A Bainite-Ferrite Multi-Phase Steel Strengthened by Ti-Microalloying

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Ti-microalloyed bainite multi-phase steels were prepared in laboratory scale. The tensile strength of examined steels are all higher than 775 MPa and the maximum value is 875 MPa, with at least 27 J impact energy at 253 K which shows a good balance of high strength and high toughness. The examined steels have uniform and fine multi-phase structure with bainite as main phase and ferrite as minor phase, the ratio of ferrite phase gradually decreases with the cooling speed of post-rolling increasing. Most of the precipitates are nano scaled particles of TiN and TiC, which disperse at grain boundaries, dislocations and other places, having effect of grain refinement strengthening and precipitation strengthening.


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1. Introduction

Low carbon bainite steel has high strength and high toughness. It emerged as required by society and the progress of metallurgical technologies over these 30 years and can fulfill multi-purpose application.1–6 At present, most of pretty fine, high dislocation density bainite matrix structure is obtained by adding less carbon (carbon content ≤ 0.06 mass%) and alloying elements such as Ti, V, Nb, Cu, Ni, Mo, etc., and using secondary refining, TMCP, tempering technologies in manufacturing processes. Experts on steel materials developed low alloy steels of 600–800 MPa grades by means of different strengthening methods, however, relatively high amount of different alloy elements were used, which make the production cost high and requires more strict production conditions.7–14

This article gives the experimental results for the development of Ti-microalloyed bainite-ferrite multi-phase steel with perfect comprehensive properties by Ti-microalloying which has relative lower cost comparing with niobium and vanadium alloying. The developed steels make use of the interaction among alloy elements like Mn and Ti, rolling control, rapid cooling after rolling and the effect of precipitation strengthening and grain refinement strengthening of Ti. The structures and properties of developed steel were tested, providing a basis for wider range of application of Ti-microalloyed steel.

2. Experiment Procedures

The rule of alloying design is to ensure effective delay of polygon ferrite formation in cooling control and obtain bainite. In order to reduce the cost of alloys addition, expensive elements V, Mo, Cu, and Ni are not used. The chemical composition is listed in Table 1.

The experimental steel was firstly melted in a vacuum induction furnace and casted into a 50 kg billet, then heated in reheating furnace, rolled to a 5.5 mm-thick plate by φ500 mm mill with rolling and cooling control. Considering the load capacity of the mill and reduction of each rolling pass, the exit thickness of the third pass of breakdown bar was 60 mm in widness, exit temperature was 1273 K and overall reduction rate was 64.7%; the overall reduction rate at the fifth pass of finishing rolling was 90.8% and the finishing temperature range was 1103 to 1143 K. After hot rolling, the steel plate was cooled by laminar water cooling, with cooling speed of 13 to 40 K/s. The rolling processes and the parameters are shown in Fig. 1 and Table 2, respectively. The Samples of 300 mm in length × 5.5 mm in thickness × width were taken after different rolling and cooling conditions for properties examination. The samples of as casted billets, billets after reheating and plates at different rolling passes were also taken for the analysis of precipitates, microstructures and mechanical properties.

The continuous cooling transformation (CCT) curve of the experimental steel was obtained from as casted billet by hot simulation experiments using Gleeble1500 simulator. The mechanical properties of the experimental steel were tested according to China National Standard GB2975-82 and GB/T228-2002. The v-shaped impact sample size is 5 × 10 × 55 (mm), and tested using impact testing machine ZWICK RKP450.
3. Results and Discussion

3.1 CCT curve of the experimental steel

The continuous cooling transformation (CCT) curve of the experimental steel is shown in Fig. 2. It can be seen from Fig. 2 that the microstructures of experimental steel consisted of ferrite (F) and pearlite (P) or ferrite (F) and bainite (B), respectively, depending on different cooling rates, which ranged from 0.1 K s\(^{-1}\) to 100 K s\(^{-1}\). The volume fraction of different phases also depends on cooling conditions. The faster cooling rate results in the lower transformation starting temperature of ferrite and also the finer ferrite grains. The microstructure of mixed F and B can be obtained if the cooling rate varies between 5.0 K s\(^{-1}\) to 100 K s\(^{-1}\). The volume fraction of B increases with the cooling rate increasing. The microstructure of steel is ferrite plus a certain amount of bainite, which show a good combination of strength and toughness. Therefore, the cooling rate after rolling in the production should be controlled to be large enough to obtain the mixed microstructure of F + B for better comprehensive mechanical properties.\(^{15}\)

3.2 Microstructure

The microstructures of final plates are shown in Fig. 3, where (a), (b), (c), (d) are steel specimens of No. 1#, 2#, 3#, and 4#, respectively, obtained in the conditions listed in Table 2. The experimental steel is composed of mainly lath bainite and a few ferrites. Matrix of experimental steel is refined bainite laths, which show as 3–6 μm bainite and a few ferrites. Matrix of experimental steel is shown in Fig. 2. It can be seen from Fig. 2 that the microstructures of experimental steel consisted of ferrite (F) and pearlite (P) or ferrite (F) and bainite (B), respectively, depending on different cooling rates, which ranged from 0.1 K s\(^{-1}\) to 100 K s\(^{-1}\). The volume fraction of different phases also depends on cooling conditions. The faster cooling rate results in the lower transformation starting temperature of ferrite and also the finer ferrite grains. The microstructure of mixed F and B can be obtained if the cooling rate varies between 5.0 K s\(^{-1}\) to 100 K s\(^{-1}\). The volume fraction of B increases with the cooling rate increasing. The microstructure of steel is ferrite plus a certain amount of bainite, which show a good combination of strength and toughness. Therefore, the cooling rate after rolling in the production should be controlled to be large enough to obtain the mixed microstructure of F + B for better comprehensive mechanical properties.\(^{15}\)

In this experiment, heavy deformation was imposed on austenite, which led to increase of energy storage in austenite, thus enhanced the driving force of ferrite nucleation and the nucleation rate of ferrite at grain boundaries as well. The nucleation rate for proeutectoid ferrite increases with the increasing of deformation zone and dislocation structures possible in austenite. The control rolling and cooling at proper rate after rolling can increases γ \(\rightarrow\) α transformation driving force and ferrite nucleation rate with the increasing of condensate depression. The time interval between deformation and γ \(\rightarrow\) α transformation is shorter, the recovery of austenite grain boundaries or transgranular dislocations and deformation band is harder, so the number of bainite and intragranular ferrite increases with the decrease of their sizes, and ferrite grain is significantly refined.

The details of microstructure of the experimental steel are shown in Fig. 4. Figure 4(a) is a typical microstructure of granular bainite composed of generally in parallel distributed platelets shaped ferrite and bar-like islands. Ultrafine bainite plates with the length about 0.5 μm could be observed in Fig. 4(b). Bainitic ferrite plates grow along a certain directions, no rigorous orientation relationship between austenite and the ferrite of granular structure is observed. The growth of some bainite plates is stilled by intragranular ferrite grains and granular structure. As a result, the length of granular bainite plates is largely reduced. Additionally, the ferrite of granular structure may grow up striding across grain boundary of the parent phase, which may help to explain why the prior austenite grain boundary in Fig. 4(b) could not easily be distinguished. According to the formation mechanism of M/A islands in granular structure,\(^{17}\) the districts surrounded by ferrite grains are carbon-enriched during the formation of granular structure, which will transform to M/A islands afterwards. Such kind of M/A islands could be seen in Fig. 4(c).

3.3 Precipitation

There exists a large amount of precipitates of TiN, TiC and Ti\(_4\)C\(_2\)S\(_2\) in Ti microalloyed steels.\(^{18}\) A few nano-sized cubic and approximate spherical precipitates exist in the experimental steel. The EDS spectrum shows that cubic particle in Fig. 5(a) is TiN. These particles play the role of grain

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<th>Table 2 Process parameters of simulated rolling.</th>
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| Table 1 Chemical composition range of experimental steels. (mass%) |
|-----------------------------|-----------------------------|-----------------------------|
| C                           | Si                          | Mn                          |
| 0.04–0.06                   | 0.25–0.45                   | 1.40–1.60                   |
| Al                          | Ti                          | N                           |
| 0.02–0.04                   | 0.06–0.12                   | 0.0030–0.0050               |
| Fe                          | Balance                     |                             |

Fig. 2 Continuous cooling transformation curve of the developed steel.
refinement strengthening through pinning austenite grain boundary during soaking and acting as ferrite core of non-spontaneous nucleation during tandem rolling, because of the high precipitation temperature of TiN. Figure 5(b) shows approximate spherical precipitates, TiC, precipitated at dislocations and grain boundaries during rolling and laminar cooling. Meanwhile, because the crystal defects provide a favorable heterogeneous nucleation site for second-phase
particles and decreases nucleation energy, moreover, solute atoms diffuse quickly along the dislocation pipes, thus, titanium carbide particles nucleate and precipitate along dislocations.\textsuperscript{19)} The small TiC particles in the ferrite grain and dislocations can prevent the dislocation movement and play a distinct role in precipitation hardening by Orowan mechanism. This is the main strengthening mechanism of the titanium microalloyed high strength steel.

3.4 Mechanical properties

Figure 6 is the typical tensile curve of the experimental steel. It is obvious that there is no yield point but presents a continuous yield on the curve with small hardening rate. This yield characteristic has close relation with bainite content and mobile dislocation density of the microstructure.\textsuperscript{20)}

Table 3 shows the mechanical properties and charpy V-Notch impact energy values of the experimental steels. The experimental steel has good mechanical properties with yield strength in the range of 686~780 MPa and tensile strength of 780~875 MPa and elongation higher than 16%. The experimental steel has a good impact toughness at room temperature and low temperature, the impact energy values at 253 K is more than 27 J. The precipitation of TiN particle at high-temperature heating process can inhibit austenite grain growth, and the ferrite to bainite transformation can be delayed effectively by alloying elements dissolved in austenite. And, titanium carbide precipitation obviously hinders the slipping of dislocations.\textsuperscript{21)}

In the process of rolling, austenite grains get small and uniform by repeated recrystallization. During finishing rolling, austenite is elongated and deformation band is formed by large deformation in austenite non-recrystallization area. After laminar cooling, the steel is rapidly cooled to coiling temperature, fine low-carbon bainite microstructure with high-density sub-structures are formed. The increase of cooling speed can prevent or delay the premature precipitation of titanium carbide during the cooling, which is ready for formation of more dispersed precipitates, further improving strength and toughness of the steel. The adverse effects of carbon on bainite toughness are minimized due to the lower carbon content, so, the experimental steel can have high strength and good toughness.

4. Summary

(1) The experimental steel mainly has refined bainite matrix and certain amount of polygonal ferrite. With the increase of the cooling speed, the volume fraction of ferrite amount decreases and approximate polygonal ferrite changes to acicular ferrite.

(2) Bainitic ferrite plates grow along a certain directions and their length is largely reduced. According to the formation mechanism of M/A islands in granular structure, the districts surrounded by ferrite grains are carbon-enriched, which transform to M/A islands afterwards.

(3) Nano-sized cubic shape TiN and approximate spherical TiC precipitates exist in the experimental steel, which can provide the strengthening effect by grain refinement strengthening and precipitation hardening so as to increase the strength and toughness.

(4) Through rational chemical composition design, control over rolling and rapid cooling, making full use of titanium precipitation hardening and grain refinement strengthening, Ti microalloyed bainite-ferrite multi-phase steel was successfully developed with good comprehensive properties and relatively lower cost. Experimental steel has tensile strength up to 875 MPa, impact energy of 27 J at 253 K, showing a good balance of strength and toughness.

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