

# Development of High Strength Construction Rebars

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**Abstract:** The research, production and application of high strength rebars in China are reviewed. Microalloying, afterheat treatment and fine-grain strengthening are the most effective methods in developing high strength rebars. V-N microalloyed rebars have noticeable advantages over those microalloyed with other elements. Enhanced nitrogen in vanadium-containing rebars promotes the precipitation of V(C,N) particles which markedly improves the precipitation strengthening effects of vanadium, 50% of which can be saved. The goal of saving costly FeV and reducing costs are realized. Based on carbon steel and 20MnSi steel, grade 3 and grade 4 rebars with yield strength of 400MPa and 500MPa respectively can be produced by afterheat treating, or ultra-fine grain technologies; the alloy consumption is reduced and resources are saved at the same time. In recent years, remarkable progress has been achieved in production and application of high strength rebars.

**Key words:** high strength rebar, V-N microalloying, precipitation strengthening, afterheat treatment, ultra-fine grain steel, seismic resistant rebar

## 0 Introduction

As the biggest consumer among steel products in China, rebars account for one-fifth of total steel production and play an important role in national economic development. In recent years, the output and consumption of hot rolled rebars have both increased significantly to meet the requirements of fast growth of building industry. Fig.1 shows the production growth of rebar in the past decade. It is visible from the fig that annual output of rebar had exceeded 100 million tons by 2007, nearly five times that in 1997. Although the production of rebar has substantially increased in the last years, the product mix has been relatively backward.

Currently, the domestic building market is dominated by grade 2 rebars with yield strength of 335MPa. After years of efforts, some achievements have been made in application of 400MPa rebars but the share of high strength rebar is still lower. Grade 2 rebars account for 60% of all products and the application of 500MPa rebars is almost blank, and not filed in the architectural design specification in our country. However, in the developed countries, rebars for construction have been upgraded to 400MPa and above. For example, grade 4 rebars with yield strength of 500MPa have been widely used in Germany<sup>[2]</sup>. In terms of applications of building rebars, our country lags far behind the world advanced level. Rebar consumption can be

saved by 14% if the strength is upgraded from grade 2 of 335MPa to grade 3 of 400MPa. Similarly, 10% of steel can be saved if the strength is upgraded from grade 3 of 400MPa to grade 4 of 500MPa. Therefore, there will be huge economic efficiency and social benefits from rebar upgrading. This paper mainly introduces the research, development and applications of high strength rebars for construction in China.



Fig.1 Rebars production in china <sup>[1]</sup>

## 1 Research and development of high strength rebars

### 1.1 History

High strengthening is an important development trend of construction rebar. In the beginning, by increasing carbon and manganese contents, the earliest high strength rebar was produced with carbon content of about 0.35%, manganese ranging from 0.90% to 1.45% depending the size of product and yield strength from 350MPa to 400MPa. In the meanwhile, another method for producing high strength rebars was evolved based on cold deformation<sup>[3]</sup>. The strength of rebars was improved by drawing low-carbon steel at

the expense of lower ductility and poor bonding with concrete. Hot rolling with pre-springing method was once commonly used in Europe to produce high strength rebar, namely “hot rolled torsion rebar”, the yield strength of which was from 360MPa to 400MPa, and 500MPa grade in a few cases. For consideration of cost, the torsion rebar was gradually replaced by other hot rolled rebars with same grades. In 1970's, welding rebar was developed rapidly, which promoted evolution of rebar production technologies. A great step forward was achieved when the micro-alloyed rebar was developed <sup>[4-9]</sup>. Micro-alloying elements such as titanium, niobium and vanadium were used to produce high strength rebars based on low carbon steel with improved toughness, ductility and welding performances. Another new technology was rebar heat treatment, known as “Tempcore” and “Thermex” <sup>[10-11]</sup>, successful applied in Europe firstly. This was called “afterheat treated rebar” and “quenching rebar”. High temperature after rolling was used for quenching and residual heat in the central part was utilized for self- tempering. This method is currently the prevailing production process for producing high strength rebars in Europe. Micro alloying and afterheat treatment are the main processes for producing high strength rebars in foreign countries. They are widely used for producing 400MPa (grade 3), 500MPa (grade 4) and 600MPa (grade 5) high strength rebars.

Functional properties like seismic

resistance, flameproof, corrosion resistance are generally required by construction rebars, which represent another important development direction. In order to improve the seismic and safety performances of structures, series of high strength seismic rebars have been developed by countries all over the world. Japan takes the lead in the field of seismic rebar applications by developing series of high strength rebars with strength ranging from 590MPa to 1275MPa<sup>[12]</sup>. Europe has placed performance requirements like high tensile/yield strength ratio, good ductility and fatigue property. In order to improve the durability of buildings, higher requirement for construction rebars are put forward, especially when the building is under marine environment. One effective method for improving rebar corrosion resistance is surface treatment, such as epoxy coating and galvanizing treatment. Adding chromium, nickel and copper are effective ways for improving inherent corrosion resistance. In order to obtain longer service life, non-corrosive rebars have been developed and used by some European and American countries in the recent years<sup>[13-14]</sup>.

The research and development on rebars in China started in the mid of 1960's. Before this, the rebar standard was developed with reference to the standard for the similar products of Soviet Union, mainly carbon rebar. Since 1960s, our country has successfully developed series of low alloyed rebar products including Mn-Si, Si-V, Si-Ti, Si-Nb, Mn-Si-V and

Mn-Si-Nb, with almost 20 brands, some of which have been brought into the national rebar standard. In the 1980's, researches on manufacturing processes, brands, performances and profiles of the low alloyed rebars were conducted based on the resources in China and internationally advanced technologies. A series of microalloyed grade 4 rebar products based on 20MnSi (grade 2) were developed by adding proper elements like vanadium, niobium or titanium, namely 20MnSiV, 20MnSiNb, 20MnTi. In addition K20MnSi afterheat treated grade 3 rebars was produced. In late 1990's, for the sake of further cost reduction and resources saving, HRB 400 and HRB 500 high strength low cost rebars were developed by V-N microalloying<sup>[15-18]</sup>. In the meanwhile, high strength carbon rebars with ultra-fine grain has been developed with the support of national " 973 " project<sup>[19]</sup>. The successful developments of these products have effectively promoted the application of grade 3 rebar in our country. However, in the field of seismic resistant, flameproof and corrosion resistant rebars, our research work is still at the initial stage.

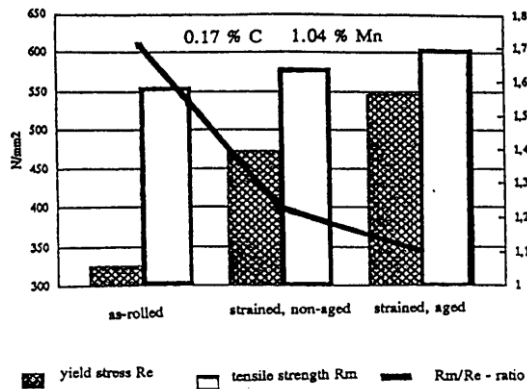
## 1.2 Production technology of high strength rebars

Rebar performance mainly depends on chemical composition and manufacturing parameters. As welding techniques are widely used in modern architectures, the way of adding carbon or equivalent content to improve strength is infeasible. In order to make up for the loss of strength due to decreased carbon content, alternative

process routes are available which include cold deformation, afterheat treatment, microalloying, grain refining and etc.

### 1.2.1 Cold deformation technology

Cold deformation is one of the earliest methods for rebar production. Although strength is obviously improved by cold deformation, the ductility is much damaged accordingly. As shown in fig.2, the strength of hot rolled low carbon rebar increases significantly while the ductility index  $R_m/R_e$  drops dramatically after 5% deformation.



(Diameter of rebar: 12mm, stretching strain: 5%)

Fig.2 Effect of cold deformation on mechanical property of rebars<sup>[2]</sup>

The strength of cold deformation rebars increases while ductility drops noticeably, which can hardly meet the requirements for construction steel, especially the seismic resistant steel. Besides, production costs

increase significantly as a result of cold deformation. Therefore, the manufacturing practice of cold deformation to improve strength of rebar has become a history.

### 1.2.2 Afterheat treating technology

Heat treatment after rolling is the primary route for producing high strength rebar in Europe and this method is to obtain tempered martensite on the surface of rebar to realize strengthening. The yield strength of common rebar can reach 400MPa and 500MPa to meet performance requirements of high strength rebar. On the basis of low carbon manganese steel, rebar with yield strength 600MPa can be produced by afterheat treated process coupled with microalloying method. Table 1 shows the chemical composition of typical high strength rebar with afterheat treated technology in the foreign country. From the table, it can be seen that through afterheat treatment content of alloying elements in the high strength rebar is lower, which shows significant cost advantages. Except one-off equipment investment (water-cooling equipment after rolling), there's little increase in production cost. Therefore, afterheat treating technology is an effective way for producing high strength low cost rebars.

Tab.1 Chemical composition of typical high strength

Yield strength level/MPa	rebar produced by afterheat treated process <sup>[2]</sup>				%
	C	Si	Mn	V	N
400	0.16~0.22	0.20~0.30	0.40~0.60		<0.012
500	0.16~0.22	0.20~0.30	0.60~0.80		<0.012
600	0.16~0.22	0.20~0.35	0.80~1.00	0.03~0.04	0.010~0.012

### 1.2.3 Microalloying technology

Microalloying utilizes two advanced technologies which are fine-grain strengthening and precipitation strengthening to improve strength. Micro alloying elements are added to rebar such as titanium, niobium and vanadium with a content ranging from 0.02% to 0.15%. Combined with appropriate process control method, the strength can increase doubly. Microalloying technology was one of the most significant achievements in physical metallurgy in latter half of 20 century, which provides another economic and effective method for producing high strength steels. The option of microalloying elements depends on the their binding abilities with oxygen, sulfur, carbon, nitrogen, etc, as well as the carbide/nitride dissolvability at different temperatures and specific conditions of production process. Besides technical consideration, economic viability is also an important factor to consider for technological selection. Three kinds of technologies, namely Ti-microalloying, Nb-microalloying and V-microalloying are introduced for rebar production and emphasis is given to the

research achievements of V-N microalloyed rebars.

#### ◆ Titanium microalloying

Titanium is the earliest micro alloyed element applied in steel. TiC is a significant contributor to precipitation strengthening, small quantity of which can increase strength significantly. However, titanium has strong binding force with oxygen, sulfur and nitrogen, forming oxides, sulfide and nitrides prior to formation of TiC. This will give rise to difficulty to control titanium content on a reliable basis, resulting in fluctuation in strength of the steel. Oxides and sulfides of titanium are formed in molten steel; Similarly, TiC is formed in solidification process and can easily become bulky inclusions. For the above reasons, titanium micro alloyed method is abandoned for strength improvement and this method has been used in the field of Ti-treatment and oxide metallurgy. Welding performance is improved by adding small quantity of titanium (generally 0.010% to 0.020%) to form fine TiO and TiN, A lot of steels containing titanium such as 20MnTi rebar in the past are discontinued in our country.

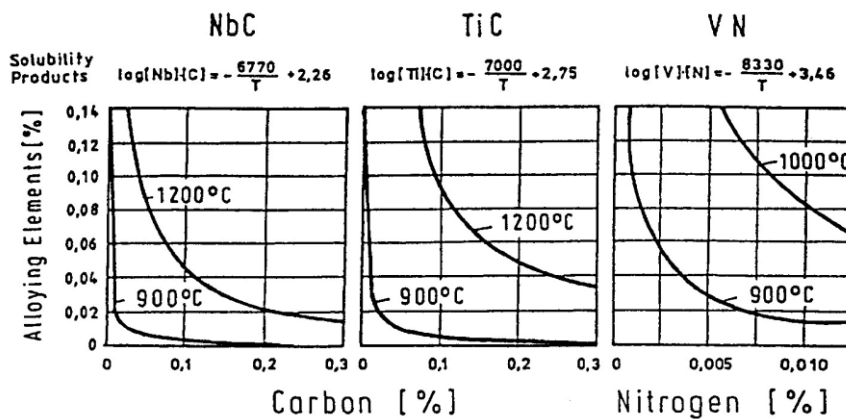


Fig.3 NbC, TiC and VN dissolvability at different temperature<sup>[3]</sup>

#### ◆ Niobium microalloying

Niobium microalloying is widely used in steel sheet and strip production. However, the application is restricted by dissolvability of Nb(C,N) in rebar production. The pass system of wire and rod mill is fixed and efficient rolling with fast speed is adopted. With heating up rolling scheme the temperature of rebar in exit of finishing stand is more than 1100°C. Therefore, it is difficult to meet technological conditions for Nb-containing steel production which requires low temperature and large deformation. Furthermore, the content of carbon in rebar is from 0.20% to 0.25%, which is relatively higher. It can be seen in Fig.3 that under typical composition of rebar (0.20%C), only 0.02% of niobium can be dissolved in the steel at the heating temperature of 1,200 °C.

Although the effect of niobium fine-grain strengthening is difficult to exert in rebar production process, the precipitation of Nb(C, N) contributes a little to strengthening. In order to make use of strengthening effect of niobium, further research has been done which has promoted the application of niobium of grade 3 rebars. The primary measure is to decrease precipitation temperature and obtain fine precipitate phase particles of Nb(C,N). Niobium microalloying is successfully applied in rebar of grade 3 by accelerated cooling after rolling and trace-titanium treatment which can reduce the adverse effects of Nb(C,N), especially for the widely used small size(  $\varnothing$

12mm~ $\varnothing$ 25mm)rebar. Based on 20MnSi, coupled with accelerated cooling process after rolling, the technical index of the rebar containing niobium of 0.02% to 0.03% can meet grade 3 rebar requirements,

#### ◆ Vanadium/vanadium-nitrogen microalloying

The microalloying process is mainly used to develop high strength weldable rebars around the world. During rebar production process, the high rolling speed and high finishing temperature are quite desirable for application of vanadium microalloying technique. The rebar standard issued in China also recommends the use of vanadium microalloying to produce grade 3 rebars with yield strength 400MPa at least<sup>[20]</sup>. However, vanadium added in rebars will increase the production costs. It is known that microalloying element takes effects by precipitation of its carbides/nitrides. Microalloyed nitrides have noticeably better strengthening effectiveness than that of carbonides, for nitrides particles are more stable. Research results<sup>[4-5]</sup> indicate that nitrogen is a cost-effective alloying element in vanadium microalloyed steels, and the strength can increase from 7MPa to 8MPa per 10ppm of nitrogen added. The successful applications of low-cost nitrogen help to improve strengthening effect of steel containing vanadium, and achieve the goals of saving alloy and reducing costs. In order to further reduce the costs of high strength rebar and explore the potential of microalloying steel,

extensive researches on production of high strength rebar with V/N microalloying have been conducted home and abroad<sup>[15-18]</sup>.

(1) Effect of nitrogen

Fig.4 shows the effect of nitrogen on strength of rebar containing vanadium. With almost the same content of vanadium, the strength of V-N microalloyed rebars is much higher than that of vanadium microalloyed steel. It can be seen that with enhancement of 100ppm of nitrogen, the yield strength and tensile strength of V-N microalloyed rebar increase by 117.5MPa and 135MPa, respectively, compared to vanadium containing steel. Experimental result shows that nitrogen markedly improves the strengthening effectiveness of vanadium in steel, which means nitrogen is a very effective strengthening element for rebars containing vanadium.

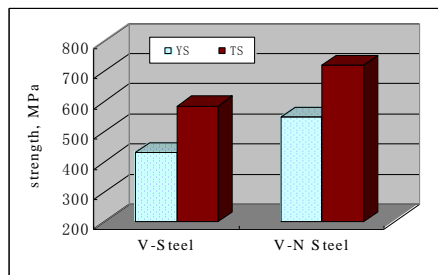


Fig. 4 Effect of N on strength of V rebars steel<sup>[16]</sup>

(2) Vanadium distribution and precipitation phase in rebars

Vanadium distribution is shown in Fig.5. It can be seen there is an evident difference in phase distribution of vanadium between high-nitrogen steel and low-nitrogen steel. In vanadium containing

steel to which FeV is added, vanadium exists mainly as solid solution which accounts for 56.3% of total vanadium content, while only 35.5% of vanadium precipitates in the form of V(C,N). The results reveal that most of the microalloying elements in vanadium containing steel do not work toward precipitation strengthening and it is a waste of vanadium. On the contrary, in V-N steel, 70% of vanadium forms V(C,N) precipitates and only 20% dissolves in the matrix. Therefore, nitrogen added to steel alters the vanadium phase distribution and promotes precipitation of vanadium dissolved in the matrix, thus improving the precipitation strengthening of vanadium.

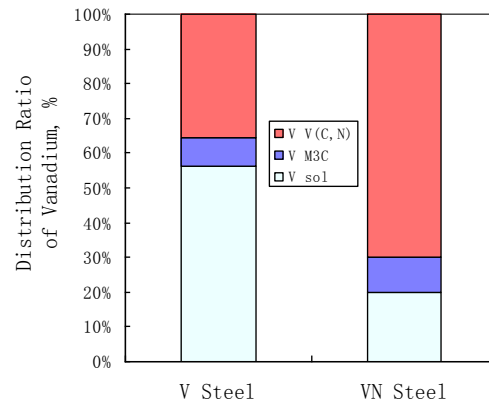


Fig. 5 Vanadium distribution in V-steel and V-N steel<sup>[15]</sup>

Phase analysis result shows that the fraction of fine particles with a size of less than 10nm in vanadium containing rebar is just 21.1%, whereas, the fraction is up to 32.2% in V-N rebar. The increase of fine and dispersed V(C,N) precipitated phase is the primary reason for strength rise of V-N rebars.

$$\sigma_S = 85.7 + 37[Mn] + 83[Si] + 17.4 \times D^{-1/2} + \sigma_{PR}$$

V-Steel:  $R_{el} = R_{el(20MnSi)} + 1056 \times [V\%]$

V-N Steel:  $R_{el} = R_{el(20MnSi)} + 1994 \times [V\%]$

(3) Strengthening mechanism of V-N rebars

On the basis of research results, the strength of microalloyed steels can be expressed as<sup>[21]</sup>:

$$\sigma_s = 85.7 + 37[Mn] + 83[Si] + 17.4 \times D^{-1/2} + \sigma_{PR}$$

where  $37[Mn] + 83[Si]$  is solid solution strengthening factor,  $17.4 \times D^{-1/2}$  is fine-grain strengthening factor and  $\sigma_{PR}$  is precipitation strengthening factor. According to experimental results of ferrite grain size and yield strength of the sample steel, the contribution of each strengthening factor to the yield strength can be estimated by the above formula and the result is shown in Fig.6.

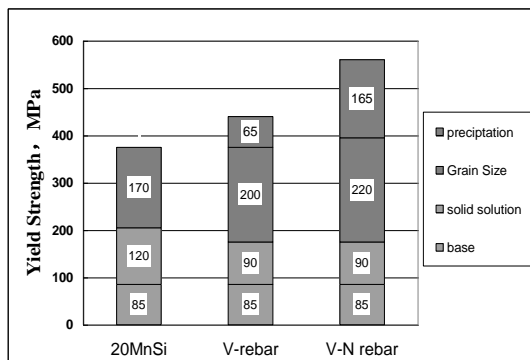


Fig.6 Strengthening Mechanism of 20MnSi, V rebars and V-N rebar

It can be seen that effect of matrix strengthening and solid solution strengthening is basically the same for the three rebars, the strength difference is caused by different effects of precipitation strengthening and fine-grain strengthening. The effect of precipitation strengthening and fine-grain strengthening of V-N steel is better than that of V containing steel,

23MPa by fine-grain strengthening and 86MPa by precipitation strengthening, totaling 109MPa. Comparison of contributing factors to the precipitation strength between the two steels suggests that  $\sigma_{PR}$  in V-N rebar doubles that in vanadium containing steel. The incremental strength from precipitation accounts for 73.2% of total strength increment of the steel. It can be seen that by addition of nitrogen, vanadium can play a greater role in precipitation strengthening and fine-grain strengthening, which contribute to significant improvement in yield strength. The result of regression equation shows that the strengthening ability of vanadium in V-N rebars almost doubles that of vanadium-containing rebar.

V-Steel:  $R_{el} = R_{el(20MnSi)} + 1056 \times [V\%]$

V-N Steel:  $R_{el} = R_{el(20MnSi)} + 1994 \times [V\%]$

(4) Effect of accelerated cooling after rolling

The products which meet the requirements of grade 3 and grade 4 rebars with lower content of vanadium can be produced through accelerated cooling process. Fig.7 indicates yield strength changing with content of vanadium for vanadium containing rebar, V-N rebar and V-N rebar produced by accelerated cooling.

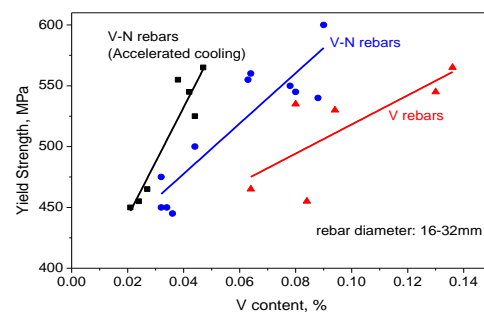


Fig.7 Effects of V content and ACC process on the strength of rebars



It can be seen that with the same strength, V-N rebar save V resources substantially compared with rebar containing vanadium only, with V consumption decreasing from 0.06% ~ 0.08% to 0.03% ~ 0.04% for 400MPa rebar, and from 0.07% ~ 0.12% to 0.06% ~ 0.08% for 500MPa rebar. By accelerated cooling process, the consumption of vanadium can be reduced to 0.02% ~ 0.03% for 400MPa V-N rebar and 0.04% ~ 0.05% for 500MPa V-N rebar. It follows that FeV consumption and costs will be saved by adopting microalloying technique combined with accelerated cooling process.

### 1.2.4 Technology of fine-grain rebar

Based on “973” ultra-fine grain steel project, the research work of high strength fine-grain rebar has been conducted in China. The ultra-fine grain structures can be obtained through DIFT technique as well as deformation at Ar3 temperature. Fig.8 shows the effects of fine grains on

the strength of carbon rebar and 20MnSi rebar. Common carbon steel is able to satisfy the performance requirements of grade 3 rebar with minimum yield strength of 400MPa by refining grains. For 20MnSi rebar, the strength obtained is more than 500MPa.

Grain refining is an effective method for raising strength while improving toughness at the expense of reducing tensile/yield ratio. It can be seen in Fig.8 that tensile/yield ratio of carbon rebar and 20MnSi rebar with fine-grain strengthening is reduced to 1.20 and below, less than the ratio of 1.25, a minimum requirement by the seismic rebar. Another problem is weldability of this kind of rebar. The grain of heat affected area will grow due to high temperature during the welding process, and welded joint will intermetallicate at the same time. Improving tensile/yield ratio and researching connection technology are the primary efforts toward promoting fine-grain rebar in the future.

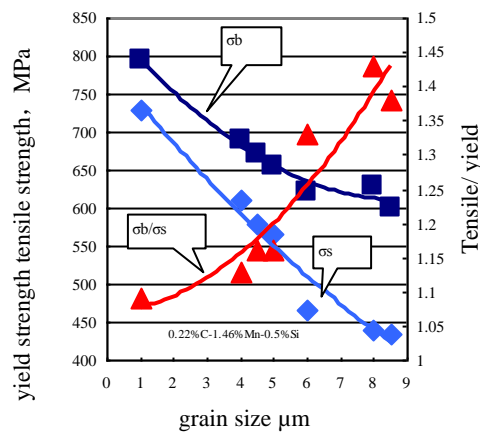
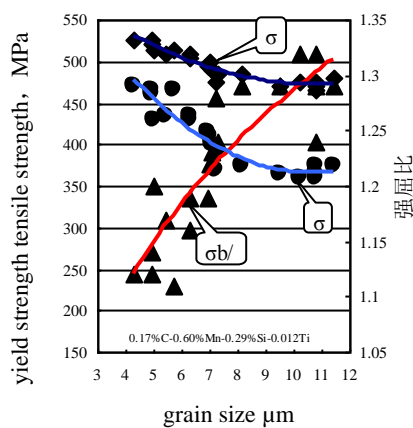


Fig.8 Effect of ferrite grain size on the strength of plain C and 20MnSi rebar<sup>[19]</sup>

## 2 Production and application of high strength rebar

Fig.9 shows production of grade 3 rebar in China in recent years. In the year

of 2000, its output was only 260 thousand tons, accounting for 1% of the total rebar production. By 2008, the output had reached 33 million tons, accounting for one-third of the total. High strength rebar production and application in China has developed rapidly. It can be seen in Fig.10 that increasing output of grade 3 rebar has significantly contributed to the product mix. Although the output of grade 3 rebar has substantially increased, its share is still lower. 20MnSi rebar of grade 2 has the biggest share in the construction rebar market, namely 60%. The application of building rebars indicate that our country still lags far behind the world advanced level.

V/V-N microalloying is the predominant process for producing high strength rebars for construction. Based on 20MnSi, appropriate vanadium or V-N is added to steel to meet performance requirements of 400MPa and 500MPa high strength rebars. Table 2 lists the typical chemical composition of 400MPa and 500MPa rebars produced by converter process. It can be seen that the consumption of vanadium needed in V-N steel is much less than that in the steel containing vanadium only with the same

strength level. V-N microalloying is adopted to play a role in strengthening precipitation as well as improving strength, saving alloy consumption and reducing production costs. Through optimization of chemical composition, the consumption of vanadium in V-N microalloying high strength rebars can be reduced to the content ranging from 0.02% to 0.04%, half that of V-Fe microalloyed rebar.

Production experiences indicate that the mechanical properties of V-N micro alloyed rebars are quite stable and the strength is controlled with a variation of 75MPa, which can satisfy class- one seismic requirements. According to the statistical data of mass V-N rebar production, the way that strength is affected by dimension specification is identified. As shown in Fig.11, statistical results indicate that the average variation of yield strength is 17MPa while the tensile strength is 19MPa by using billets with the same chemical composition to produce rebars of different specifications. V-N micro alloyed rebars of different specifications exhibit similar properties suggesting that the effects of specification are not evident.

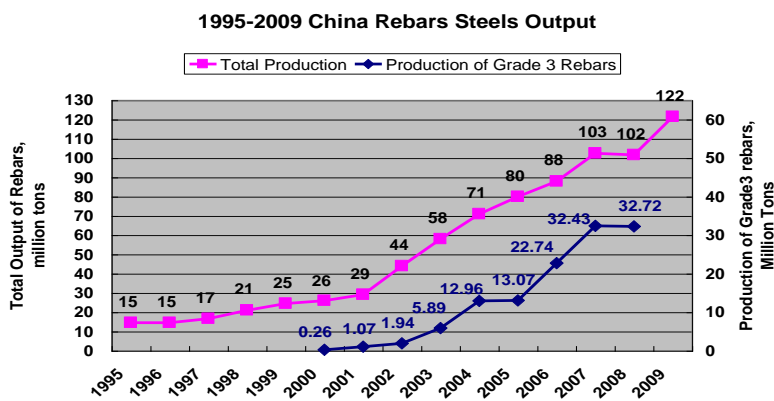


Fig.9 Production of Grade 3 Rebars in China

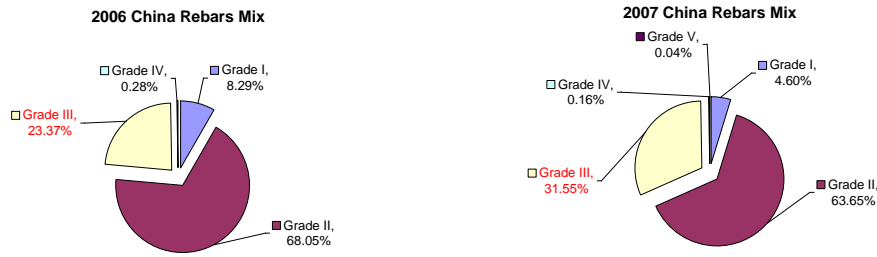


Fig.10 Rebar product mix in China

Tab.2 Chemical composition of 400MPa and 500MPa rebars produced by converter process

Grade	Alloy	C	Si	Mn	P, S	V	N	%
400MPa	V-N	0.20-0.24	0.45-0.60	1.25-1.45	<0.035	0.03-0.04	0.008-0.012	Φ 16- Φ 40
						0.02-0.03		Φ 6- Φ 16
	V-Fe	0.20-0.24	0.45-0.60	1.25-1.45	<0.035	0.07-0.09	0.003-0.006	Φ 16- Φ 40
						0.05-0.07		Φ 10- Φ 16
500MPa	V-N	0.20-0.24	0.45-0.60	1.40-1.55	<0.035	0.05~0.07	0.010-0.015	Φ 16- Φ 32
						0.07-0.09		0.012-0.018
	V-Fe	0.20-0.24	0.45-0.60	1.40-1.55	<0.035	0.07~0.12	0.003-0.006	Φ 16- Φ 32

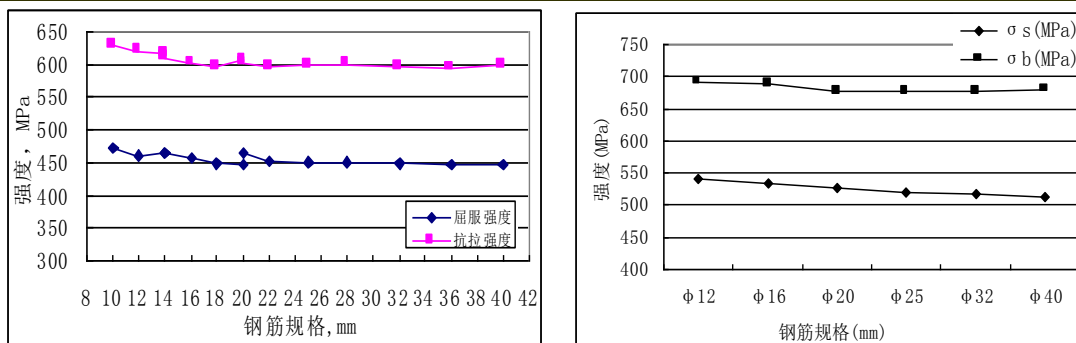


Fig.11 Effect of the size of rebars on mechanical properties<sup>[22]</sup>

A significant advantage of V-N rebars is the excellent anti-strain aging performance. Table 3 shows the results of the strain aging evaluation of V-N rebars and 20MnSi rebars. The results show that strain aging phenomenon occurs obviously

in 20MnSi rebar after strain aging treatment, which results in significant strength increase. However, V-N rebar eliminates the adverse effects of strain aging on properties of steel and non-strain aging steel is obtained.

Tab.3 Strain Aging Behavior of V-N and 20MnSi Rebars

Steel	Non-aging			After aging		
	$\sigma_s$ /MPa	$\sigma_b$ /MPa	$\delta_5$ /%	$\sigma_s$ /MPa	$\sigma_b$ /MPa	$\delta_5$ /%
V-N	460	640	27	470	655	25
20MnSi	380	575	30	425	615	24.5

The successful application of V-N microalloying technology in high strength rebars provides a new effective and economic method for producing high strength rebar. Nitrogen is added into vanadium containing steel to play a role in precipitation strengthening, as well as improving strength, saving costly FeV and reducing production cost. V-N microalloyed rebars of grade 3 are widely produced, obtaining great economic and social benefits.

### 3 Conclusions

(1) Remarkable progress has been made in production and application of high strength rebars in China and the output of 400MPa rebars has reached 33 million tons, accounting for one-third of the total rebar production. However, 500MPa rebar has been virtually not used in China, lagging far behind the world advanced level. It will be a lasting and arduous task to promote upgrading of products and enlarge proportion of grade 3 and grade 4 rebars for construction.

(2) V-N microalloying is an effective way for producing high strength low cost rebars. Nitrogen added into V-containing rebars can play a role in promoting V precipitation, thus improving strengthening effect remarkably, so as to save costly FeV and reduce production costs. Compared with vanadium microalloying, V-N microalloyed rebars can save 50% of vanadium, showing evident cost-saving advantages. In addition, V-N microalloyed rebars exhibit

performance advantages such as reliable performance, little strength variation, low strain aging sensibility, excellent weldability which can meet seismic design requirements.

(3) Grain refinement is an effective method for producing low cost high strength rebars. Based on common carbon steel and 20MnSi steel, grade 3 and grade 4 rebars with yield strength of 400MPa and 500MPa respectively can be produced by ultra-fine grain technology, the alloy consumption is reduced and resources are saved. The applications of afterheat treated rebars are restricted in many aspects. More efforts should be made to develop associated application technologies such as welding process, connecting technology as well as development of standards and specifications, etc.

### References

- [1] "Annual report on China Iron & Steel Statistics", China Iron & Steel Association, (2006-2009).
- [2] D.Russwurm and P.Wille. "High Strength Weldable Reinforcing Bars". Microalloying'95, Pittsburgh, PA, ISS, 1995.
- [3] H.G. Trotter, High Strength Steel Reinforcement, The Metallurgist and Materials Technologist, February 1977, p.73-76.
- [4] Vanadium Steel-Reinforcing Bars, VANITEC Monograph No.1, Publication No. V025, 1976.
- [5] A.M. Sage, Effect of V, N, Al on the mechanical properties of reinforcing bar steels, Metals Technology, February, 1976.
- [6] I. Lindberg, Weldable high strength reinforcing bars microalloyed with vanadium and nitrogen, Vanadium Steels Conference, Krakow, 9-10 October 1980.

- [7] M.Korchynsky. "Overview". Proc. 8th Process Tech. Conf., Iron and Steel Society, 1988:79~87.
- [8] S.Zajac, T.Siwechi, *etal.* 'strengthening mechanism in vanadium microalloyed steel intended for long products', ISIJ International, vol.38, No.10, 1998:1130-1139.
- [9] S.Zajac, R.Lagneborg, T.Siwechi. "The Role of Nitrogen in Microalloyed Steels". Proc. Int. conf. Microalloying '95, Pittsburgh, PA, ISS, 1995:321~340.
- [10] M. Economopoulos, Y. Respen, G. Lessel, G. Steffes, Application of the Tempcore Process to the Fabrication of High Yield Concrete-reinforcing Bars, C.R.M., No.45, December 1975.
- [11] P. Simon, M. Economopoulos, P. Nilles, Tempcore: A new process for the production of high-quality reinforcing bars, Iron and Steel Engineer, March 1984, p.53-57.
- [12] N.KURODA, M.YOSHIKAWA, High Production Capacity Steel Bar Mill of High Strength Steel Bars for Concrete Reinforcement, Kobe steel technical Newspaper, Vol.58, No.2, 2008, p.7-11.
- [13] Guidance on the use of stainless steel reinforcement, The Concrete Society, 1998.
- [14] M.Rosso, M.Comoglio, G.Metotti, D.Gyppaz, La Metallurgia Italiana, Vol.90, No.2, 1998, p.35.
- [15] Yang Caifu, Zhang Yongquan, Liu Shuping, Precipitation Behavior of Vanadium in V-N Microalloyed rebars Steels, HSLA Steels'2000 (eds. Liu Guoquan,etal, Metallurgical Industry Press, 2000,10), 4<sup>th</sup> International Conf. on HSLA Steels, Oct.30-Nov.2, Xi'an China, p152-157.
- [16] Zhang Yongquan, Yang Caifu, Liu Shuping. Research on economic grade 3 rebars for buildings .Iron and Steel, vol.35, No.1, 2000, p.43-46.
- [17] Yang Caifu, Zhang Yongquan, Liu Shuping, Strengthening mechanism of V-N micro alloyed rebars, Iron and Steel, vol.36, No. 5, 2001, p.55-57.
- [18] Ji Huaizhong, Yang Caifu, Zhang Yongquan, Strengthening effects of nitrogen on 20MnSi rebar containing vanadium. Special Steel, Vol.21, No.5, 2000, p.20-23.
- [19] Weng Yuqing, Ultra-fine grain steel, Metallurgical Industry Press, Beijing, 2003.
- [20] National Standard GB1499-1998, "Hot Rolled Ribbed Steel Bars for the Reinforcement of Concrete", 1998.10. (in Chinese).
- [21] Yong Qilong, Ma Mingtu, Wu Baorong, "Micro-alloyed steel-physics and mechanical metallurgy" Mechanical Industry Press, Beijing, 1989:57.