Microstructure evolution during continuous cooling process in Ti microalloyed steel

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Abstract: The phase transformation law and microstructure evolution of austenite in Ti microalloyed steel under different continuous cooling rates (0.1-30°C/s) after a two-stage deformation were studied based on the Gleeble-3800 Thermo-Mechanical Simulator. The continuous cooling transformation (CCT) curve was obtained by thermal expansion method combining with microstructures. The results showed that the Ac1 and Ac3 of the steel were 835°C and 902°C, respectively. With the increase of cooling rate, the austenite phase transition temperature decreased, from 778.5-712.2°C at 0.1°C/s to 633.7-488.7°C/s at 30°C/s. Accordingly, the austenite transformation structure changed from polygonal ferrite and pearlite to granular bainite. In addition, with the increase of cooling rate, the ferrite transformation was inhibited, and the transformation region of granular bainite was increased.

1. Introduction
High strength low alloy steel (HSLA) is widely used in various structural parts because of its good mechanical properties[1]. In recent years, through microalloying technology, the properties of steel can be greatly improved by adding microalloyed elements such as Ti, Nb, V and Mo, through microalloying technology[2,3]. The strengthening effect mainly comes from the refine grain strengthening and precipitation strengthening effect by microalloyed elements in steel[4]. Due to the low cost and significant precipitation strengthening effect, Ti is one of the most used microalloyed elements.

During the hot rolling process, TiN nanoparticles precipitated at high temperatures are extremely stable, which pin grain boundaries to suppress the growth of austenite grains, and meanwhile, provide nucleation sites for ferrite transformation, so as to further refine ferrite grains[5, 6]. In practical industrial production, the phase transformation of steel occurs in the continuous cooling process after deformed at high temperatures. The microstructures are the link between the preparation process and performance of materials[7]. The production of Ti microalloyed steel is to obtain the required mechanical properties by optimizing the microstructures[8]. Therefore, how to control the cooling rate to obtain the optimal microstructures has important theoretical significance for formulating and optimizing the controlled rolling and cooling process of steel.
The main work of this paper was to explore the microstructure evolution in Ti microalloyed steel under different continuous cooling rates after a two-stage deformation (simulating the rough rolling and finish rolling process), based on the new TMCP process, and draw the continuous cooling transformation curves, so as to provide a theoretical basis for microstructure control and the development of Ti microalloyed high strength steel.

2. Materials and experimental procedure
The tested steel is the billet smelted in the laboratory, and then hot forged into a bar with $70 \times 70$ mm$^2$ square cross-section. The main chemical composition of the tested steel is shown in table 1. In order to study the phase transformation behavior in the tested steel during continuous cooling process, the controlled cooling experiments were performed as shown in Fig. 1. After austenization at 1200℃ for 5 min on the Gleeble-3800 Thermo-Mechanical Simulator equipped with a thermal expander, the specimens were subjected to a 20% deformation at 1050℃, simulating the rough rolling process in the industrial production of Ti-microalloyed steel. The deformed specimens were then cooled to 900℃ at a rate of 20℃/s and deformed by another 20% to simulate the finish rolling process. Finally, the specimens were cooled to room temperature at the cooling rates of 0.1, 0.3, 0.5, 1, 3, 5, 10, 20 and 30℃/s.

3. Results and discussion
3.1. Phase transition temperatures at different cooling rates
During the heating and cooling process, the temperature change of the specimen can be monitored and recorded by the K-type thermocouple spot welded in the center of the sample surface. Due to the different thermal expansion coefficients of different phases in steel, the thermal expansion of steel changes significantly when the austenite phase transformation occurs. Therefore, the phase transformation kinetics of the test steel during continuous cooling process was studied by using the expansion data along the radial direction of the specimen collected by the thermal dilatometer. Fig. 2 shows the variation curve of thermal expansion with temperature when specimen was cooled to room temperature at 20℃/s. During the cooling process, the thermal expansion decreased linearly with the decrease of temperature, and increased sharply when austenite transformation occurred; After the phase transition finished, the expansion continued to decrease linearly with the decrease of temperature. In this test, the start and end temperatures of austenite phase transformation during continuous cooling of austenite were determined by the tangent method, as shown in points A and B in Fig. 2. The temperature at the tangent points A and B were defined as the starting temperature ($P_s$) and finishing temperature ($P_f$) of austenite phase transition, respectively.
Fig. 2 Change of radial thermal expansion curve of Ti steel with 20°C/s

According to the tangent method, the Ac1 and Ac3 temperatures of Ti microalloyed steel were determined to be 835°C and 902°C, respectively. Table 1 shows the starting and finishing temperatures of austenite phase transformation in Ti microalloyed steel after two-stage deformation with cooling rate in the range of 0.1-30°C/s. It can be found that the austenite transformation starting and finishing temperatures decreased with the increase of cooling rate. In addition, the faster the cooling rate, the greater the difference between the starting temperatures and finishing temperatures of the austenite transformation. For example, when the cooling rate was 0.1°C/s, the difference between them was 66.3°C. However, when the cooling rate increased to 30°C/s, the corresponding difference increased to 145°C. This indicated that increasing the cooling rate increased the undercooling of austenite in the tested steel, and then expanded the temperature ranges of the austenite transformation.

Table 1 The starting and finishing temperatures of austenite transition at different cooling rates for the three test steels

| V(°C/s) | 0.1  | 0.3  | 0.5  | 1    | 3    | 5    | 10   | 20   | 30   |
|---------|------|------|------|------|------|------|------|------|------|
| T(°C)   |      |      |      |      |      |      |      |      |      |
| P_s     | 778.5| 770.8| 764.3| 744.3| 727.7| 659.2| 650.9| 644.1| 633.7|
| P_f     | 712.2| 705.6| 690.4| 643.2| 533.3| 524.8| 512.1| 509.7| 488.7|

3.2. Microstructure evolution under different continuous cooling rates

The microstructures of the tested steel after the two-stage deformation with different cooling rates, are shown in Fig.3. When the cooling rate was less than 0.5°C/s, the microstructure was mainly composed of uniformly equiaxed polygonal ferrite (PF), and a small amount of pearlite (P) distributed on grain boundaries. When the cooling was 0.5°C/s, the pearlite distributed on the ferrite grain boundary basically disappeared. As the temperature ranges of austenite transformation changed from 764-690°C at 0.5°C/s to 744.3-643.2°C at 1.0°C/s, the diffusion rate of C element in austenite decreased, which inhibited the growth of ferrite grains. As a result, part of polygonal ferrite grains became irregular block structure with uneven distribution. When the cooling rate was 5°C/s, the starting temperature of austenite transformation decreased significantly, from 744.3°C at 1°C/s to 659°C at 5°C/s. The ferrite grain boundaries basically disappeared, while a large number of island microstructure appeared. The microstructure mainly consisted of granular bainite (GB) and quasi polygonal ferrite (QF), whose volume fractions were 79% and 21%, respectively. When the cooling rate was further increased, the volume fraction and grain size of ferrite were reduced, while the volume fraction of granular bainite was
increased. When the cooling rate reached 30℃/s, the ferrite was not been observed, and the microstructure was completely granular bainite. the temperature range of austenite transformation was 633-488℃, that is to say, when the starting temperature of austenite transformation in the Ti microalloyed steel dropped to 633℃, the ferrite transformation was completely suppressed.

Fig. 3 Microstructure evolution of the Ti microalloyed steel at different cooling rates after the two-stage deformation (a) 0.1°C/s; (b) 0.5°C/s; (c) 1°C/s; (d) 5°C/s; (e) 20°C/s; (f) 30°C

According to the evolution of microstructure and austenite transformation temperatures, it can be concluded that the polygonal ferrite grain size decreased, accompanied by a significant decrease in volume fraction with the increase of cooling rate. The morphologies of ferrite changed from regular shape to irregular shape, and the corresponding microstructure evolved into polygonal ferrite, quasi-polygonal ferrite, and finally completely into granular bainite. This shown the diffusion characteristics of ferrite transformation, that is, the number and grain size of the newly formed ferrite depended on the movement rate of austenite/ferrite phase interface, and the diffusion rate of carbon atoms during austenite transformation[9].
3.3. Austenite Continuous Cooling Transformation Curves

The austenite continuous cooling transformation curves in the cooling rate range of 0.1-30°C/s in the microalloyed steel after a two-stage deformation were determined based on the thermal expansion curve and microstructure, shown in Fig. 4. The undercooled austenite in Ti microalloyed was mainly transformed into ferrite, pearlite and granular bainite. With the increase of cooling rate, the transformation temperature from austenite to ferrite decreased. The transformation temperature range of ferrite and pearlite were both reduced. On the contrary, the temperature range of granular bainite transformation was expanded. In addition, when the cooling rate exceeded 0.5°C/s, the pearlite transformation was basically inhibited. When the cooling rate was beyond 10°C/s, austenite was almost transformed into granular bainite.

Fig. 4 The continuous cooling transformation curves of the three test steels after two-stage deformation

4. Conclusions

(1) Both the starting and finishing temperatures of austenite transformation in the Ti microalloyed steel decreased with the increase of cooling rate. The temperature range of austenite transformation from 778.5-712.2°C at 0.1°C/s changed to 633.7-488.7°C/s at 30°C/s. In addition, the faster the cooling rate, the greater the difference between the starting temperatures and finishing temperatures of austenite transformation.

(2) The morphologies of ferrite changed from regular shape to irregular shape with the increase of cooling rate, and the corresponding microstructure evolved into polygonal ferrite, quasi-polygonal ferrite, and finally completely into granular bainite. The increase of cooling rate inhibited the ferrite transformation, and expanded the bainite transformation temperature region.

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