RESEARCH, PRODUCTION AND APPLICATION OF HIGH STRENGTH REBARS

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Abstract: The paper reviewed the research, production and application of V-N microalloyed high strength rebars in China. Enhanced nitrogen in V-containing rebars promotes precipitation of fine V(C,N) particles, and improves markedly precipitation strengthening effectiveness of vanadium. Therefore, V addition in V-N rebars can be reduced by 40% compared with the same strength level of V-containing rebars. V-N microalloyed technology is a cost-effective way for the development of high strength rebars in China.

Key Words: high strength reinforcing bars; V-N microalloyed; precipitation strengthening

1 Introduction

In order to meet the requirements of rapid development of construction industry, the production and consumption of hot-rolled rebars have a great increase in China last years. Fig. 1 shows the production and consumption of rebars in China since 1995. We can learn, the annual consumption of rebars since 2001 was close to 30 million tons, almost doubled the consumption of 1995. The consumption of rebar is always the largest among steel products in China, accounts for 20% of national steel output and plays a decisive role to the development of national economy.

The output and consumption of rebars have a great increase last years, however, the products mix of rebars are not changed much, but comparatively single and backward. In the construction market of China, 20MnSi Grade I rebar with a yield strength of 335 MPa plays a dominant role, accounts for more than 95%. However, in foreign countries, rebars more than 400 MPa (Grade III) have been used already for many years. In some developed countries in Europe, such as Germany, rebars more than 500 MPa (Grade IV) are mainly used. If high strength rebars are used to replace low strength rebars, 14% of steel can be saved. Therefore, the upgrading of rebars has a large social and economical benefits.

In order to adapt to international practice as soon as possible as well as to save steel products, China has accelerated the upgrade of construction rebars and is now promoting the application of 400 MPa high strength weldable rebars. This paper
summarized the work that has been done in last years for the research of high strength rebars in China, with emphasis on the research, trial production, comprehensive property and application of VN micro – alloyed high strength rebars, and analyzed the economical benefit of VN micro – alloyed rebars.

2 The Test and Research of VN Microalloyed High Strength Rebars

Micro – alloying is the main technical route worldwide to develop high strength rebars\cite{1-3}. Because long products like rebars have high production speed, high rolling temperature, finish rolling temperature normally above 1000 °C, this process characteristics decides that VN micro – alloying technology is suitable for the alloying design of rebars\cite{2}. In the new issued Chinese standard for rebars, using V – alloying process to produce 400 MPa high strength rebars is also recommended. However, the addition of vanadium increases the cost of rebars. We know, the micro – alloying element contributes by the formation of carbonitrides. Because the stability of nitrides in the steel is higher than carbides, the precipitates are more fine and dispersed, so, the precipitation result is remarkably improved. A lot of research result indicates\cite{4,5}, N is a very effective micro – alloying element in vanadium – containing steel. $10 \times 10^{-6}$ of N increase in vanadium – containing steel will lead to 6 MPa increase of strength. By fully using cheap nitrogen, the strengthening result of vanadium steel can be remarkably improved so as to save the alloy amount and lower the cost. In order to further reduce the cost of high strength rebars and fully utilize the potential of micro – alloy steel, the research work for VN micro – alloyed high strength rebars has also been implemented\cite{6-9}.

2.1 The Role of N

Fig. 2 shows the effect of N to the strength of vanadium containing rebars. Although the vanadium content in V micro – alloyed rebars and VN micro – alloyed rebars is almost identical, the strength of VN steel is higher than V steel evidently. From the result of Figure, we can learn, due to approx. $100 \times 10^{-6}$ addition of N to VN steel, the yield strength and tensile strength are increased by 117.5 MPa and 135 MPa respectively. The test result clearly indicates, nitrogen contributes highly to strengthening of vanadium – containing rebars. Therefore, we can say N is a very effective strengthening element for vanadium – containing rebars.

![Fig. 2 The strength of V-steel and VN steel](image)

<table>
<thead>
<tr>
<th>Steel</th>
<th>YS/MPa</th>
<th>TS/MPa</th>
</tr>
</thead>
<tbody>
<tr>
<td>V-Steel</td>
<td>442.5</td>
<td>585</td>
</tr>
<tr>
<td>V-N Steel</td>
<td>560</td>
<td>720</td>
</tr>
</tbody>
</table>

2.2 Distribution of V in the steel and precipitates

The distribution of vanadium in the steel is shown in Fig. 3. From the Figure, we can learn, the inter – phase distribution of vanadium in high nitrogen steel and low nitrogen steel is different evidently. In the FeV micro – alloyed steel, V exists mainly in the form of solid solution. Solid V accounts for 56.3% of total vanadium content, only 35.5% of V formed into V (C, N) precipitates. This means, a great deal of micro – alloying ele-
ments do not attribute to the precipitation strengthening and is a waste of vanadium. VN steel is just on the contrary, 70% of vanadium formed into V (C, N), only 20% of vanadium left in the base. This indicates the addition of nitrogen changes the interfacial distribution of V, promotes the transformation of vanadium from solid solution to V(C, N) precipitation phase, thus makes vanadium contribute more to precipitation strengthening.

![Vanadium distribution in V - steel and V - N steel](image)

Table 1 indicates the analysis result of V(C, N) precipitates in V steel and VN steel. We can learn, the V(C, N) amount precipitated in VN steel is doubled the precipitation amount in V steel. This means, the addition of nitrogen greatly promotes the precipitation of vanadium. The adequate precipitation of V(C, N) is a main reason for the strength increase of VN steel.

![Grain size distribution of V(C,N) precipitates in V - steel(a) and V - N steel(b)](image)

2.3 Strengthening mechanism of VN rebars

Based on a great deal of research result, the formula of strength of micro-alloyed steel can be\(^{[10]}\):

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

among which, 37[Mn] + 83[Si] represent solid solution strengthening items of Si and Mn, 17.4 \times
represents strengthening items of grain refinement and \( \sigma_{PR} \) represents precipitation strengthening items. Based on the grain sizes of actual measurement and the test result of yield strength of tested steel, we can estimate the contribution of various strengthening mechanism to yield strength. Fig. 5 illustrates the contribution of various strengthening mechanism to yield strength. From the figure, we can learn, the base strengthening and solid solution strengthening of three kinds of rebars are basically identical, the difference of strength are mainly caused by the difference of precipitation strengthening and grain refinement. The precipitation strengthening and grain refinement of VN steel has obviously improved in comparison with V steel, grain refinement contributes for approx. 23 MPa higher, and precipitation contributes for 86 MPa higher, totally 109 MPa. Comparing the contribution of two kinds of precipitation, we can see, \( \sigma_{PR} \) in V – N steel is doubled comparing with V steel; the increment of precipitation strengthening accounts for 73.2% of total strength increment of steel. Therefore, after nitrogen enhancing in the steel, the precipitation strengthening and grain refinement of vanadium in the steel is brought into full play and the yield strength is remarkably improved.

3 Industrial Trial Production and Comprehensive Property of VN Microalloyed Rebars

3.1 Optimization of chemical composition of VN rebars

On the basis of laboratory research, industrial trial production was made for V and VN rebars adopting the process of BOF + continuous caster. Considering the influences of sizes, through the addition of V – Fe and V – N, the V rebars and VN rebars with different vanadium content were tested. Among which, the V content in V – steel is 0.06% ~ 0.13%; the V content in VN – steel is 0.03% ~ 0.09%. The correlation of strength of different sizes of rebars with the changes of V content is shown in Fig. 6. We can see, under same strength level, the vanadium content needed in VN steel is remarkably lower than the vanadium content needed in V steel. The result of statistical analysis indicates, the strengthening capability of V in VN rebars is almost doubled comparing with the strengthening capability of V in V rebars. The result of industrial trial production also indicates: the strengthening function of V can be brought into full play with VN micro-alloying, so the improvement of strength, saving of micro-alloy and lowering of production cost can be realized. Through the optimization of alloying composition,
after VN micro-alloying is adopted, the V content in 400 MPa high strength rebars can be lowered to a level between 0.02% ~ 0.04%. Comparing with V-Fe micro-alloyed rebars, V content is lowered half, refer to Table 2.

### 3.2 Production process of VN rebars

<table>
<thead>
<tr>
<th>Alloy</th>
<th>Sizes of billets/ mm</th>
<th>C</th>
<th>Si</th>
<th>Mn</th>
<th>P,S</th>
<th>V</th>
<th>Size/ mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>V-N</td>
<td>140 x 140</td>
<td>0.18 - 0.24</td>
<td>0.45 - 0.60</td>
<td>1.25 - 1.45</td>
<td>&lt; 0.035</td>
<td>0.03 - 0.04</td>
<td>Ø16 - Ø40</td>
</tr>
<tr>
<td></td>
<td>120 x 120</td>
<td>0.18 - 0.24</td>
<td>0.45 - 0.60</td>
<td>1.25 - 1.45</td>
<td>&lt; 0.035</td>
<td>0.07 - 0.09</td>
<td>Ø16 - Ø40</td>
</tr>
<tr>
<td>V-Fe</td>
<td>140 x 140</td>
<td>0.18 - 0.24</td>
<td>0.45 - 0.60</td>
<td>1.25 - 1.45</td>
<td>&lt; 0.035</td>
<td>0.05 - 0.07</td>
<td>Ø6 - Ø16</td>
</tr>
<tr>
<td></td>
<td>120 x 120</td>
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</tr>
</tbody>
</table>

Using Nitrovan VN alloy to produce high strength rebars, the recovery of V and N are very stable. The large batches of industrial production in Shougang indicates, the fluctuation range of V in VN rebars is very little. For 120 mm² of billets, V content is between 0.024% ~ 0.028%; for 140 mm² of billets, V content is between 0.033% ~ 0.038%. Therefore, the V content in the steel can controlled stably, the fluctuation level is up to 0.004% and create a good condition for the stability of rebar property. However, in V-Fe alloyed rebars, the fluctuation range of V content is much larger, up to 0.015% ~ 0.02%. The big fluctuation of V content in steel lead to instability of rebar property. In fact, the strength fluctuation of V-rebars with the addition of V-Fe is very difficult to control within 80MPa, i.e. very difficult to reach the requirements of Grade I aseismic rebars.

The nitrogen level in the steel mainly depends the addition of vanadium. When using Nitrovan12 (12% N) to add V and N, each 0.01% of V can bring approx. 10 ppm of nitrogen into the steel.

Comparing with other micro-alloyed steel, V and VN steels have such advantages as easy for continuous casting, little deformation resistance, suitable for rolling under high temperature zone, low dissolution temperature of precipitates etc. Therefore, there is no special requirements for the production process of VN rebars, basically identical with the process of 20MnSi rebars. Attention should be made is; in order to fully utilize the strengthening mechanism of vanadium, the complete solid solution of vanadium should be guaranteed during reheating, normally the temperature can be controlled between 1 150 ~ 1 200 °C.

### 3.3 Stability of property

Based on the statistical data of VN rebars of large batches of production, the regularity of the effect of rebar sizes to the strength and elongation is accomplished, as shown in Fig.7. Statistical
result indicates, $\sigma_a$, average fluctuation is 17 MPa, $\sigma_b$, average fluctuation is 19 MPa. The property of different sizes of VN rebars is very close and very stable which implies the effect of VN rebar sizes is not obvious.  

3.4 Comprehensive property  
(1) Basic mechanical property  
According to the chemistry of Table 2, the production for various sizes of VN micro-alloyed high strength rebars was implemented. The mechanical property statistics of various sized VN micro-alloyed 400 MPa rebars is shown in Table 3 and Table 4. From the result of industrial trial production, we can learn, the property of VN micro-alloyed high strength rebars are very stable. The fluctuation of yield strength of rebars is between 425 ~ 500 MPa, the fluctuation range is 75 MPa; The fluctuation of tensile strength of rebars are between 575 ~ 660 MPa, the fluctuation range is 80 MPa; Elongation is between 19% ~ 32%. All sized rebars meet the Grade I aseismic requirements of $\sigma_a / \sigma_b > 1.25$. Therefore, the defined chemistry of VN micro-alloyed rebars is appropriate.

<table>
<thead>
<tr>
<th>Sizes / mm</th>
<th>$\sigma_a$ / MPa</th>
<th>$\sigma_b$ / MPa</th>
<th>$\delta_s$ / %</th>
</tr>
</thead>
<tbody>
<tr>
<td>010</td>
<td>480 - 500</td>
<td>493</td>
<td>26 - 33</td>
</tr>
<tr>
<td>012</td>
<td>460 - 490</td>
<td>478</td>
<td>26 - 33</td>
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<tr>
<td>014</td>
<td>450 - 500</td>
<td>482</td>
<td>26 - 33</td>
</tr>
<tr>
<td>016</td>
<td>430 - 485</td>
<td>463</td>
<td>26 - 32</td>
</tr>
<tr>
<td>020</td>
<td>465 - 490</td>
<td>478</td>
<td>22 - 29</td>
</tr>
<tr>
<td>022</td>
<td>445 - 485</td>
<td>468</td>
<td>24 - 27</td>
</tr>
<tr>
<td>025</td>
<td>450 - 500</td>
<td>474</td>
<td>19 - 31</td>
</tr>
<tr>
<td>028</td>
<td>425 - 475</td>
<td>447</td>
<td>22 - 29</td>
</tr>
<tr>
<td>032</td>
<td>455 - 480</td>
<td>467</td>
<td>20 - 23</td>
</tr>
<tr>
<td>036</td>
<td>440 - 500</td>
<td>458</td>
<td>22 - 24</td>
</tr>
<tr>
<td>040</td>
<td>445 - 465</td>
<td>455</td>
<td>18 - 25</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Sizes / mm</th>
<th>Chemical composition / %</th>
<th>$\sigma_a$ / MPa</th>
<th>$\sigma_b$ / MPa</th>
<th>$\delta_s$ / %</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ø6</td>
<td>0.23 0.23 1.41</td>
<td>0.030</td>
<td>475 - 530</td>
<td>22 - 36</td>
</tr>
<tr>
<td>Ø6</td>
<td>0.23 0.23 1.41</td>
<td>0.030</td>
<td>495 - 520</td>
<td>21 - 28</td>
</tr>
<tr>
<td>Ø6</td>
<td>0.21 0.21 1.36</td>
<td>0.023</td>
<td>460 - 475</td>
<td>25 - 30</td>
</tr>
</tbody>
</table>

(2) Ageing behavior  
After 5% pre-stressed deformation, manual ageing test was performed under 250 °C for 1 hour. The property before and after ageing test is shown in Table 5. We can learn, the elongation property of VN rebars changed very little before and after ageing test, this means, VN rebars have a good ageing behavior resistance.  

(3) Weldability  
With flash butt welding, gas pressure welding, manual electrical arc weld and electroslag pressure welding, the weldability of VN micro-alloyed rebars were evaluated. The test result is shown is Table 6. We can see, VN micro-alloyed hot-rolled rebars have an excellent weldability, fully suitable for flash butt welding, gas pressure welding, manual electrical arc weld and electroslag pressure welding.
(4) Low cycle fatigue property

High strain low cycle fatigue test was simulated on MTS8100 material tester. Constant strain control was adopted for the test, with a frequency of 0.144 - 0.249, cyclic strain range is 4% ~ 7%. Fig. 8 shows the curve of VN rebars fatigue life. During fatigue test, cyclic hardening and softening phenomena occurred for specimen, the stress amplitude value was changed, and the tested steel grade become stable after the third week. The ability of material for absorbing seismic energy can be express as \( a_{\text{amax}} \cdot \Delta \varepsilon_t \), among which, \( a_{\text{amax}} \) takes the stress amplitude value of 10th week when \( \Delta \varepsilon_t = 5\% \); \( \Delta \varepsilon_t \) takes cyclic strain range when fatigue life is approximately \( N_f = 100 \) weeks; the result can be accomplished by regression formula according to the correlation between fatigue life and strain. The comparison of fatigue property between two kinds of rebars is shown in Table 7. We can learn, the seismatic property of VN rebar is better than 20MnSi rebar, among which \( a_{\text{amax}} \cdot \Delta \varepsilon_t \) value of VN rebar is 1.04 times of 20MnSi rebar.

4 Analysis of Cost and Benefit of VN Rebars

With VN micro-alloying, the addition of V in the steel is reduced evidently. Comparing with V-Fe micro-alloying, more 40% of vanadium can be saved, the cost of micro-alloying can be lowered by approx. 50%.

Taking Shougang’s VN micro-alloyed Grade
III rebars as example, with Nitrovan VN for alloying, according to the market price then, the cost increase per ton of steel was controlled within 45 YUAN, 40 YUAN can be saved per ton of steel comparing with V – Fe micro – alloyed rebars. In 2001 and 2002, about 300 000 tons of VN micro – alloyed rebars were produced in total, more than 10 million YUAN was saved for the cost of micro – alloying. Also, due to the price increase of Grade III rebars, the added value increases; therefore, on the basis of the profit from Grade II rebars, tens of millions of profits are increased.

Using Grade III rebars, the economical benefit for the customers is also very evident. Upgrading rebars from Grade II to Grade III, 14% of steel consumption can be saved. In summary, the successful application of VN micro – alloying technology in Grade III rebars will break a new path for the development of high strength rebars in China. The annual output of rebars in China is more than 30 million tons, which implies the wide use of VN micro – alloyed Grade III rebars has a great economical and social benefits.

5 Production and Application of High Strength Rebars in China

In last years, under the vigorous organization of related government authorities, through the common efforts from research, production, design and end – user etc., rapid development of high strength rebars in China was realized. In 2000, the output of Grade III rebars in China is 260 000 ton. In 2001, it was 1 050 000 tons. In 2002, it was up to 1 500 000 tons. From the trend of development, the increase speed is very quick. However, we should notice, the portion of high strength Grade III rebars in total rebar output is still very low, accounts for less than 5%. Therefore, it is still a very arduous task to promote the application of high strength Grade III rebars in China.

Along with the issue and implementation of new construction specification in China, higher requirements are provided for the safety reserve of construction structure. New specification advocates Grade III rebars should be used as the main rebars for reinforced concrete structure in China. According to the plan of Ministry of Construction, it is required that the consumption of Grade III rebars should reach 80% of total current consumption by the end of “10th Five Year Plan” period. This indicates, Grade III rebars will be dominant construction rebars in China. We believe, with the efforts of all fields, the output of high strength rebars will have a substantial leap in next years.

6 Conclusions

(1) Adopting VN micro – alloying with fully utilization of cheap nitrogen element, promotes the V precipitation in rebars, remarkably improves the result of precipitation strengthening, reached the aim of alloy saving and lowering of cost. VN micro – alloying technology has opened a new, economical and efficient path for the development of high strength rebars in China.

(2) The V content in VN micro – alloyed Grade III rebars can be lowered to a level between 0.02% ~ 0.04%. Comparing with V micro – alloyed rebars, 40% of V can be saved, the cost of micro – alloy per ton of steel can save about 50%, and technical and economical advantages are fully demonstrated.

(3) The property of VN micro – alloyed rebars is stable, with less fluctuation range of strength. The range of yield strength is within 75MPa, the range of tensile strength is within 80MPa, fully reached the requirements of Grade I
as seismic rebars.

(4) The VN micro-alloyed rebars has a good using property. High strength is accomplished on the basis of high ductility, and features with low sensibility to ageing behavior, excellent weldability and good seismic property etc. The rebars are suitable for various welding methods, such as flash butt welding, gas pressure welding, manual electrical arc welding and electroslag pressure welding.

(5) The successful research and practical application of VN micro-alloyed Grade III rebars have brought benefits to both customers and manufacturers. The promotion and application of this technology has a remarkable economical and social benefits.

(6) The percentage of high strength rebars in China is now still very low, accounts for less than 5% of total rebar consumption. Strengthening the promotion and application of high strength rebars need the common efforts of government departments, production enterprises, design and research institutions.

References: