Microstructure and Performance Control of High strength and High Toughness Ti-Nb Microalloyed Marine Steel Plate

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Abstract: Adopting Ti-Nb microalloying design technology, this paper studied the austenitic recrystallization law of Marine steel plate, control rolling process, control cooling process and steel normalizing process control systematically. The thickest 60 mm special Marine steel plate developed which has reached the yield strength of 420MPa and charpy impact energy of more than 200J (-20℃), has high strength, impact toughness, laminar tear resistance and good welding performance, meeting the technical requirements of thick specification high strength and high toughness special Marine steel plate and realizing the application in large ships.

1. Introduction
In order to comply with the development of shipbuilding industry and meet the requirements of lightweight design of ships, the development of low alloy and high strength Marine steel plate is one of the hot spots of current research. The maximum size of steel plate is expected to reach 4.5 m ×22.5 m, and the thickness of steel plate will increase with the size of ships[1-3]. In terms of variety and quality, in the past, the quality of ship board used in general bulk carriers was generally D class, with only more than 20 varieties. With the upsizing of ships, there are more than 1200 varieties of ship board, covering all classes and developing towards E, F and Z[4-6].

In view of some common key technical problems existing in the manufacturing technology of high-performance steel plate for Marine engineering and ships, this paper, based on the technical requirements of thick special Marine steel plate with high strength and high toughness, adopting Nb and Ti microalloying design technology, studied the austenitic recrystallization law of Marine steel plate, control rolling process, control cooling process and steel normalizing process control systematically. The thickest 60 mm special Marine steel plate developed which has reached the yield strength of 420MPa and impact toughness of more than 200J (-20℃), has high strength, impact toughness, laminar tear resistance and good welding performance, meeting the special requirements of large-scale shipbuilding.

2. Materials and test methods

2.1. Testing materials
Using the 60 mm special marine experimental steel as experimental materials, steel plate mechanical properties depend on its chemical composition and microstructure. According to the requirement of the American petroleum institute and CCS classification rules, the chemical composition of experimental steel adopt the Ti - Nb microalloyed technology, strictly controlled within the standard requirement, as shown in table 1[7-9].

Table 1. Chemical composition design of experimental steel plates (wt.%)  
| C  | Si | Mn  | P  | S  | Nb+Ti | Als | Ceq |
|----|----|-----|----|----|-------|-----|-----|
| ≤0.20 | ≤0.55 | ≤1.7 | ≤0.03 | ≤0.03 | 0.05-0.20 | ≥0.015 | ≤0.42 |

2.2. Testing methods
Samples were taken from a plate with a thickness of 60mm and their mechanical properties were tested by ASTM E8 on a tensile tester. Samples were taken from the plate with a thickness of 60mm by linear cutting. The samples were ground, mechanically polished, eroded with 4% nitric acid alcohol solution and observed under a metallographic microscope of LEICA DM 2500M, and metallographic photos were taken. The metal charpy impact sample was 10mm×10mm×55mm, and the groove depth was 2mm. Charpy impact test was conducted on the PTM2200-B1 pendulum impact testing machine.

In two high reversible experiment (Ф450mm) on 60 mm thickness steel plate rolling into 12 mm thick plate, sheet and will be made into Ф8mm×15mm cylindrical specimens. Thermal simulation test was conducted on Greeble3800 thermal simulation test machine to test the CCT curve of steel. The test process method of sample CCT curve is shown in Fig 1. At last, the samples were cooled to room temperature at different cooling rates of 0.1~100℃/s. We test the thermal expansion curve of the sample during the cooling process, and then draw the CCT curve of the experimental steel. The specific parameters are shown in table 2.

Fig 1. CCT curve test process

| Types | Strain | Heat preservation Temperature/℃ | Strain rate/s | Cooling rate ℃/s |
|-------|--------|---------------------------------|---------------|------------------|
| EH40  | 0.3    | 820                             | 4             | 0.1, 0.5, 1, 2, 5, 10, 15, 20, 30, 40 |

3. Results and Discussion

3.1. Measurement of dynamic CCT curve
For the experimental materials, we cooled them to room temperature at different cooling rates of 0.1~100℃/s and tested the thermal expansion curve of the samples during the cooling process, then drawn CCT curve of the experimental steels according to the expansion curve, as shown in Fig 2.
For experimental materials, when the cooling rate is 0.5℃/s, as shown in Fig 3 (a), the metallographic structure of experimental materials is mainly composed of polygonal ferrite, a small amount of pearlite and a small amount of acicular ferrite. When the cooling rate is greater than 10℃/s, as shown in Fig 3 (b), the metallographic structure of the experimental material is mainly composed of acicular ferrite and a small amount of bainite. With the increase of cooling rate, the content of bainite increased, and the bainite changed from granular to strip. When the cooling rate is greater than or equal to 30℃/s, complete lamellar bainite structure is obtained, as shown in Fig 3 (c).

3.2. Thermo Mechanical Control Process (TMCP)
For Nb and Ti microalloyed low alloy and high strength steels, we can control the high temperature austenitic microstructure, the austenitic recrystallization process and the austenitic ferrite transformation process by adopting Thermo Mechanical Control Process (TMCP), so as to control the microstructure type of the steel plate and achieve the proper matching of the steel plate microstructure and mechanical properties\[9,10\]. We measured the CCT curve by the aforementioned thermal simulation test and determined the corresponding key parameters of TMCP.

3.2.1. Rolling technology
The experimental steel is rolled in recrystallized zone and unrecrystallized zone. During the process of fully heated austenitization, Nb and Ti carbonitride in steel were controlled to be fully dissolved in austenitic by controlling the heating temperature and heating time, meanwhile the abnormal growth of the original austenitic grains was effectively prevented.

3.2.2. Cooling technology
The billet of the same composition was rolled into 30mm plate by the same rolling process, and the experiment was carried out under five different cooling conditions. The test results are shown in Fig 4-7. In the figure, with the decrease of the final cooling temperature, the strength increases, the elongation decreases and the toughness shows no significant difference. The tissues obtained by different cooling
processes are shown in table 3 and Fig 8. Among all the processes, the banded structure gained by the air-cooling process reached level 2, the grain size was the lowest, the macroscopic performance strength could not meet the standard requirements, and the toughness was relatively poor.

Because the Marine steel plate needs to go through various pretreatment, cold processing, welding and assembly in the manufacturing process, there are special requirements for the steel plate's strain aging impact toughness performance. The aging impact toughness of the materials developed in this experiment under different cooling processes meets the requirements of ship board certification. The strain aging of steel are influencing by many factors, including the composition of steel plate, smelting method, residual stress in rolling process, plastic working and welding residual stress \[11,12\]. Controlling the content of residual elements S, N, O and Si in the steel can reduce the aging impact energy of the steel, ensure sufficient deoxidation during the smelting process, reduce the total oxygen of the steel, and reduce the oxide impurities. Adding an appropriate amount of Ti, generally around 0.015%, can improve the aging impact toughness of steel. TIN was formed by titanium and nitrogen, and dispersed TIN particles were precipitated at high temperature, which could effectively hinder the growth of austenite grains. Ti precipitates in ferrite could refine grains, improve toughness and reduce strain aging tendency.

Therefore, according to the test results, different cooling processes are adopted in the actual production process according to the thickness of the steel plate to obtain the required structure types to ensure the strength and toughness. The billet thickness of the experimental material is 250mm, the rolling thickness is 60mm, the heating time is required to be more than 10 min/cm, the billet rolling
The temperature is guaranteed to be 1050–1120°C, and the final cold temperature after rolling is controlled below 540°C.

Table 3. Metallographic microstructure, inclusions and banded microstructure of different cooling processes

| Cooling processes | Final cooling temperature ℃ | Cooling rate ℃/s | Banded structure | Nonmetallic inclusion | Grain size | Microstructure               |
|-------------------|----------------------------|------------------|------------------|-----------------------|-----------|------------------------------|
|                   |                            |                  |                  |                       |           | Air cooling                  |
| 680               | 4                          | A0.5D0.5         | 9                | ferrite + pearlite    |
| 640               | 2-8                        | D0.5             | 9.5              | ferrite + pearlite    |
| 540               | 10-15                      | B1.5D0.5         | Bainite + block ferrite |
| 480               | 10-15                      | D0.5             | Bainite + block ferrite |

Fig 8. Microstructure in different cooling processes (a: 680℃, b: 640℃, c: 540℃, d: 480℃)

3.3. Heat treatment process control

The specification effect of strong and high toughness ship plate is mainly reflected in that the strength and impact toughness can not meet the requirements when the plate is thicker than 36mm [6,7]. In particular, the thickness of the material in this experiment is 60mm steel plate, which controls low final cooling temperature and faster surface cooling speed, so that the microstructure of the thick rolled steel plate is not uniform in the thickness direction, the grain size of the steel plate center and surface is more than 1 level different, and the thickness of 1/4 with the microstructure between the center, the surface and the thickness of 1/4 is also different. Therefore, the ship plate with a thickness of more than 36mm shall be under normal heat treatment after controlled rolling and controlled cooling process.

The experiment steel with a thickness of 60mm adopts the normalizing process. The treatment process is as follows: the heating temperature is Ac3+ (50-100℃), and the temperature is kept for a certain time and then cooled in the air.

After normalization, the microstructure and impact toughness of the experimental steels at different thickness directions are shown in Fig 9 and Fig 10. After normalizing, the center and 1/4 of the steel plate were made up of fine equiaxial ferrite and evenly distributed block pearlite, and the defects of coarse ferrite and banded structure were improved obviously. Normalization reduces the dislocation density in steel and significantly improves the aging impact toughness of thick ship plate. After normalization, the impact toughness at the center and 1/4 of the thick steel plate reaches more than 200J. At the same time, normalizing also ensures that the thick steel plate has good low-temperature aging toughness, as shown in Fig 11.
Fig. 9 Microstructure of 1/4 thickness (a) and 1/2 thickness (b) of the experimental steel after normalization

Fig. 10 Impact value - Temperature curve of experimental steel

Fig. 11 Strain aging sensitivity coefficient - Temperature curve of experimental steel

4. Summary

Based on technical requirements of thick special Marine steel plate with high strength and high tenacity, the 60 mm thick specifications special Marin steel plate adopt Nb, Ti microalloyed composition design. With 420 Mpa yield strength and more than 200 J (-20 °C) impact toughness, the steel plate has high strength, impact toughness, lamellar tearing resistance and good welding performance, meeting the special requirements of the large ship manufacturing.

Studying the austenitic recrystallization law of ship plate, we controlled rolling technology, cooling technology and normalizing process. Adopting recrystallization zone and non-recrystallization zone two-stage controlled rolling with the heating temperature Ac3 + (50-100 °C), through cooling in the air after the heat preservation in a certain time normalizing process, thick steel plate can obtain fine
equiaxed ferrite and block pearlitic structure of uniform distribution with good aging toughness at low temperature.

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