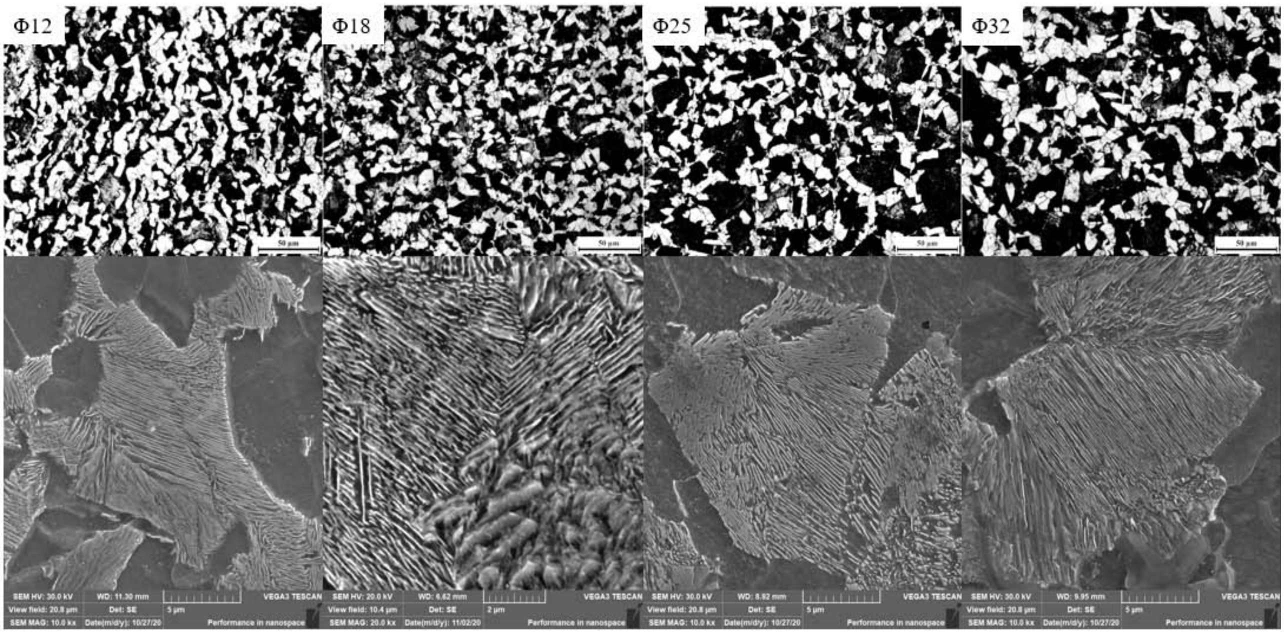


Fig. 8 Microstructure analysis results for mass production samples.

Table 8 Phase analysis results of HRB600E.

Chemical compositions								
Steel No.	C	Si	Mn	Cr	Nb	V	N	Ceq
No. 1	0.27	0.56	1.53	0.044	0.012	0.12	0.0167	0.55
No.2	0.28	0.77	1.56	0.029	0.011	0.14	0.0169	0.58
Weight percentage of each element, wt%								
	V	Nb	Ti	Cr	C	N	∑	
No. 1	0.092	0.0086	0.0022	0.0020	0.0031	0.0138	0.0842	
No.2	0.010	0.0080	0.0035	0.0025	0.0107	0.0140	0.1246	

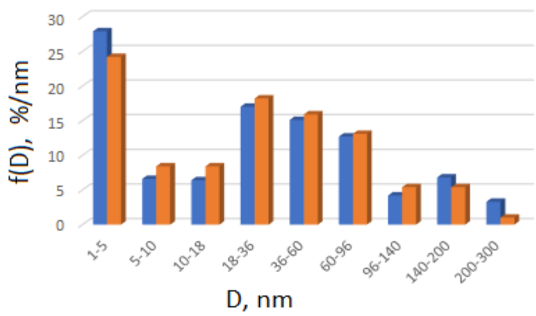


Fig. 9 Distribution of precipitate particles.

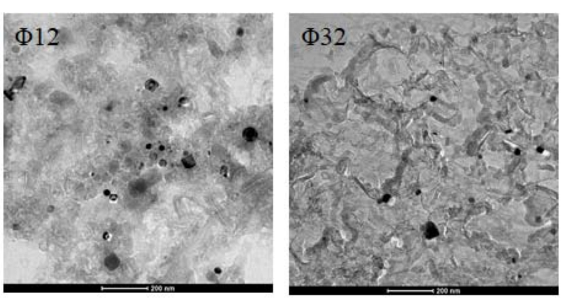


Fig. 10 Analysis results of V precipitate by TEM.

reheating temperature, so added niobium contents remain in solution, which should contribute to transformation strengthening. As the precipitation strengthening potential of niobium in ferrite, it shall depend on precipitation volume and precipitate sizes. Here one important point is why niobium additions are limited to 0.02% or 0.015%. When added niobium contents precipitate before transformation as Nb(C,N), which will fix some nitrogen contents and decrease the precipitation strengthening effects of vanadium.

Fig. 12 shows the contributions to yield strength through different strengthening mechanisms. The calculations have been done following the procedure of experience equations respectively. By comparison, it is obvious that the contribution by transformation strengthening of Nb plus V design is higher than that of only V design.

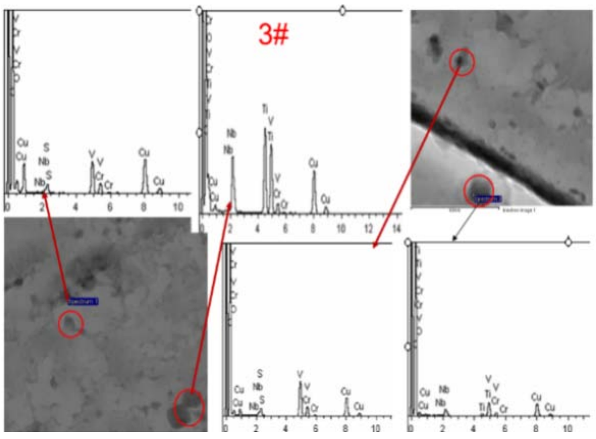


Fig. 11 Analysis results of Nb precipitate by TEM.

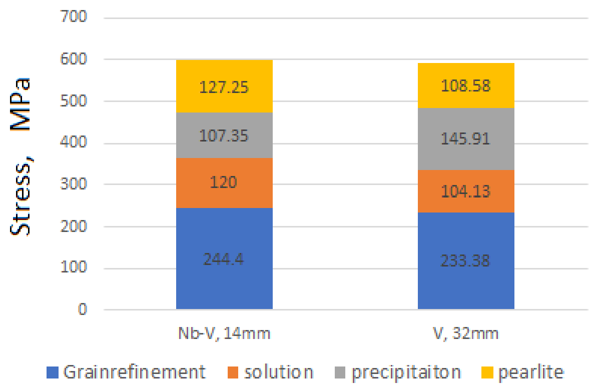


Fig. 12 Strengthening mechanisms analysis.

6. Conclusions

Anti-seismic 600 MPa reinforcing bar with ferrite-pearlite has been developed and produced in commercial scale. During this study, following conclusions can be obtained:

(1) Vanadium plus niobium is the best way to produce high-strength and anti-seismic reinforcing bars, especially for sizes of 25 mm and less.

(2) For the requirements of tensile-to-yield ratio, high pearlite volume fraction and moderate ferrite grain size are key.

(3) For the role of niobium additions, transformation strengthening is important to ensure required tensile-to-yield ratio, which is different with conventional controlled rolling concept.

(4) For the role of vanadium contents, microalloying with vanadium nitrogen alloy makes it possible to maximize the precipitation of VN, but stable and fine VN precipitates also refine grain sizes.

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