Application of V-N Microalloying Technology on Section Steel

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INTRODUCTION

The production of the section steel can be backdated to a long time ago. With plenty of grades and sizes, they are widely used in many industries including construction, machinering manufacture, shipbuilding, railway, bridge, mining, defense and agriculture.[1] Although the ratio between plate and long products has been increasing worldwide, the percentage of the section steel remains at a high level (30 – 60%). Except for a small amount which require for control-rolling, cooling or heat-treated after rolling, most of the section steels are supplied in the as-rolled conditions with lower requirements for properties and especially for the impact toughness. Generally, the yield strength is typically lower than 235MPa, and no low-temperature impact requirement or only room temperature impact toughness requirement.

However, the property requirements for section steel are increasing along with the extension of their application field, especially in high-end equipment manufacturing or project like large vessel and high-voltage transmission tower. Such requirements focus on higher yield strength (above 390 – 420 MPa), improved low-temperature toughness (impact at -20 or -40°C), larger sizes, and easier welding. The comprehensive properties of section steel improved rapidly with the progress of production equipment, process, quality and alloy designing, for instance the higher metallurgical quality of product; the enhanced automation, rolling and production capacity; application of new TMCP and microalloying technology.[2]

CHARACTERISTICS OF SECTION STEEL ROLLING

The main features of section steel production can be summarized as follows:

(1) Irregular section shape. In addition to the simple shapes like square, round and flat, most of the section steels have irregular section that makes the deformation in the roll pass more difficult.

(2) High slab reheating temperature. In China most of the section steels are produced with quick heating at high temperature. In order to increase the production efficiency, a major portion of section steels is produced with higher slab reheating temperature (>1,250°C) and shorter reheating time (approx. 2 – 3 hours), but this causes coarser prior austenite grain size in the slabs.

(3) Low deformation of rolling passes. Due to the pass design, the deformation of single pass is limited for rolling of section steel, and the deformation is influenced considerably by the section shape.

(4) High finish rolling temperature. The finishing temperature of section steel rolling is higher than that of plate product rolling by approx. 100 – 200°C, i.e. typically at 900 – 1,100°C. Due to the limitation of the rolling force, the low temperature rolling technology is hardly to be adopted for the section steel. Also the finishing temperature fluctuates due to control difficulties.

(5) Air cooling applied mainly after rolling. Except for a small portion such as some H-beam, the section steels are mainly air cooled instead of controlled cooling after rolling. Due to higher finishing temperature and slower cooling rate, the grain size of the prior austenite is coarser and so is the final structure after cooled down to the ambient temperature.

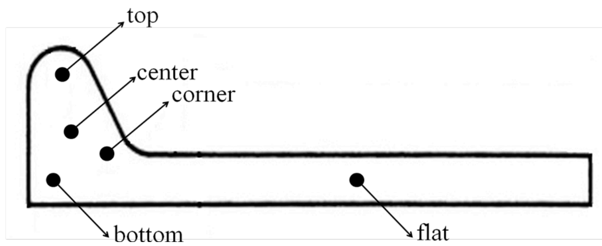
(6) Uneven sectional deformation and cooling. Due to the sectional homogeneity, it cannot assure the same deformation across the whole section during pass rolling, and the deformation in some special areas is much lower than that in the flat area. Furthermore, the uneven section causes the different cooling rates and consequentially the different structures and properties in different areas.

To sum up, due to the limitation of the rolling equipment, it is impossible for section steels to have both high strength and good toughness by application of controlled rolling, controlled cooling, low temperature finish rolling and high reduction ratio. Therefore, the application of V-N microalloying technology makes it possible to produce high quality section steel under the conventional process conditions.[3]

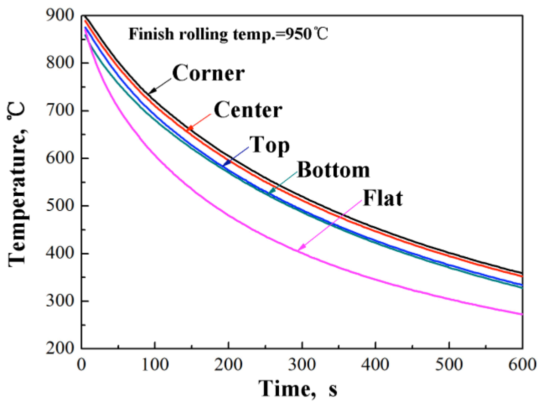
SECTIONAL HOMOGENEITY OF SECTION STEEL

The cross sectional shape of section steel is complex with large size differences between different areas. As a result, the homogeneity of the structure and properties on the cross section is a challenge for the section steel. As the engineering structures tend to be large-scale and heavy-duty, the demand for section steel is stricter than ever in respect of comprehensive properties especially sectional homogeneity. For example, the H-beam is requested to test the mechanical properties at the web and flange with different thickness as well as at the R corner; the bulb flat steel is requested to test those of the bulb and flat with different sizes; and the angle steel for towers is requested to test the sectional homogeneity along the right angle side. The microalloying technology is considered to be the best means to improve the sectional homogeneity of section steel. Taking the bulb-flat steel as an example, this article will discuss the effect of the V-N microalloying technology on section steel for improvement of the sectional homogeneity.

As shown in Figure 1, the section shape of the bulb flat steel is complex. The large difference between the deformations at the bulb center and the flat when rolling leads to a large deviation of the final structure. To investigate such deviation thoroughly the ANSYS finite element analysis software is used to develop a two-dimensional model for the cooling of the bulb flat steel after rolling (Figure 1a). It can be seen from the figure that when the bulb flat steel is cooled continuously the cooling rates are all different at the bulb top, center, corner and bottom and the flat, among which the corner and the center are cooled the slowest and the flat is cooled the fastest (Figure 1b). In Figure 1c the time dependence of the temperature difference between the bulb center and the flat is shown, and it can be found that the maximum difference (120°C) is reached when the steel has been cooled for approx. 150 s. The sectional inhomogeneity of the bulb flat steel is the primary reason that the different positions of the bulb and also the flat have different cooling rates.



(a)



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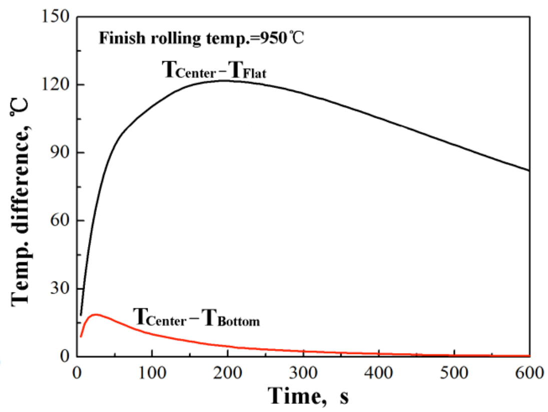

(c)

Figure 1 Results of the Finite Element Simulation for Bulb Flat Steel Cooling After Rolling
(a) Section Shape (b) Simulated Cooling Curves
(c) Temperature Difference between Bulb Center and Flat

Based on the finite element simulation model for cooling the V and V-N microalloyed steel grades are trial produced, which chemical analyses are given in Table Ⅰ and the tensile and impact properties of the bulb center and the flat shown in Figure 2. It can be seen from Figure 2 that the yield strengths of the flat are close to each other for the two grades, but for those of the bulb center the V-N microalloyed steel is higher significantly than the V steel by approx. 55 MPa. For the same grade, there is only a small difference between the yield strength of the bulb center and that of the flat (just 5 MPa) for the V-N steel, but it is a big difference for the V steel (approx. 45 MPa). As for the impact energy at -40°C, the V-N steel has higher values for both the bulb center and the flat than those of the V-steel that means the better low-temperature toughness for the former. It can be concluded that with V-N microalloying the comprehensive properties of the bulb flat steel are improved: the yield strength of the bulb center is increased, the strength difference between the bulb center and the flat is reduced, and the low-temperature toughness at -40°C is increased significantly.

Table Ⅰ Chemical Analyses of the Steel Trial Produced (wt%)

Grade	C	Si	Mn	S,P	Ti	V	N
V Steel	0.10	0.47	1.28	≤0.015	0.013	0.062	0.0060
V-N Steel	0.10	0.49	1.25	≤0.015	0.014	0.064	0.0140

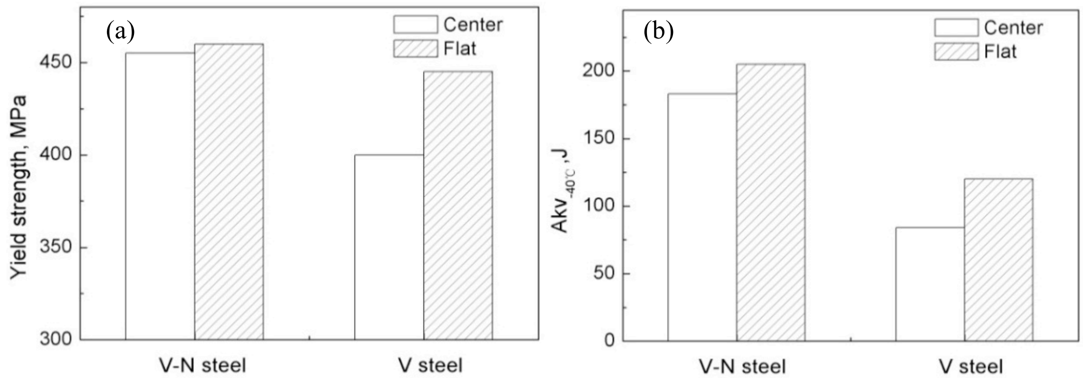

Figure 2 Mechanical Properties of the Steel Trial Produced

(a) Strength (b) Impact Toughness

The microstructures of the bulb center and the flat are shown in Figure 3 for both steel grades. It can be found that the pearlite-ferrite structure is dominant in all the samples featuring the varying ferrite grain sizes at different positions. The difference of the ferrite grain sizes between the bulb center and the flat is larger for the V steel (approx. 3.11 μm) and smaller for the V-N steel (approx. 1.24 μm). It is obvious that the mean size of the ferrite grains of the V-N steel is smaller compared with that of the V steel regardless of the positions at the bulb center, the corner or the flat (Figure 4), which indicates the refinement of the ferrite grains, their reduced sizes, and the decreased difference between the grain sizes of the bulb center and the flat due to V-N microalloying.

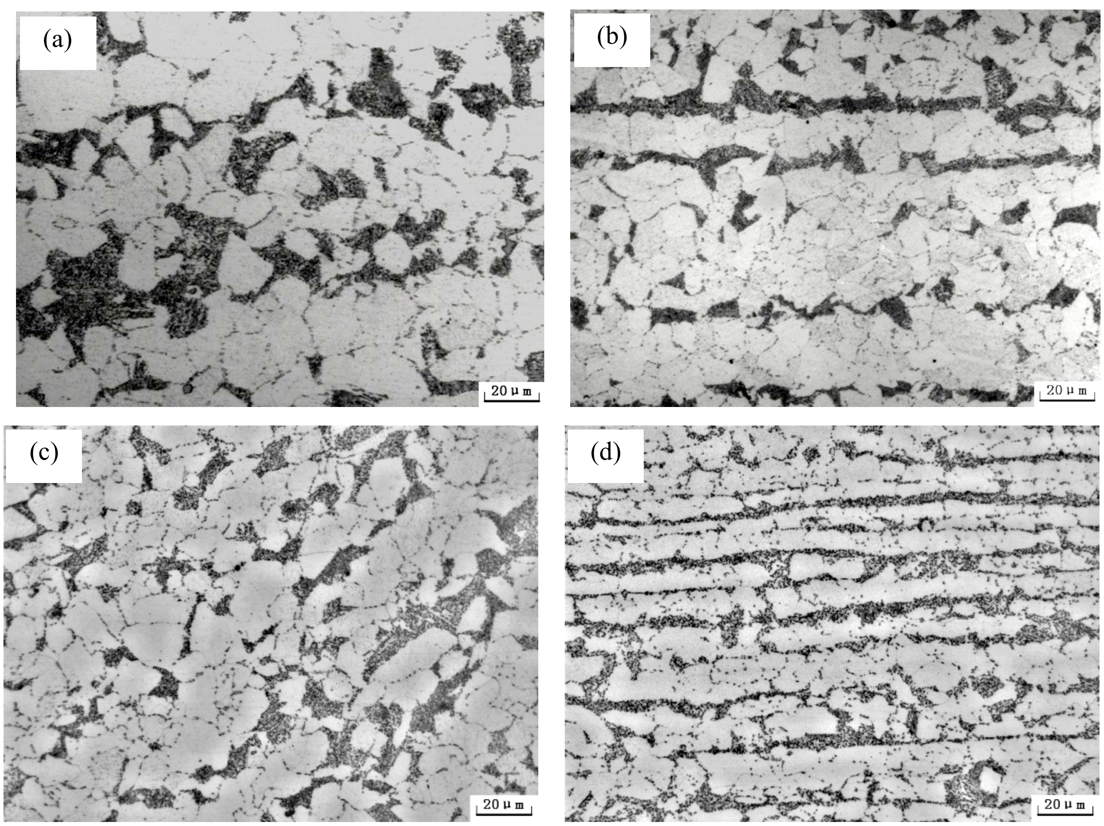

Figure 3 Microstructure of the Test Samples

(a) Bulb Center of V Steel (b) Flat of V Steel (c) Bulb Center of V-N Steel (d) Flat of V-N Steel

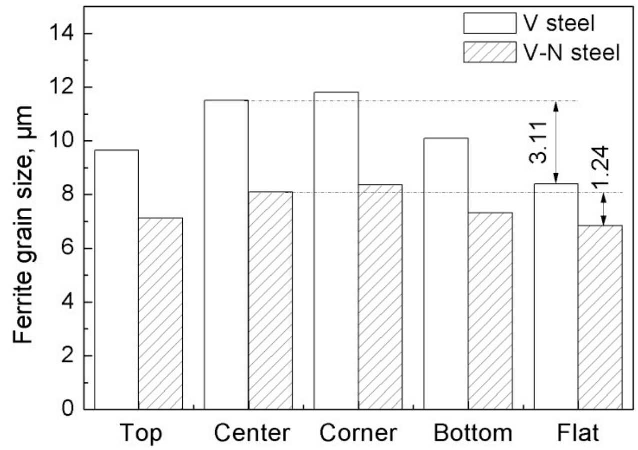

Figure 4 Mean Size of Ferrite Grains at Different Positions of Test Samples

With phase analysis the precipitates at the bulb center and the flat of the V-N steel are investigated and the results are listed in Table Ⅱ. Precipitated in the form of V(C,N), the V amount at the bulb center, i.e. 67.8%, is higher than that at the flat (56.71%). As a result, the enhancement by V(C,N) is more significant at the bulb center than at the flat, and this compensates the strength loss of the bulb due to its dimensions. It is shown by the simulation for the temperature field when cooling that there has a big difference between the cooling rate at the bulb center and that at the flat, and the former is much slower than the latter. It can be concluded that the slower cooling at the bulb center is favorable for the V precipitation in ferrite, which increases the V amount that is precipitated resulting in improvement of the strength of the base material. It can be seen based on the grain size distribution of the precipitated phases (Figure 5) that for the V-N steel the amount of the finer V(C,N) particles (0 – 36 nm) is remarkably higher at the bulb center than at the flat. According to the Hall-Petch theory, the more the amount of the second-phase precipitates and the smaller their sizes, the greater their contribution to the yield strength.

Table □ V Distribution at Different Positions of V-N Microalloyed Bulb Flat Steel

Form of Vanadium	Center	Flat
V(C,N)	67.80%	56.71%
M_3C	6.25%	4.68%
Solid Solute in Ferrite	25.95%	38.61%

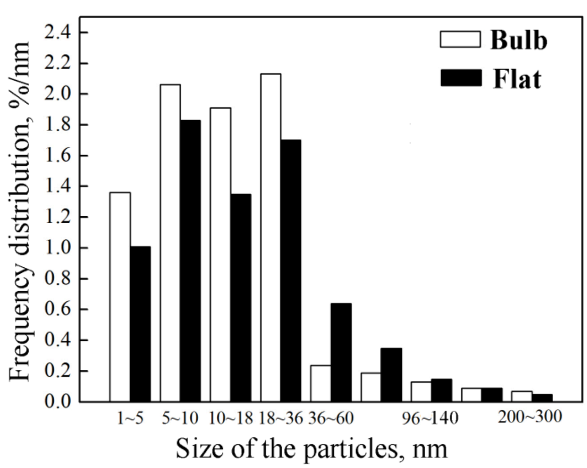

Figure 5 Frequency Distribution of V(C,N) Particles in V-N Steel

To sum up, the V-N microalloying contributes greatly to the bulb flat steel with improved yield strength and low-temperature toughness, reduced properties variation between the bulb center and the flat, and increased structure homogeneity at different positions. The comprehensive properties of the V-N microalloyed bulb flat steel are dramatically enhanced, and this can be explained with the strengthening and toughening mechanism of the V-N microalloyed bulb flat steel as sketched in Figure 6. For the V steel (Figure 6a and b) with low N content, most of vanadium remains as a solid solute instead of carbonitride precipitate, hence its strengthening effect is not obvious. Also, due to the different deformation and cooling rates after rolling, the ferrite grain sizes at the bulb center and the flat are quite different from each other and this causes the uneven sectional properties. On the contrary, the V-N microalloying (Figure 6c and d) favors the precipitation of a major portion of vanadium in the form of V(C,N) particles that enhances precipitation strengthening significantly. Furthermore the slower cooling at the bulb center boosts the V precipitation and the particles refinement, and plenty of the dispersed finer V(C,N) particles compensate the strength at the bulb center. Many researches [4-5] have demonstrated that the VN precipitates can promote effectively the formation of the intragranular ferrite and refine dramatically the ferrite grains. The present study also shows that the size difference between the ferrite grains at the bulb center and those at the flat is smaller for V-N steel than for V steel. The precipitation of vanadium refines the microstructure and improves the low-temperature toughness of the bulb center.

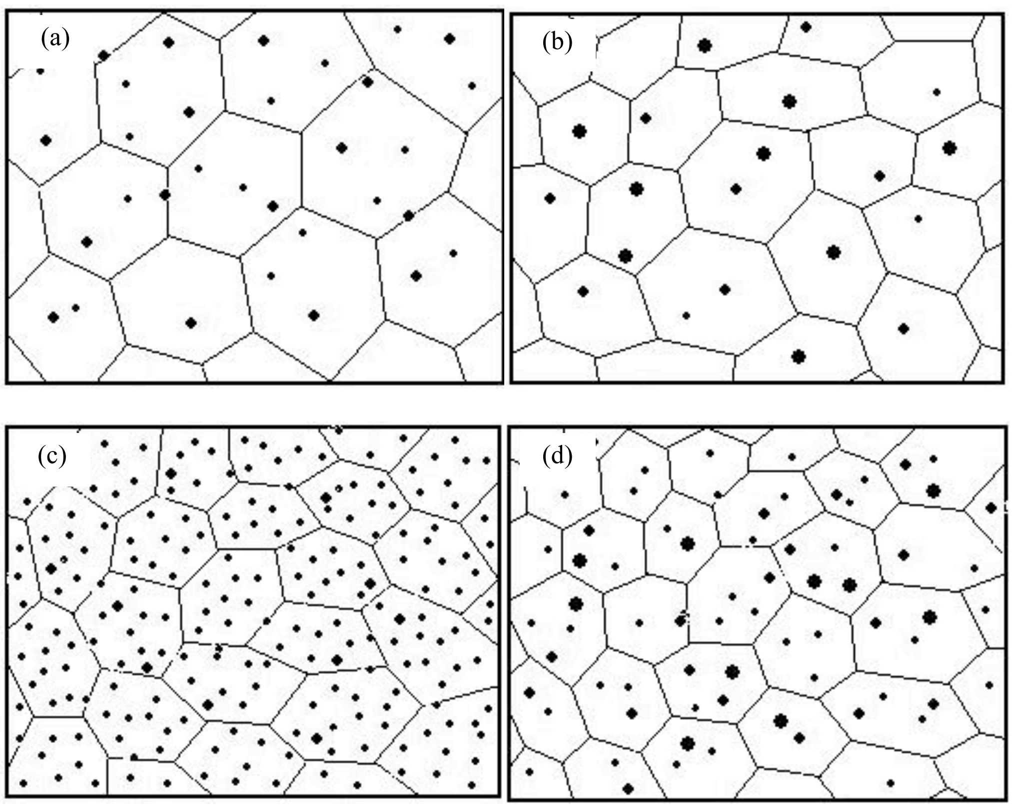

Figure 6 Sketch of Strengthening and Toughening Mechanism for V and V-N Steel
(a) Bulb Center of V Steel (b) Flat of V Steel (c) Bulb Center of V-N Steel (d) Flat of V-N Steel

APPLICATION OF V MICROALLOYING TECHNOLOGY ON SECTION STEEL

High Strength Angle Steel for Towers

With the construction of high-voltage transmission lines up to 750 and 1,000 kV in China and their tendency to be suitable for long distance, high power and low energy loss, the high strength angle steel for towers such as Q345, Q420 and Q460 is highly demanded. Also, the angle steel for towers shall meet the requirements for improved low-temperature toughness and larger sizes so as to avoid the towers being destroyed by the extreme cold weather in winter.

The microalloying is one of the main enhancing approaches for the high strength angle steel for towers. The chemical analyses of the hot-rolled angle steel for towers are clearly defined in YB/T 4163-2007 (refers to TableⅢ). The vanadium shall be added into the Q345/Q420/Q460 grades with V-Fe or V-N alloys.

Table □ Chemical Analyses of Hot-Rolled Angle Steel for Towers as Defined in YB/T4163-2007 (wt%)

Code	C ≤	Si ≤	Mn ≤	S ≤	P ≤	V	Nb	Ti
Q235T	0.20	0.35	1.40	0.045	0.045			
Q275T	0.21	0.35	1.50	0.045	0.045			
Q345T	0.20	0.55	1.70	0.040	0.040	0.01 – 0.15	0.005 – 0.060	0.01 – 0.20
Q420T	0.20	0.55	1.70	0.040	0.040	0.02 – 0.15	0.005 – 0.060	0.01 – 0.20
Q460T	0.20	0.55	1.70	0.040	0.040	0.02 – 0.15	0.005 – 0.060	0.01 – 0.20

For the conventional 16MnV grade a higher V content up to 0.07 – 0.10% shall be added in order to meet the requirement for yield strength (> 420 MPa), but the enhancement effect of V precipitation is limited in this way. From the point of view of resource conservation and cost minimization, the utilization of only vanadium for microalloying is not the best option to improve the strength of angle steel. Instead, the V-N combined microalloying allows the precipitation of a majority of vanadium in the form of V(C,N), which can on the one hand lead to a dramatic improvement of steel strength, and on the other hand save the V addition without compromising the strength. This will be helpful for reducing the production costs. The investigation on the relationship between the contents of V and N and the tensile strength of the angle steel (Figure 7) shows that the yield/tensile strengths will rise when the V and N contents increase. On the basis of the C-Mn steel, the addition of just approx. 0.04% V will reach the nominal strength of Q420 angle steel, and the addition of just approx. 0.06% V will further reach that of Q460 grade. It can be seen from the microstructures of the angle steel (Figure 8) that the higher the V and N contents, the finer the ferrite grains. The V-N combined microalloying contributes greatly the ferrite refinement and the strength improvement of angle steel.

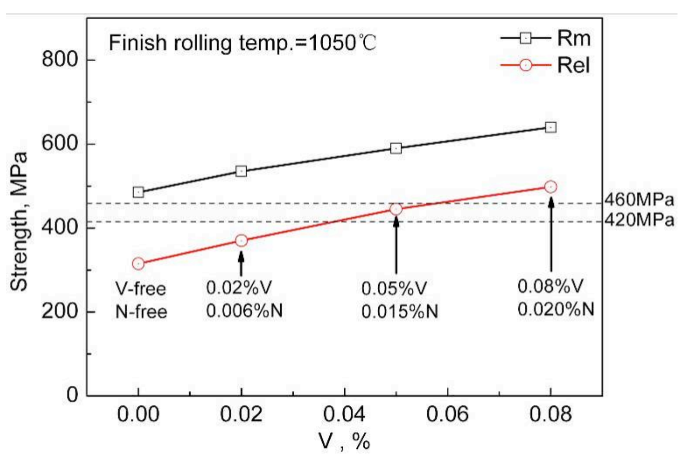

Figure 7 Dependence of Tensile Strength on Contents of V and N for Angle Steel

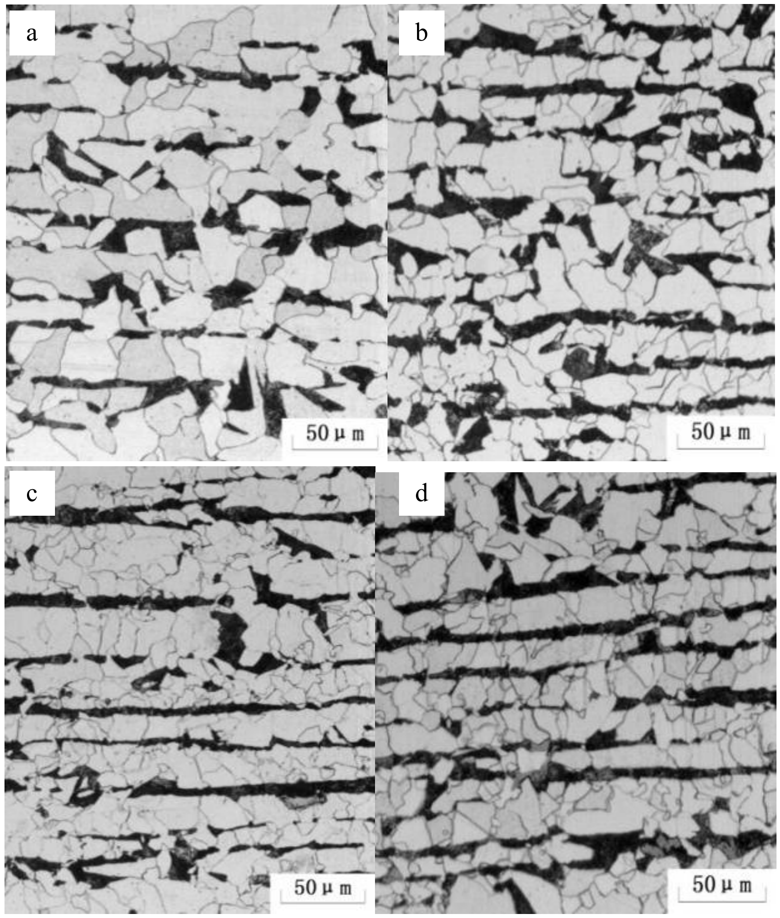

Figure 8 Microstructures of Ferrite for Angle Steel with Different V/N Contents
(a) 16Mn (b) 0.02%V-0.006%N (c) 0.05%V-0.015%N (d) 0.08%V-0.020%N

The dimensional effect of angle steel influences considerably its properties: both the strength and toughness will decrease when its thickness increases. The ultrahigh-voltage transmission towers up to 750 kV and above demand for large-sized high-strength angle steel (thickness reaching 32 mm, side length > 200 mm). By optimization of V-N microalloying in combination with improved control of the rolling and cooling processes, the large-sized high-strength angle steel has been produced successfully that meets the requirements for the mechanical properties. Its chemical analysis and mechanical properties are listed in Table □and□, respectively. The large-sized high-strength angle steel produced with V-N microalloying technology features excellent and stable mechanical properties that can satisfy the demand for the critical structural materials of the ultrahigh-voltage transmission towers.

Table □ Chemical Analysis of Large-Sized Angle Steel for Towers (32 mm thick, 20#) (%)

Alloy	C	Si	Mn	S	P	V	N
V-N	0.16	0.30 – 0.55	1.25 – 1.45	≤0.010	≤0.015	0.08 – 0.12	0.0016

Table□Mechanical Properties of 20# Angle Steel with Thickness of 32 mm

Sampling Position	Rel, MPa	Rm, MPa	A, %	Akv20°C
1/3 of Side Length	465/460	685/590	25.5/25.5	67/66/58

Heavy Wall H-Beam

The high strength medium and thick plates are typically produced with the controlled rolling strategy featuring "low temperature and large reduction ratio", but the heavy wall H-beam has to be produced with the traditional route featuring "high temperature and soft reduction". [6] When rolled with the traditional route, the heavy wall H-beam will have the structure of ferrite + pearlite that is coarser than in the plates, which means the mechanical properties of the heavy wall H-beam will be poorer than those of the plates, especially there will have big variations between the structure and properties at different areas of the H-beam.

To refine the grains of the heavy wall H-beam, the VN precipitation is utilized for the formation of the intragranular ferrite (IGF) in combination with the use of recrystallization controlled rolling (RCR) process. In respect of the alloy design the steel must contain higher V and N amount to facilitate the VN precipitation in the austenite. As for the rolling process the reheating temperature shall be kept as low as possible to refine and homogenize the austenite grains. The relatively low solid solution temperature of V(C,N) in the V-N steel makes possible the reheating at a low temperature. The rolling process shall consist of two steps: the first is to roll the steel at the recrystallization zone with high temperature, and this will refine the austenite grains by their repeated recrystallization; the second is to induce the VN precipitation in the austenite by deforming the steel in the range of VN precipitation temperature, and this will provide the cores of nucleation for the ferrite transformation leading to the increased nucleation density and subsequently the refined austenite grains. With this technology the high strength H-beam with the yield strength up to 450 MPa, 55C, has been produced successfully, which chemical analysis and mechanical properties are listed in Table□and□. With V-N microalloying and the carbon equivalent of ≤0.42%, the good weldability is assured for the grade. The as-rolled heavy wall H-beam with thickness of 30 mm features the ferrite grains size of Class 11 and the yield strength of exceeding 480 MPa.

Table □ Chemical Analysis of High Strength H-beam 55C, wt%

Code	C	Si	Mn	P	S	V	N	Ceq
55C	0.15-0.17	0.46-0.50	1.38-1.45	0.013-0.028	0.018-0.028	0.101-0.128	0.018-0.021	0.38-0.42

Table □ Mechanical Properties of High Strength H-beam 55C at Different Positions

Sampling Position	Rel, MPa	Rm, MPa	A, %	Ψ, %
Flat	495/490	625/630	25.5/25.5	67/66
Flange	498/500	635/635	26/26.5	64/65.5
R Corner	485/480	625/620	23.5/25.5	65/64

Bulb Flat Steel

The bulb flat steel is commonly used as the stiffener for the large-sized ships. It consists of two parts: the bulb and the flat. The cross section is nearly a ball shape at one end to resist the bending deformation. The bulb is quite different from the flat in dimensions with max. ratio of 4:1, thus the properties of the bulb are typically deviated from those of the flat with only 2/3 of the latter. This is the reason why the V or V-N microalloying technology is often used for alloy design of the bulb flat steel.

The chemical analysis and mechanical properties of the typical 14#D36 bulb flat steel are listed in Table □ and □. By adding approx. 0.04% V and increasing the N content (100 ppm) the yield strength of both the bulb and the flat of D36 grade will be improved up to 445 – 450 MPa and 480 MPa, respectively, with a gap of approx. 30 – 35 MPa.

Table □ Chemical Analysis of V-N Microalloyed Bulb Flat Steel 14#D36

Code	Analysis, wt%							
	C	Mn	Si	S	P	V	N	Ti
D36	0.06	1.50	0.28	0.002	0.009	0.04	0.0100	0.014

Table □ Mechanical Properties of V-N Microalloyed Bulb Flat Steel 14#D36

Sampling Position	R_{el}, MPa	Rm, MPa	A, %	Z, %	Cold Bending	$Akv_{-20°C}$, J		
Bulb	445/450	550/555	33/33	82/79	-	224	234	229
Flat	480/480	555/550	32/31	-	Good	236	245	232

Among the existing bulb flat steel grades, the hot-rolled HP430 x 20mm D40 is the one for civil use with the largest size, the highest strength and the most demanding quality. By the application of V-N microalloying technology to control the V and N contents in combination with the control of reheating temperature and deformation per pass, both the strength and the toughness can be improved remarkably. It can be seen from the comparison of the low-temperature impact energies (Figure 9) that the V-N steel can reach a high value of the low-temperature impact energy in a wide working range, but the V-Nb steel can only reach a relatively high valve at lower finishing temperature and larger reduction ratio of the final pass.

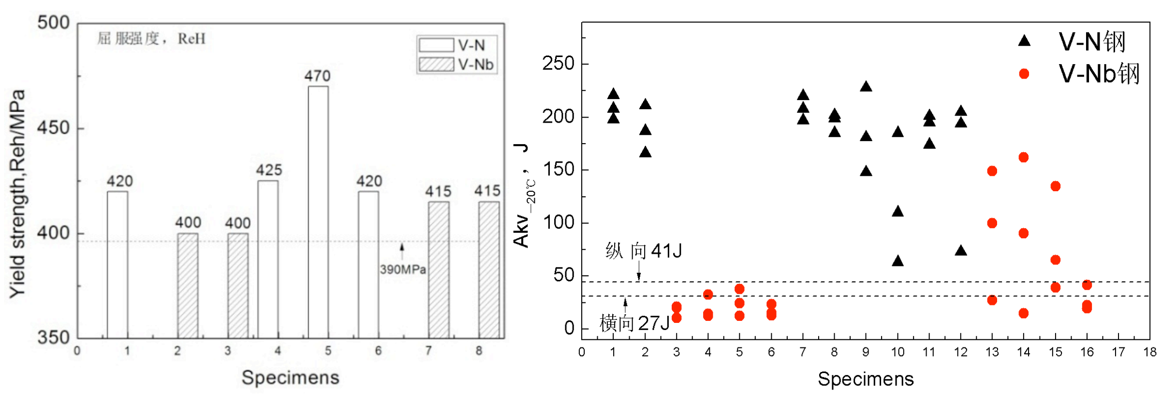

Figure 9 Comparison of Mechanical Properties Between Large-Sized V-N and V-Nb Microalloyed Bulb Flat Steel D40
(a) Yield Strength (b) Low-Temperature Impact Energy

CONCLUSION

The production of section steel features small pass deformation, sectional deformation inhomogeneity, and high finishing rolling temperature. Therefore, the ideal of V-N microalloying technology is applied to HSLA steels, which improve the strength through VN precipitation in the ferrite, enhance the toughness by nucleation of intragranular ferrite and subsequent refinement of ferrite grains through VN precipitation in the austenite. The slower cooling at corner section is favorable for the VN precipitation, which compensates the strength loss due to the coarser grains. The V-N microalloying technology is an ideal alternative for production and application of large-sized section steel with high strength and high toughness.

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