**Niobium Bearing Structural Steels**
*Edited by: Steven G. Jansto and Jitendra Patel*
***TMS (The Minerals, Metals & Materials Society), 2010***

# MICROSTRUCTURE AND MECHANICAL PROPERTIES OF 420-550MPA GRADE HEAVY GAUGE OFFSHORE PLATFORM STEEL

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Keywords: Nb-bearing, Heavy Gauge, Offshore Platform Steel, TMCP

## Abstract

Extra high strength off-shore platform plate steels have been developed in An-steel and obtained the certification of nine country specification institutes. The high performance heavy gauge plate steel was manufactured by ultra low carbon, Nb-bearing microalloying approach and optimized thermomechanical control process (TMCP). It shows that 0.03-0.05% carbon content Mn-Nb system (with low alloy Cr, Ni, Cu, Mo) can meet the strength of 420MPa, 460MPa, 500MPa and 550MPa grade with excellent toughness at -60°C. The low carbon approach can also obtain the homogeneous intermediate transformation structure of acicular ferrite and/or bainite at a wide cooling rate range for the heavy gauge plate during on-line accelerated cooling.

## Introduction

In recent years, Chinese ship and marine engineering manufacturing develops extraordinarily quickly, and production capacity of ship ranked the 2th all over the world.23000,000 tons of carrying capacity for the producing ship has been reached in 2008, and13000,000 tons of steel has been consumed. An-steel has about 50 years history of manufacturing ship plate; and more than 10000,000 tons of ship plate has been produced until now. At present, An-steel owns 4 production lines of medium and heavy plate, in which there is the largest 5500 heavy plate rolling machine in the world. Production capacity of An-steel has achieved 6000,000 tons each year, among which the percentage of ship plate is about 70%. An-steel is the earliest factory which obtained the certification of nine country specification institute. Variety and standard of production consists of series of plain, high strength and extra high strength TMCP plate including A, B, D, E grade 6-100mm thickness plate, 32, 36, 40 (A, D, E, F) grade, 6-80mm thickness extra high strength plate. All grade steels can satisfy Z15, Z25 and Z35 anti-Z direction tearing.

Through the processing of these steels on advanced steelmaking and rolling equipment, high performance structural steel produced by TMCP has any advantages such as good toughness, low alloy contents and shorter process [1, 2]. To develop the high performance TMCP steel, the physical metallurgy phenomenon should be controlled in the whole production process [3, 4]. By making use of the theory of physical metallurgy, a microstructure of acicular ferrite and bainite can be obtained by refining the grain size of austenite, controlled rolling and cooling [5, 6]. Optimizing alloy design as well as TMCP technology is keys to successfully develop these high performance steels [7]. In this paper, the alloy design and microstructure control to produce extra high strength steels has been researched. The microstructure and mechanical properties of heavy gauge plate steel from industry trials have been investigated.

## Ultra Low Carbon Design – The influence of carbon content on the microstructure and mechanical property

The influence of carbon content on the microstructure and mechanical properties of low carbon bainitic steel is studied by the microalloying approach as shown in Table 1. It can be seen that Cu, Ni, Mo were added with at same level in these experimental steels. The carbon content was changed from 0.01% to 0.1%.

Table 1. Composition of various carbon contents steels (wt%).

| Heat | C | Si | Mn | S | P | Nb | Ti |
|---|---|---|---|---|---|---|---|
| 1 | 0.01 | 0.24 | 1.73 | 0.005 | 0.01 | 0.05 | 0.01 |
| 2 | 0.03 | 0.30 | 1.77 | 0.005 | 0.01 | 0.04 | 0.02 |
| 3 | 0.05 | 0.29 | 1.77 | 0.005 | 0.01 | 0.05 | 0.02 |
| 4 | 0.10 | 0.31 | 1.79 | 0.005 | 0.01 | 0.04 | 0.02 |
| Cu, Ni, Mo (total) ≤1.2% | | | | | | | |

These steels with different carbon contents were control rolled, and then cooled by direct quenching and air-cooling. Table 2 shows the mechanical properties of these steels. It can be seen that, when the carbon content is 0.01 % (steel 1#), despite some amounts of the Mo, Ni, Cu alloys have been added, the yield strength is less than 400MPa. However, when the carbon content is around 0.03% to 0.05% (steel 2# and 3#), after direct quenching, the yield strength can be higher than 700MPa, and it is not much more influenced by the carbon content in this carbon content range. Moreover, if the carbon content is as high as 0.1 %( steel 4#), the yield strength is higher than 900MPa for the quenched steel, but the toughness is relatively poor. On the other hand, if the steels, with a carbon content between 0.03-0.10%, are air-cooled, the yield strength does not change very much being in the range of 470MPa-490MPa. It also can be seen from the experimental data in Table 2 that with increasing carbon content, the strength difference of air-cooling and direct quenching is more and more distinct.

In order to maintain a consistent cross-sectional strength, the lower carbon content has to be considered. Although the strength of 0.01% C steel is uniform under the various cooling rates, it does not meet the requirement of higher strength. From the results shown in Table 2, it can be seen that, for the 0.03-0.05%C steels, by accelerated cooling process control, the yield strength of 500-700MPa grade steel can be developed.

Table 2. The mechanical properties of the steels.

| Heat | Cooling | Rm /MPa | Tel/MPa | A % | Ak(half size)/J | | |
|---|---|---|---|---|---|---|---|
| | | | | | 20℃ | -20℃ | -40℃ |
| 1-1 | Direct-quenched | 498 | 380 | 31 | 143 | 134.7 | 145.3 |
| 1-2 | Air-cooled | 495 | 365 | 32 | 157 | 122 | 119 |
| 2-1 | Direct-quenched | 843 | 712 | 14.5 | 99.3 | 102.7 | 94.7 |
| 2-2 | Air-cooled | 625 | 472 | 22 | 79.7 | 135.7 | 121.7 |
| 3-1 | Direct-quenched | 955 | 770 | 11.3 | 76.3 | 74 | 78.3 |
| 3-2 | Air-cooled | 695 | 475 | 22 | 103 | 98 | 109 |
| 4-1 | Direct-quenched | 1235 | 978 | 11.5 | 45 | 46 | 43 |
| 4-2 | Air-cooled | 783 | 493 | 19.5 | 107.7 | 58 | 58 |

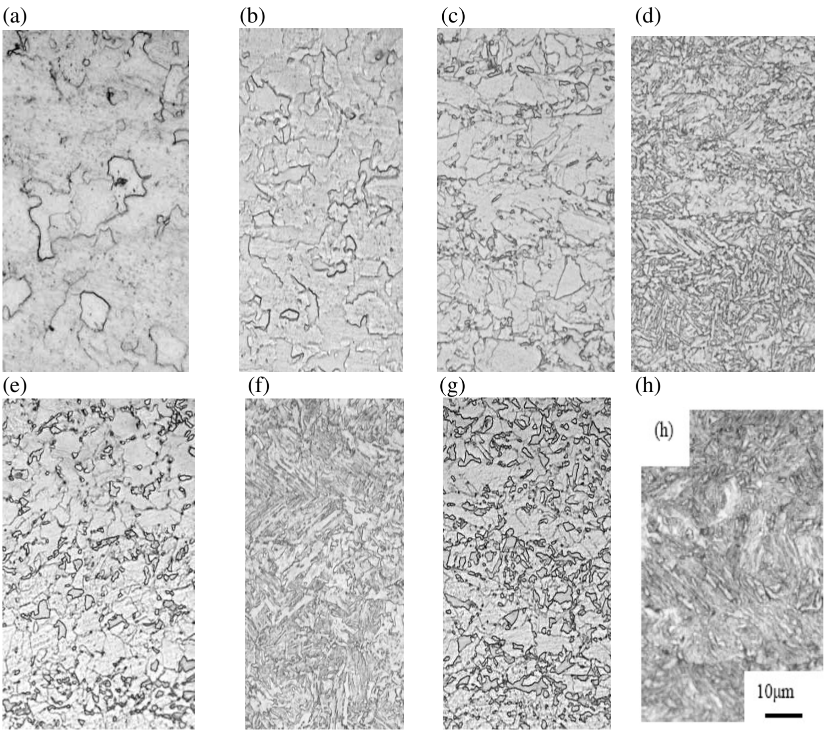


Figure 1. The microstructure of steel: (a)#1, (c)#2, (e)#3, (g)#4 after air cooling and (b)#1, (d)#2, (f)#3, (h)#4 after direct quenching

The microstructures of these steels are shown in Figure 1, it can be seen that for steel #1 (Figure1 (a) and (b)), the as-rolled microstructures after air-cooling and direct quenching are much more similar to each other. The cooling rate does not deeply influence the transformation microstructure. Both the microstructure is composed of polygonal ferrite (PF), quasi-polygonal ferrite (QF) and a little bit acicular ferrite (AF). As the dislocation density in the ferrite matrix is very low, the strength cannot be high enough. Figure 1(c) and (d) show the microstructures of steel # 2 after air-cooling and direct quenching, it can be seen that, after air-cooling, the microstructure is composed with QF, AF, GB and a bit of M/A. If it is direct quenched, the microstructure is mainly bainitic ferrite. From Figure 1(e) and (f), it can also be seen that the microstructures of steel 3# are as same as the steel #2 after air-cooling and direct quenching. As the carbon content is as higher as 0.1%, there are more M/A constituents (as shown in Figure 1 (g)) in the air-cooled specimen that would result in the increasing of tensile strength (as shown in Table 2). But the direct quenched structure of steel #4 is only composed with bainitic ferrite and/or lath martensite (as shown in Figure 1 (h). Although, the strength is higher because of carbon solidification in the ferrite matrix, the low temperature impact energy is lower because of the harmful effect of lath martensite (as shown in Table2). Otherwise, the good toughness of steel #2 and #3 is resulted by the lower carbon.

**Continuously cooling transformation microstructure of low carbon Mn-Nb alloy system**

Nb can be used as a microalloying element to refine the prior-austenite grain size. Meanwhile, by TMCP, the refinement less pearlite microstructure can be obtained. For developing 420-550MPa grade heavy gauge plate steel, the ultra-low carbon bainitic steel concept has been used. The alloying design approach was 0.03-0.05%C-Mn-Nb, with Cu-Cr-Ni-(Mo) addition depending on the strength and thickness of plate. The microstructures of specimens of 460MPa grade steel that cooled at different rates (0.5°C/s, 1°C/s, 5°C/s and 20°C/s) are shown in Figure 2. We can see that some fraction of polygonal ferrite can be observed while cooling at 0.5°C/s-1°C/s. In the continuous cooling microstructure (as shown in Figure 2 (a) and (b)), there is few pearlite or coarse M/A island in the matrix. Acicular ferrite and lath bainite are observed in specimens cooled faster than 5°C/s. The bainitic ferrite and /or lath martensite were observed in the specimen that cooled at 20°C/s. The width of lath ferrite becomes much thinner with the cooling rate increasing. The specimens of the 460MPa grade steel were isothermally held at different temperatures. The micrographs of the specimens are shown in Figure 3. It can be seen that after isothermally held at 630°C for 900s, the isothermal transformed phase is polygonal ferrite (the white phase as shown in Figure 4(a)). While held at 600°C and 580°C (as shown in Figure 3(b) and (c)), the quasi-polygonal ferrite appeared in the matrix except the polygonal ferrite. Moreover, after held at 550°C and 530°C, the microstructure of the isothermal transformed phase is mainly composed of acicular ferrite (as shown in Figure 3 (d), (e)). When isothermally treated at 480°C, the microstructure shows that there is only lath-like bainite (Figure 3 (f)).

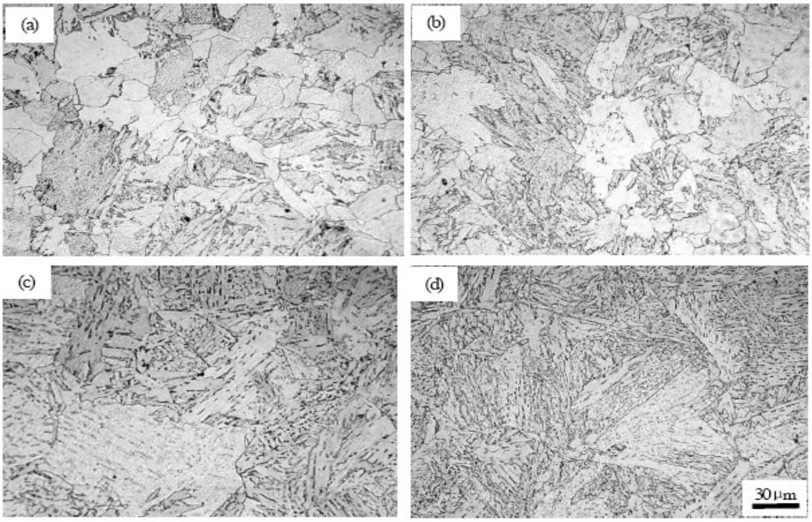


Figure 2. Continuously cooling microstructure of 460 grade steel cooled at (a) 0.5°C/s, (b)1°C/s, (c) 5°C/s, (d) 20°C/s

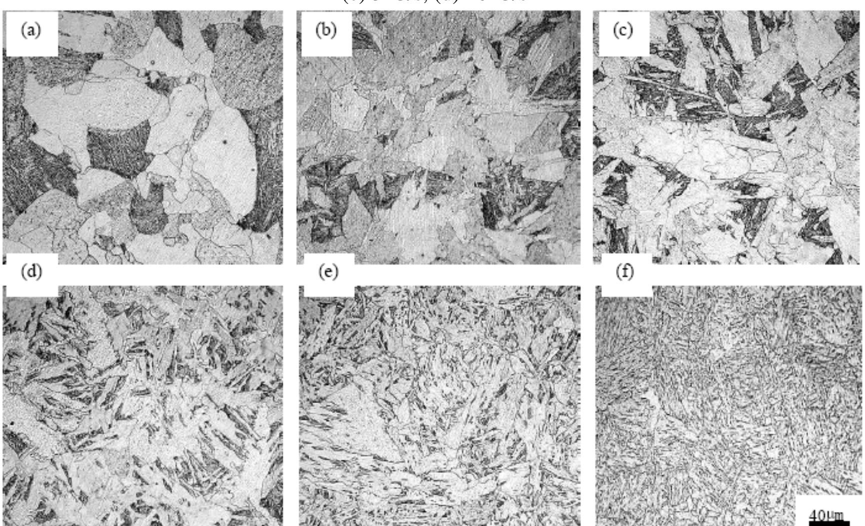


Figure 3. Microstructures of isothermal heat treatment specimens, (a) 630° held for 900s, (b) 600°C held for 900s, (c) 580°C held for 900s, (d) 550°C held for 900s, (e) 530°C for 900s, (f) 480°C held for 900s

The CCT microstructure of 550MPa grade steel is shown in Figure 4. It can be seen that when continuously cooled at 0.5°C/s, the microstructure is mainly quasi-polygonal ferrite and degenerated pearlite and/or MA constituents. However, when the cooling rate is higher than 1°C/s, the bainite structure is the main phase, the lath width is thinner, MA is more dispersive and fine as the cooling rate increases. Compared with 460 steel, it can be seen that the hardenability of 550MPa steel is a bit higher than 460MPa if the cooling rate at the center of the heavy gauge plate is around 0.5°C, then the bainite microstructure cannot be obtained. The solute strengthening mechanism had to play the role in strengthening the center strength without harming toughness.

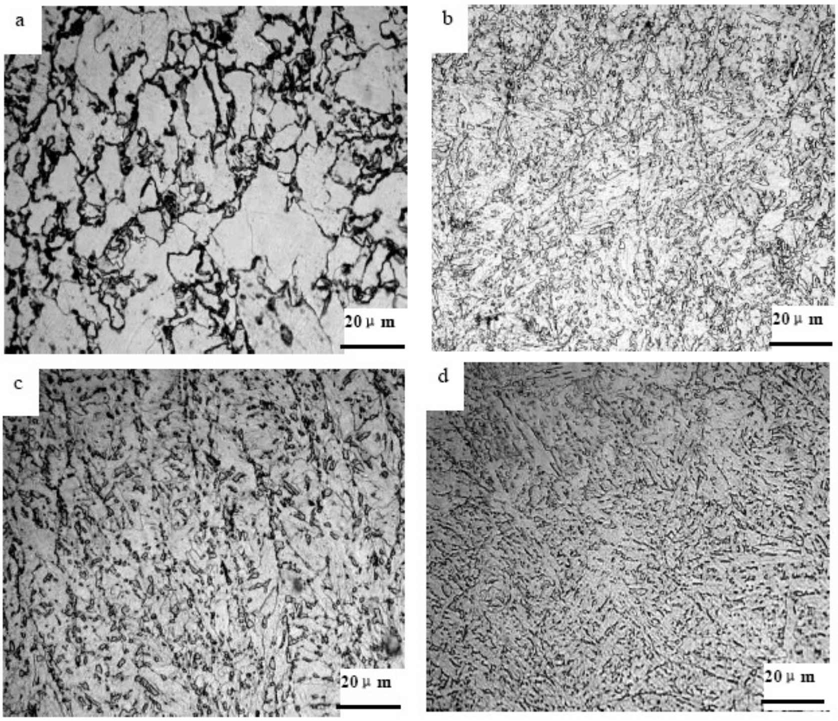


Figure 4. Continuously cooling microstructure of steel that cooled at (a) 0.5°C/s , (b)1°C/s, (c)5°C/s, (d)10°C/s

It can be seen that for the low carbon Mn-Nb system 460MPa grade and 550MPa grade steels, even cooled as slower than 1°C/s, the transformation microstructures are mainly less pearlite, quasi-polygonal ferrite and/or acicular ferrite. If the cooling rate is faster than 5°C/s, the bainite ferrite can be transformed homogeneously. Even more, the transformation microstructures of the specimen cooled with faster cooling rates are not much different from the slower ones. Therefore, the low carbon Mn-Nb system can be used to develop heavy gauge plate steel.

### Homogeneous microstructure and properties of heavy gauge plate

The compositions of the industry trial of 460MPa grade steels are shown in Table 3. There are some differences in alloy additions of the three heats. The steels were control rolled to 16mm, 30mm, 60mm and 80mm and accelerating cooled. The cooling rate, cooling start and finish temperature were controlled.

Table 3. Chemical composition of 460MPa grade steel (wt%).

| Heat | C | Si | Mn | P | S | Nb | Ti | other |
|---|---|---|---|---|---|---|---|---|
| 1 | 0.032 | 0.25 | 1.58 | 0.0089 | 0.0027 | 0.048 | 0.014 | total≤1.0 |
| 2 | 0.040 | 0.27 | 1.45 | 0.009 | 0.003 | 0.049 | 0.020 | total≤1.5 |

Table 4 shows the mechanical properties of three heats steel. It can be seen that, with less alloy addition of heat 1, 16mm and 30mm thickness plate can reach 460MPa grade with excellent toughness. But the 60mm thickness plate cannot reach 460MPa grade steel. However, with a little higher alloy addition of heat 2, the yield strength of 80mm thickness plate can reach 460MPa grade.

Table 4. Mechanical properties of as rolled steels at 1/4t of 460MPa grade steel.

| Heat | thickness, mm | Rel, $N/mm^2$ | Rm, $N/mm^2$ | A% | -40℃, Akv, J | | |
|---|---|---|---|---|---|---|---|
| 1 | 16 | 460 | 570 | 32.5 | 360 | 424 | 394 |
| 1 | 30 | 465 | 595 | 26.5 | 386 | 330 | 375 |
| 1 | 60 | 405 | 520 | 28.5 | 311 | 330 | 335 |
| 2 | 80 | 475 | 590 | 30 | 298 | 295 | 298 |

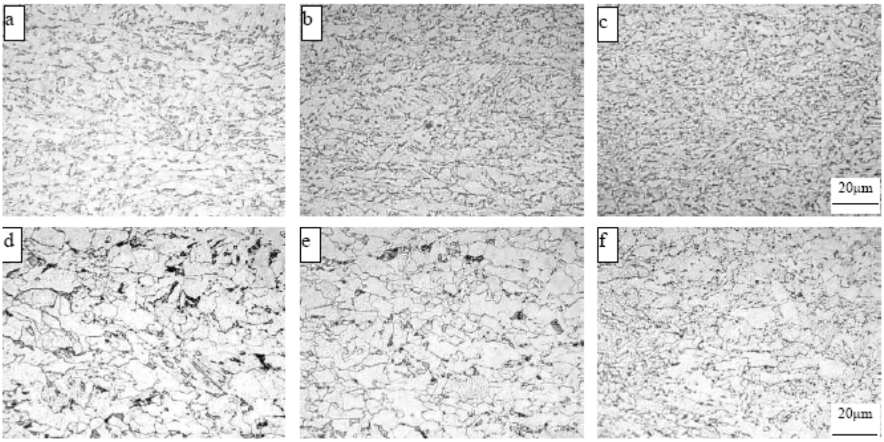


Figure 5. The as rolled microstructure of heat 1 steel, (a) 1/2 t , (b)1/4t ,(c) surface of 30mm thickness plate;(d) 1/2t,(e) 1/4t (f) surface of 60mm thickness plate

From Figure 5, it can be seen that, microstructures at the surface and 1/4t are mainly granular bainite with less acicular ferrite, in the center the MA island is a bit larger compared with the outside part of the 30mm thickness plate. The microstructure of 30mm thickness plate is homogeneous across the thickness section. However, for the same composition Steel (heat 1), the microstructure of 60mm thickness plate are different from the 30mm plate. The main microstructure is quasi-polygonal ferrite with large MA constituent at 1/4t and 1/2t. The microstructure and composition of 60mm thickness plate results in the low strength. Figure 6 shows the microstructure of the 80mm thickness plate of heat 2 steel. As the cooling rate is between 0.5-1°C/s in the center of the plate, the microstructure is quasi-polygonal ferrite and very large MA constituent. The SEM morphology of the large constituent (as shown in Figure 7) shows that it is composed of bainite. The dual phase of quasi-polygonal ferrite, bainitic constituent and the composition can improve the matrix strength for such heavy gauge plate processed by TMCP.

Figure 6 shows the microstructure of the 80mm thickness of heat 2 steel. As the cooling rate is just about 0.5-1°C/s in the center for such thickness plate, the microstructures are quasi-polygonal ferrite and very large MA constituent. The SEM morphology of large constituent (as shown in Fig.7) shows that it is composed of bainite. The dual phase of quasi-polygonal ferrite, bainitic constituent and the composition can improve the matrix strength for such heavy gauge plate processed by TMCP.

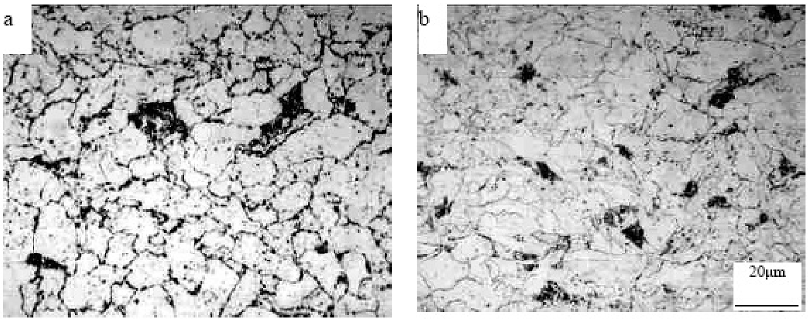


Figure 6. The as rolled microstructure of 80mm thickness plate of heat 2 steel (a) 1/2t, (b) 1/4t

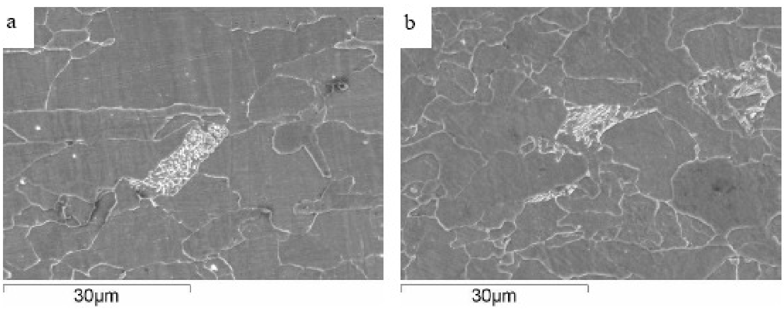


Figure 7. SEM micrograph of 80mm thickness heat 2 steel (a) 1/2t (b) 1/4t

Figure 8 shows that for the 30mm thickness plate, the yield strength at 1/2t is just about 10MPa less than the surface, but for the 60mm thickness plate, the yield strength at 1/2 is 390MPa and the yield strength decreases evidently at 1/4t. There is about 40MPa variation between surface and center. However, for the 80mm thickness plate of heat 2 steel, the yield strength at the center is just about 20MPa lower than 1/4t and the yield strength at 1/2t and 1/4t is higher than 460MPa.

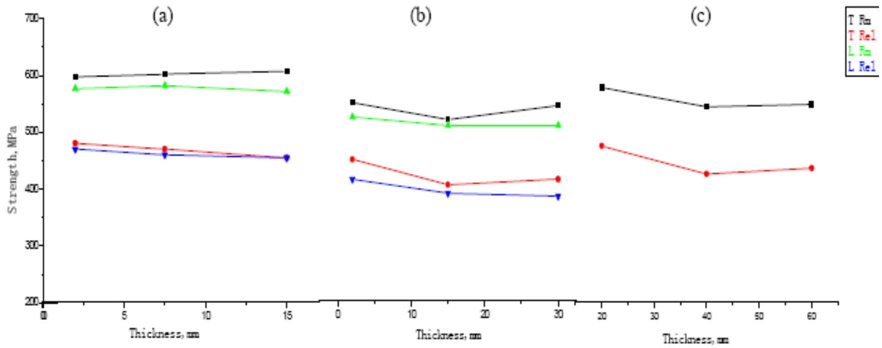


Figure 8. The transverse and longitudinal strength across the thickness section (a) heat 1, 30mmthickness plate (b) heat1 1, 60mm thickness plate (d) heat 2, 80mm thickness plate.

## Mechanical Properties of the Developed Heavy Gauge Plate Steel

The extra high strength ship hull and/or offshore platform heavy gauge plate steel has been developed in An-steel and passed the specifications of nine countries. With the optimized alloy design and TMCP, the as rolled plates can reach 420,460,500 and 550MPa grade in the thickness range from 14 to 80mm.The strength of 460MPa grade plates are shown in Table 5. It can be seen that the 14mm, 50mm and 80mm thickness plate can reach 460MPa grade at the center and 1/4 thickness, both in the transverse and longitudinal directions. The mechanical property at the head and tail is almost same. The mechanical properties of the plate steels are uniform. Table 6 shows the mechanical properties of 550MPa grade plate steel. It can also be seen that the properties are uniform and excellent even for the 80mm thickness plate.

Table 5. 460MPa grade head and tail properties comparison

| Thickness mm | Specimen Direction | Position | Rel $N/mm^2$ | Rm $N/mm^2$ | A % | Position | Rel $N/mm^2$ | Rm $N/mm^2$ | A % |
|---|---|---|---|---|---|---|---|---|---|
| 14 | T | H | 530 | 640 | 21.0 | T | 535 | 650 | 21.0 |
| | L | H | 515 | 635 | 20.0 | T | 525 | 645 | 20.5 |
| | T | H | 530 | 645 | 20.0 | T | 545 | 655 | 20.0 |
| | L | H | 515 | 640 | 22.5 | T | 510 | 620 | 23.0 |
| 50 | T1/4 | H | 480 | 630 | 27.5 | T | 465 | 620 | 25.5 |
| | L1/4 | H | 490 | 595 | 28.5 | T | 495 | 600 | 28.5 |
| | T1/2 | H | 495 | 635 | 24.0 | T | 480 | 595 | 28.5 |
| | L1/2 | H | 470 | 615 | 27.5 | T | 465 | 605 | 20.5 |
| 80 | T1/4 | H | 470 | 595 | 27.0 | T | 470 | 600 | 27.5 |
| | L1/4 | H | 465 | 590 | 28.5 | T | 475 | 590 | 26.5 |
| | T1/2 | H | 495 | 615 | 24.0 | T | 485 | 610 | 22.0 |
| | L1/2 | H | 470 | 595 | 26.0 | T | 465 | 590 | 23.5 |

Table 6. 550MPa grade head and tail properties comparison.

| Thickness mm | Specimen Direction | Position | Rel $N/mm^2$ | Rm $N/mm^2$ | A % | Position | Rel $N/mm^2$ | Rm $N/mm^2$ | A % |
|---|---|---|---|---|---|---|---|---|---|
| 14 | T | H | 580 | 720 | 18.5 | T | 580 | 715 | 16.5 |
| | L | H | 565 | 695 | 20 | T | 565 | 705 | 18.5 |
| | T | H | 575 | 720 | 16.5 | T | 575 | 720 | 17 |
| | L | H | 560 | 695 | 17 | T | 560 | 690 | 20.5 |
| 50 | T1/4 | H | 590 | 705 | 25.5 | T | 590 | 715 | 23.5 |
| | L1/4 | H | 575 | 690 | 28 | T | 580 | 715 | 25.5 |
| | T1/2 | H | 580 | 700 | 22.5 | T | 590 | 720 | 21.5 |
| | L1/2 | H | 570 | 690 | 26 | T | 575 | 700 | 25.5 |
| 80 | T1/4 | H | 590 | 705 | 26.5 | T | 585 | 750 | 25 |
| | L1/4 | H | 580 | 700 | 25.5 | T | 565 | 710 | 28 |
| | T1/2 | H | 590 | 715 | 25 | T | 590 | 720 | 25 |
| | L1/2 | H | 570 | 690 | 27 | T | 570 | 700 | 26.5 |

Table 7. As rolled and aging toughness of 460MPa grade plate steel.

| Thickness mm | Specimen direction/position | Head/tail | Akv-60℃ | | | Aging, Akv-60℃ | | |
|---|---|---|---|---|---|---|---|---|
| 14 | T1/4 | H | 278 | 266 | 256 | | | |
| | L1/4 | H | 268 | 272 | 279 | 248 | 254 | 272 |
| | T1/4 | T | 278 | 242 | 236 | | | |
| | L1/4 | T | 292 | 290 | 292 | 282 | 280 | 268 |
| 50 | T1/4 | H | 286 | 272 | 276 | | | |
| | L1/4 | H | 282 | 290 | 284 | 262 | 273 | 265 |
| | T1/2 | H | 278 | 282 | 284 | | | |
| | L1/2 | H | 280 | 260 | 286 | 275 | 262 | 257 |
| | T1/4 | T | 281 | 282 | 264 | | | |
| | L1/4 | T | 278 | 282 | 290 | 264 | 262 | 276 |
| | T1/2 | T | 274 | 210 | 272 | | | |
| | L1/2 | T | 286 | 282 | 298 | 264 | 267 | 270 |
| 80 | T1/4 | H | 198 | 196 | 222 | | | |
| | L1/4 | H | 226 | 184 | 206 | 202 | 180 | 175 |
| | T1/2 | H | 204 | 206 | 210 | | | |
| | L1/2 | H | 220 | 228 | 236 | 200 | 212 | 218 |
| | T1/4 | T | 234 | 244 | 246 | | | |
| | L1/4 | T | 244 | 224 | 242 | 224 | 210 | 214 |
| | T1/2 | T | 240 | 213 | 226 | | | |
| | L1/2 | T | 198 | 210 | 220 | 201 | 183 | 180 |

Table 8. As rolled and aging toughness of 550MPa grade plate steel

| Thickness mm | Specimen direction/position | Head/tail | Akv-60℃ | | | Aging, Akv-60℃ | | |
|---|---|---|---|---|---|---|---|---|
| 14 | T1/4 | H | 362 | 372 | 340 | | | |
| | L1/4 | H | 385 | 380 | 405 | 310 | 365 | 355 |
| | T1/4 | T | 370 | 372 | 340 | | | |
| | L1/4 | T | 360 | 365 | 375 | 354 | 345 | 365 |
| 50 | T1/4 | H | 280 | 250 | 278 | | | |
| | L1/4 | H | 250 | 345 | 245 | 310 | 330 | 325 |
| | T1/2 | H | 325 | 315 | 322 | | | |
| | L1/2 | H | 360 | 320 | 365 | 345 | 338 | 341 |
| | T1/4 | T | 285 | 325 | 312 | | | |
| | L1/4 | T | 300 | 295 | 280 | 310 | 315 | 310 |
| | T1/2 | T | 380 | 380 | 400 | | | |
| | L1/2 | T | 380 | 345 | 375 | 315 | 306 | 315 |
| 80 | T1/4 | H | 205 | 58 | 40 | | | |
| | L1/4 | H | 365 | 320 | 340 | 65 | 54 | 180 |
| | T1/2 | H | 240 | 65 | 280 | | | |
| | L1/2 | H | 275 | 260 | 320 | 250 | 74 | 70 |
| | T1/4 | T | 245 | 270 | 300 | | | |
| | L1/4 | T | 310 | 370 | 320 | 198 | 295 | 250 |
| | T1/2 | T | 280 | 330 | 300 | | | |
| | L1/2 | T | 320 | 292 | 280 | 270 | 370 | 300 |

The toughness of 460MPa grade and 550MPa grade steel at -60°C are shown in Table 7 and 8. It can be seen that the impact energy of 460MPa grade steel at -60°C is excellent. The Ak (-60°C) is from 200J-300J. The impact energy after aging is excellent. The impact energy of the 550MPa grade steel can also meet the specifications.

## Conclusions

1) The 0.03-0.05% carbon content Nb-bearing low alloy steel can achieve a homogeneous microstructure of bainite in a wide cooling rate range. The high strength and excellent toughness can be obtained for 420MPa to 550MPa grade for heavy gauge off-shore platform plate steel.

2) The low carbon bainitic TMCP ship hull and/or offshore platform heavy gauge plate steels have been produced in An-steel with excellent mechanical properties. The steels meet the requirement of increasing demanding from the ship building industry. An-steel is the first steel

company to pass nine country's certification requirements for 80mm thickness TMCP extra high strength structural steel in China.

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