Continuous Cooling Transformation Diagram of Offshore Structural Steel

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***Abstract-* Continuous cooling rate after final rolling is an important parameter which controls the microstructure and mechanical properties of the high strength low alloy (HSLA) steels extensively used in offshore engineering. Continuous cooling transformation (CCT) diagram was drawn using the dilatation-temperature curve of the offshore HSLA steel cooled at rates covered from 0.1℃/s to 100℃/s after austenitized at 950℃ for 15 minutes. 0.5℃/s was a critical cooling rate for bainite formation. When the cooling rate was set to be less than 0.5℃/s, only ferrite and pearlite were formed. 20.0℃/s was a critical cooling rate for martensite formation. When the cooling rate was higher than 100℃/s only martensite was recognized. The mixed microstructure of ferrite, pearlite and bainite was formed while the cooling rate ranged between 0.5℃/s and 20℃/s. Bainite and martensite were formed in the offshore steel cooled at rates from 20℃/s to 50℃/s. The CCT diagram is a significant tool for steel production.**

Keywords- CCT Diagram; HSLA Steel; Offshore

I. INTRODUCTION

The controlled rolling and controlled cooling (CRCC) in steel plate production have been extensively employed to produce offshore structural steel [1-3]. Expected strength and toughness of the structural steel need appropriate microstructure. The cooling rate was an important parameter in the offshore steel plate production. Recent years more particular efforts have been stressed on high performance HSLA steels with suitable microstructure [4-8]. The traditional offshore steels, for instance, EH36, E460, etc. exhibit lower quality and lower performance unless the microstructure was carefully controlled. In order to lengthen the service life of offshore engineering the high quality steels with expected microstructure should be used. On the other hand, the security of the offshore structure has been increased when servicing in the ocean. CRCC, which is defined as an advanced route in steel plate manufacturing, has been used to produce the HSLA steels. The CRCC steels consist of relatively lower carbon content. The microstructure of CRCC steels is composed of ferrite and bainite ferrite, which exhibits favorable strength, impact toughness and corrosion resistance. The purpose of the present work is to study the effect of cooling rate after final rolling on the microstructure formation of an offshore structural steel.

II. EXPERIMENTAL PROCEDURES

The HSLA offshore steel was prepared using primary alloy element C, Mn, Cr and Mo. The microalloy elements added were Nb, Al and Ti. The cold crack sensitive index Pcm=C+Mn/20+Cu/20+Cr/20+Si/30+Ni/60+Mo/15+V/10+5B should be limited to less than 0.25% to satisfy the weldability of the offshore structural steels. The principal chemical composition used in the new steel consisted of C ≤ 0.15, 0.20Si, 1.50Mn, P ≤ 0.02, S ≤ 0.01, Cr ≤ 0.30, Mo ≤ 0.30, Al ≤ 0.050, Nb ≤ 0.060, Ti ≤ 0.050, Pcm=0.24 in weight percent. The microalloyed offshore HSLA steel was prepared by melting high purity of iron, graphite ferroalloys bearing the alloying elements and cast into 50 kg ingot in a vacuum induction furnace. The billet was rolled to 20×200×1600 mm dimensions using CRCC process. The specimens with a dimension of Φ10×20mm were machined from the rolled plate for the microstructure transformation in continuous cooling. The CCT tests were carried out on a Formastor-F Dilatometer. Tangent method was used to determine the critical temperature of phase transformation on the dilatation-temperature curve. The samples were heated to 950℃ for 15 minutes followed by cooling down to room temperature at rates of 0.1℃/s, 0.2℃/s, 0.5℃/s, 1℃/s, 2℃/s, 3℃/s, 5℃/s, 10℃/s, 20℃/s, 30℃/s, 50℃/s and 100℃/s. The measured temperatures were within a range of less than ± 2°C throughout the experimental work. The sample was mechanically ground, polished and etched in 4% nital solution for microstructure observation. Metallographic analysis was carried out on a PME3-323UN Olympus optical microscope.

III. RESULT AND ANALYSIS

The typical dilatation-temperature curves of the steel cooled from 950℃ at cooling rates of 0.1℃/s, 2.0℃/s, 10℃/s and 30℃/s are given in Fig. 1 through Fig. 4. It is well known that the volume of the steel decreases with the temperature dropping down. However, if the phase transformation takes place during continuous cooling from the austenitized temperature, the volume dilatation occurs. The density of austenite in 950℃ is the highest than the other phases, for instance, ferrite, pearlite and martensite, etc. So the solid phase transformation can be recognized according to volume changes in dilatation-temperature curves with different cooling rates. Figure 1 shows the dilatation-temperature diagram of the steel sample cooled from the austenitized temperature at a cooling rate of 0.1℃/s. The volume-temperature curve should be smooth if there were no dilatation occurring. However, the present steel is a hypoeutectoid steel. The phase transformation happened during cooling from the austenitized temperature 950℃ to room temperature. The tangent lines to the dilatation-temperature curve were drawn in Fig. 1. Volume dilatation was recognized at 755℃. It may deduce that the austenite→ferrite reaction started at 755℃. The phase transformation finished at 641℃. At the 596℃ was another phase transformation according to the slope of the dilatation-temperature curve. The reaction may be austenite→pearlite due to the reaction temperature scope. The phase transformation ended at 578℃.

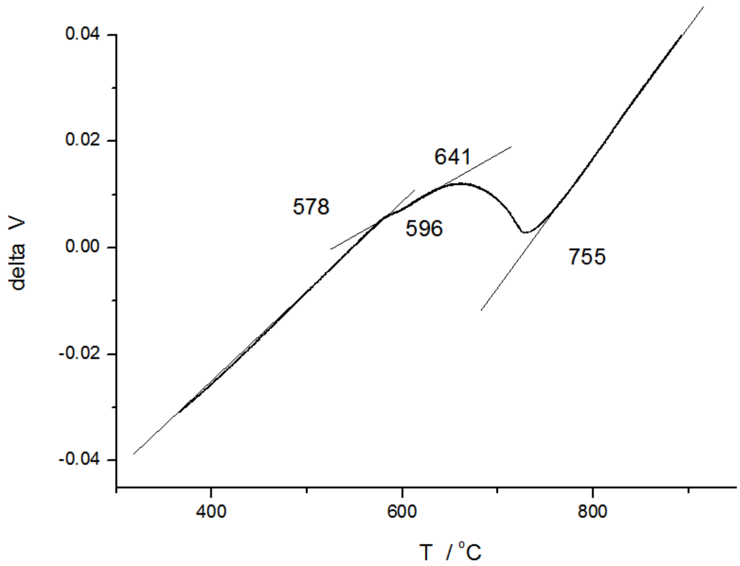

Fig. 1 Dilatation-temperature curve of the offshore steel with cooling rate of 0.1℃/s.

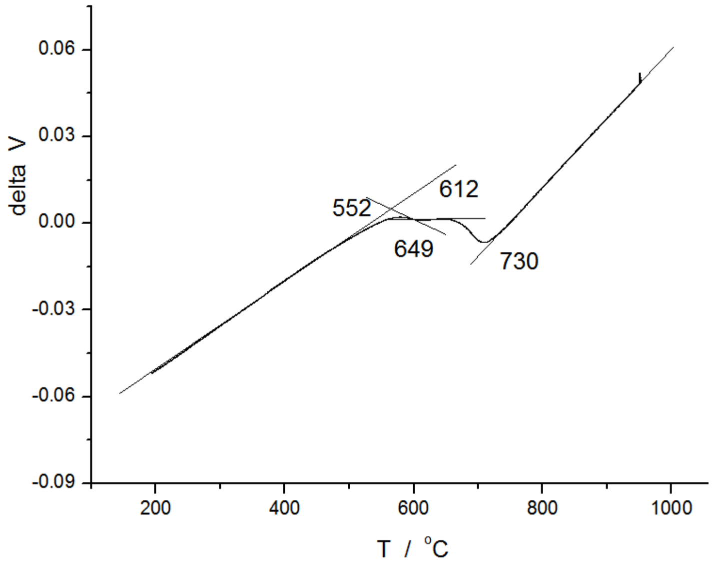

Fig. 2 Dilatation-temperature curve of the steel with a cooling rate of 2.0℃/s

Figure 2 shows the volume dilatation–temperature curve of the steel with a cooling rate of 2.0℃/s. According to the variety of the slop of the curve, solid phase transformations occurred at 730℃, 612℃, 649℃, 552℃. The reaction products may include proeutectoid ferrite, pearlite and bainite. Fig. 3 shows the volume dilatation-temperature curve of the steel sample cooled from the austennitized temperature to room temperature at a rate of 10.0℃/s. Phase transformation started at 691℃ and finished at 455℃. Only one reaction product, i. e. bainite, was recognized. The volume dilatation-temperature curve of the steel cooled from 950℃ to room temperature at a rate of 30.0℃/s is given in Fig. 4. Two phase reactions occurred at 588℃ and 424℃, respectively, were seen. The phase transformation ended at 309℃. The final phase reaction products were thought to be bainite and martensite.

The microstructure of the offshore steel with a cooling rate of 0.1℃/s from 950℃ to room temperature is shown in Fig. 5. Only ferrite and pearlite were recognized. The lamellar structure was clearly seen and arrayed fully in the sample. The particle of the ferrite and pearlite was measured to be less than 20 um. The microstructure which consists of ferrite and pearlite is thought to be equilibrium and stable structure. This kind of microstructure is formed due to the slow cooling rate. Long distance diffusion of Fe and C atoms occurs and leads to the equilibrium phase transformation. The banded structure is formed owing to the carbon dendrite segregation.

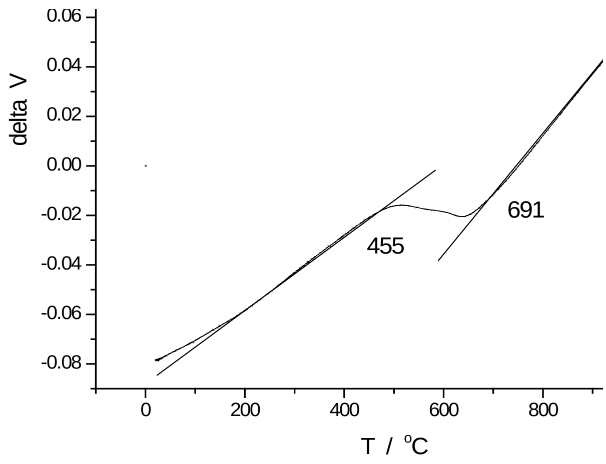

Fig. 3 Dilatation-temperature of the steel with a cooling rate of 10.0℃/s.

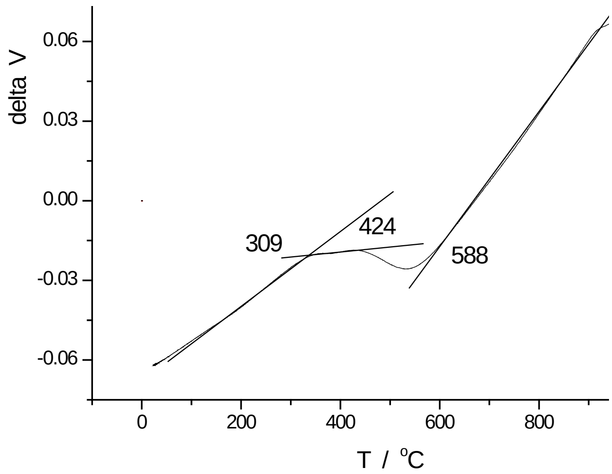

Fig. 4 Dilatation-temperature of the steel with a cooling rate of 30.0℃/s.

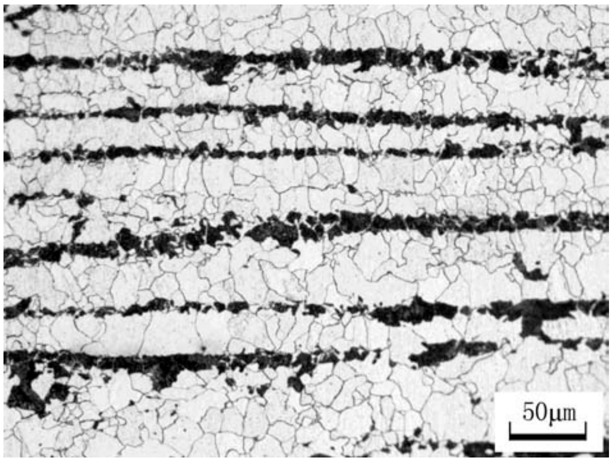

Fig. 5 Microstructure of the offshore steel with a cooling rate of 0.2℃/s

Figure 6 shows the microstructure of the offshore steel cooled to room temperature at a rate of 2.0℃/s after holding for 15 minutes at 950℃. A small amount of bainite was observed. A great number of polygonal ferrite was recognized. Different from the typical pearlite nature, the pearlite decorated in the ferrite matrix microstructure existed in degenerated pearlite feature. The bainite was seen in carbide free bainite. The other categories of bainite, for instance, granular bainite, upper bainite, lower bainite, etc, were not observed. The size of the carbide free bainite was measured nearly twice than that of the ferrite. The degenerated pearlite particle was smaller than that of the ferrite. In general, the microstructure which was composed of polygonal ferrite, degenerated pearlite and bainite showed homogeneous. This category of microstructure is thought to have expected mechanical properties and relatively low ratio of yield strength to tensile strength. The relatively higher cooling rate leads to insufficient diffusion of interstitial atoms, for instance, carbon, nitrogen, etc. So the bainite structure was formed, which supersaturated in carbon atom. The strength of the bainite is higher than that of the ferrite.

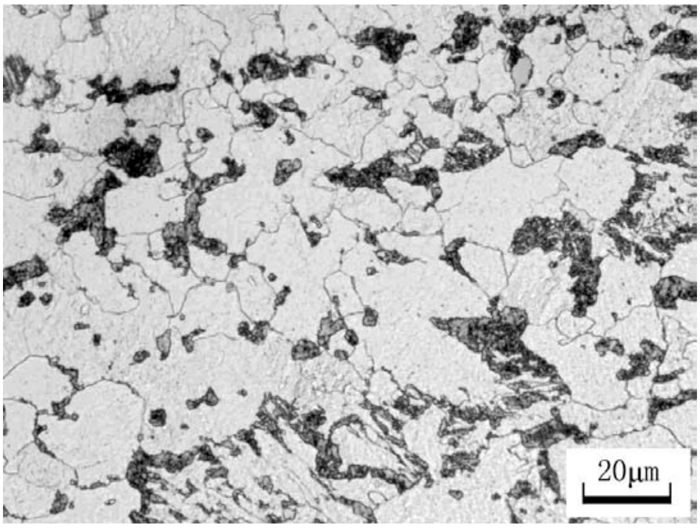

Fig. 6 Microstructure of the offshore steel with a cooling rate of 2.0℃/s

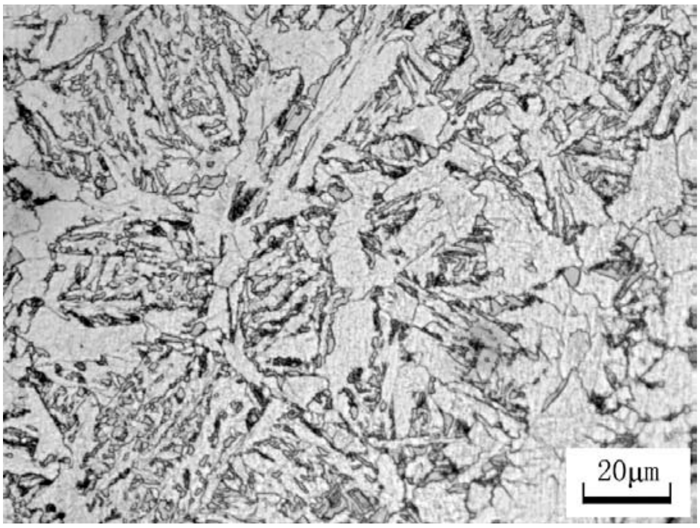

Fig. 7 Microstructure of the offshore steel with a cooling rate of 10.0℃/s

The microstructure of the offshore structural steel cooled to room temperature from 950℃ at a rate of 10.0℃/s is given in Fig. 7. Compared with the microstructure in Fig. 6, the microstructure in Fig. 7 was mostly composed of carbide free bainite which was similar to the bainite formed at a cooling rate of 2.0℃/s. Carbon atom diffusing control mechanism may be used to interpret the present solid phase transformation. When the cooling rate increases, carbon atom diffuses difficultly. In general, the short distance diffusing of the interstitial atoms takes place. A few amount of pearlite was observed. The size of the pearlite particles was measured to be much smaller than that imbedded in Fig. 6. The pearlite was thought to be the degenerated one similar to that formed in Fig. 6. The proeutectoid ferrite was recognized at the pre-austenite grain boundaries. Most ferrite was formed in polygonal shape. More amount of bainite was seen with increasing cooling rate after austenized at 950℃ for 15 minutes. The strength of this combined microstructure is considered higher due to the interstitial solution strengthening. However, the ratio of yield strength to fracture strength increases.

Figure 8 shows the microstructure of the offshore steel cooled from 950℃ to room temperature at a rate of 30.0℃/s. Martensite was observed. The microstructure was much finer than those in Fig. 5, Fig. 6 and Fig. 7. No proeutectoid ferrite and pearlite were recognized. The amount of the bainite was higher than that of martensite. The strength is thought to be much greater than those without martensite. The ratio of yield strength to tensile strength was higher than 0.9. The impact absorbed energy of this kind microstructure which reflects the fracture toughness is lower than that of ferrite + carbide free bainite structure.

The microstructure constitutes of the steel cooled down to room temperature from the austenitized temperature at rates of 0.1℃/s, 0.2℃/s, 0.5℃/s, 1℃/s, 2℃/s, 3℃/s, 5℃/s, 10℃/s, 20℃/s, 30℃/s, 50℃/s and 100℃/s are shown in table I. The microstructure was ferrite and pearlite when the cooling rate was not higher than 0.2℃/s. Ferrite, pearlite and bainite were recognized in the steel when the cooling rate ranged from 0.5℃/s to 10℃/s. Pearlite constitute was not observed when the cooling rate was set to be greater than 20℃/s. Martensite was seen in the steel cooled at a rate of 30.0℃/s.

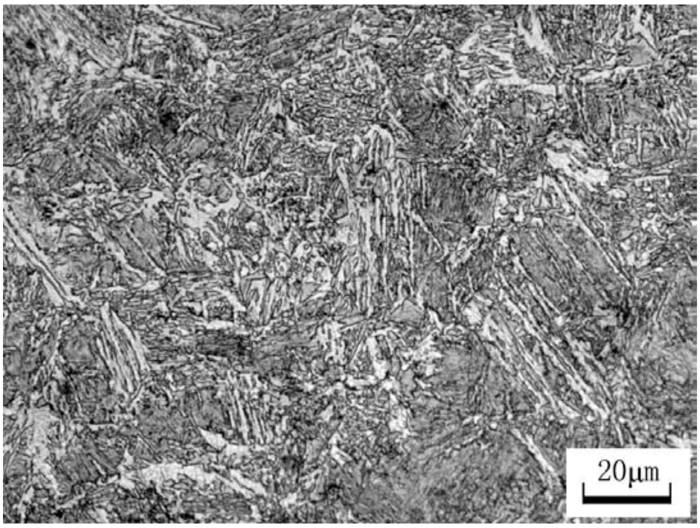

Fig. 8 Microstructure of the offshore steel with a cooling rate of 30.0℃/s

TABLE I MICROSTRUCURE CONSTITUTES OF THE STEEL WITH COOLING RATES

Cooling rate / ℃/s	**Microstructure constitute**	**Cooling rate / ℃/s**	**Microstructure constitute**
0.1	Ferrite, pearlite	5.0	Bainite, ferrite, a few pearlite
0.2	Ferrite, pearlite	10.0	Bainite, ferrite, a few pearlite
0.5	Ferrite, pearlite, a few bainite	20.0	Bainite, a few ferrite
1.0	Ferrite, pearlite, a few bainite	30.0	Bainite, martensite
2.0	Bainite, ferrite, pearlite	50.0	Martensite, bainite
3.0	Bianite, ferrite, a few pearlite	100.0	Martensite

The continuous cooling transformation diagram was drawn using above information. The CCT diagram is given in Fig. 9. The martensite starts formation temperature (Ms) was calculated employing formula Ms=550−361C −39Mn−35V−20Cr−17Ni−10Cu−5(Mo+W)+15Co+30Al. The Ms was calculated as 470℃. The martensite reaction finished temperature was tested to be 310℃. The microstructure at room temperature may be composed of 5% residual austenite even though martensite reaction occurs when the cooling rate is high enough for martensite transformation. The final microstructure constitutes displays clearly in Fig. 9 with different cooling rates. In practical steel production the microstructure may be designedly controlled for special mechanical properties.

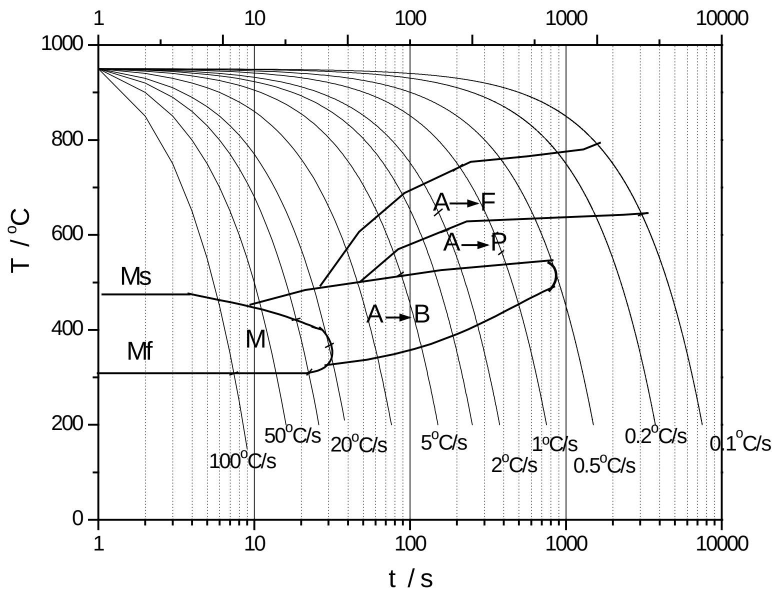

Fig. 9 CCT diagram of the offshore steel

IV. CONCLUSIONS

The continuous cooling transformation diagram was achieved using the volume dilatation-temperature curve and metallographic observation. When the cooling rate was set to be less than 0.5℃/s, only ferrite and pearlite was formed. 20.0℃/s was a critical cooling rate for martensite formation. When the cooling rate was higher than 100℃/s only martensite was recognized. The mixed microstructure of ferrite, pearlite and bainite was formed while the cooling rate ranged between 0.5℃/s and 20℃/s. Bainite and martensite microstructures were formed in the offshore steel cooled at rates from 20℃/s to 50℃/s.

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