Research on Bainite-Matrix TRIP Steel Produced by Fully Austenitized Heat Treatment

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Abstract
With the improvement of people's living standards, the performance requirements of steel are also constantly changing and improving. When the undercooled austenite is in the temperature range between the pearlite transformation temperature and the martensitic transformation temperature, the bainitic transformation will occur. Bainitic steel refers to steel that is bainite-based under normalizing conditions or under continuous cooling conditions. Because bainite has good strength and toughness, bainitic steels have an excellent mechanical property, which promotes the research, development and application of the bainitic steel. This paper mainly studies the bainite matrix steel which can be obtained under normalized or continuous cooling conditions. After the bainitic steel completely austenitizing at 960 °C, the isothermal treatment was carried out at different two-phase treatment temperatures, the microstructure was observed by optical microscopy and electron microscopy, the hardness of the microstructure was measured. Based on this, the formation mechanism of TRIP steel on bainitic matrix was revealed, and the intrinsic relationship between microstructure and hardness and other properties was explored. In this paper, some studies on the bainitic steels have been carried out, which has greatly promoted the development of the bainitic TRIP steels.

Key words: TRIP steel, Bainite, Isothermal treatment, Microstructure

1. Introduction

The rapid cooling of the critical zone usually produces transformation induced plasticity (TRIP) steels; the bainite transformation zone helps to produce a thermodynamic process for the microstructure of ferrite, bainite and retained austenite. During the bainite transformation, the formation of carbides is suppressed due to the effect of alloying elements such as silicon and aluminum; austenite is carbon-rich at room temperature due to the retention of carbon. Preserved metastable austenite is considered beneficial because phase change induced plasticity can provide important boost to material formability and energy absorption during deformation. Bainitic steel is a kind of steel with bainite or bainite-martensite duplex structure after heating and air-cooling, and it is a kind of steel with bainite microstructure in use. Its chemical composition is low carbon and low alloy elements, carbon content is generally <0.05%, the main alloying elements are Mn, Cu, Ni, Mo, B and so on (Wang et al., 2014). By carbon content it can be divided into low carbon bainitic steel, carbon bainitic steel, high carbon bainitic steel (Rossini et al., 2015). By composition it can be divided into Mo-B-based or Mo-based bainitic steel, Mn-B-based bainitic steel, Si-Mn-Mo-based bainitic steel and other bainitic steels, low-carbon bainitic steel, bainitic duplex steel. Compared with non-quenched and tempered steel, bainite has higher plasticity and toughness, higher fatigue resistance (including impact fatigue and strain fatigue) and wear resistance than tempered martensite.

Because bainitic steels have good comprehensive mechanical properties, and their cost is relatively low, bainitic steels have been widely used in practical industrial production. In the actual production of the following types have been widely used as bainitic non-quenched and tempered steel, ultra-high-strength bainitic steels, non-quenched and tempered plastic mold steel, wear-resistant steel, bainitic steel sheet. In the domestic bainitic steel research and development, elements are adding for the general alloy elements, there are no smelting, casting, rolling, and other difficulties; the enterprise can increase production without equipment, as long as air-conditioned conditions can be (Huyghe et al., 2017). Therefore, bainitic steels have obvious advantages in terms of their performance-to-price ratio, and their application prospects in China will be very broad. Bainite series of steel research is still in the bainite transformation mechanism and bainitic steel development. Recently, Speer et al. proposed a novel concept of heat treatment called "Quenching and Partitioning" (Q & P) process in the development of multi-phase steels containing a considerable amount of retained austenite microstructure. The Q & P process is quenched by the first step (quenching process) at a temperature below the Martensitic Initial Transformation (Ms) temperature. During this heat treatment, alloying elements such as silicon and aluminum are used to avoid the precipitation of carbides during the redistribution of carbides, because the precipitation of
carbides means the precipitation of carbon, which means that austenite stabilization is no longer present. In combination with the previous partial austenite and the heat treatment, a microstructure consisting of ferrite, carbon-depleted martensite, and carbon-rich retained austenite is obtained.

In recent decades, the research and development of bainitic steels has aroused great attention of academics and engineering circles, and significant progress has made in the research innovation and practical application of bainitic steels. However, the carbon bainitic steel actually produced is not composed of a single bainitic structure, often a variety of microscopic coexistence; it does not directly reflect the relationships between the mechanical properties and bainitic microstructure (Chiang et al., 2015). In view of this situation, this paper takes low-carbon TRIP steel as the research object, and conducts the controlled rolling and controlled cooling test in a steel company.

2. The Test materials and methods

2.1. Sample preparation
The test material is a low carbon bainitic steel in a rolled state with a sample size of $20 \times 20 \times 15$ mm. The chemical composition of the material used in this work is shown in Table 1. The high-resolution dilatometer is applied to the heat-treated specimen. The sample was heated at a rate of $5^\circ\text{C/s}$, held at $960^\circ\text{C}$ for 10 minutes, completely austenitized, and then cooled to $125^\circ\text{C}$ at a rate of $100^\circ\text{C/s}$. The specimens were reheated to $250^\circ\text{C}$ or $350^\circ\text{C}$ and incubated for different time before being quenched to room temperature.

Table 1. The chemical composition of the test steel (mass percentage)

<table>
<thead>
<tr>
<th>C</th>
<th>Mn</th>
<th>Si</th>
<th>Ni</th>
<th>Cu</th>
<th>Al</th>
<th>P</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.19</td>
<td>1.61</td>
<td>0.35</td>
<td>0.52</td>
<td>1.01</td>
<td>1.10</td>
<td>0.09</td>
</tr>
</tbody>
</table>

2.2. Experimental Methods
The purpose of a suitable heat treatment process is to optimize the properties of the steel (Zhao et al., 2014). For TRIP purposes, the proper matrix structure and the optimized TRIP effect are obtained, while the optimized TRIP effect is predominant to get a reasonable match between the content and the stability of retained austenite. Due to the original TRIP steel composition, the content of alloying elements, heat treatment process is also very much. We can only learn from the experience of our predecessors to explore the laws.

By convention, the main purpose of controlled rolling is usually passed.
(1) Refine the initial austenite grains.
(2) The shape changing of the grains, such as pie-shape, helps to increase the grain boundary area per unit volume.
(3) Increase the density of intra-granular defects (deformation zone and twin boundaries) to refine the ferrite grain size.

A computer simulation approach is taken; Figure 1 shows a comprehensive assessment of these parameters.

![Figure 1](image-url) Isothermal transformation at each temperature type and product

The region to the left of A1-Ms and the transition start line is the sub cooled austenite region. Change the end of the line to the right and Mf following the transformation of the product area (Ormsuptave & Uthaisangsuk, 2017). The two lines are between Ms and Mf for the transition zone.
Controlling the rolling process includes heating the billet to the optimum temperature, controlling the amount of deformation and deformation temperature during rolling, and cooling the steel according to the process requirements after rolling. Control rolling process is usually divided into three stages.

(1) Deformation and austenite recrystallization are carried out at the same time, that is to say, the austenite grains are coarsened gradually after being heated and recrystallized in austenite recrystallization region to be gradually refined;

(2) In the low-temperature austenite deformation stage, when the rolling deformation enters into the austenite non-recrystallized region, the deformed austenite grains no longer undergo recrystallization but exhibit work-hardening state, and this work-hardened austenite has the function of promoting the nucleation of the ferrite phase transformation and makes the crystal grains of the phase transformation small;

(3) Deformation in the two-phase zone (austenite + ferrite), when the rolling temperature continues to decrease below the Ar3 temperature, not only austenite grains but also part of the ferrite grains after transformation have to be rolled and deformed, intra-granular formation of sub grains helps to promote a grain refinement.

3. Metallographic experiment

In order to study the influence of different austenitized bainite transformation and the same sample under different isothermal temperature with the isothermal time, it is necessary to observe the microstructure of the sample after different isothermal temperature treatment tests for comparative analysis.

3.1. Bainite formation mechanism and microscopic mechanism

First, macroscopically bainite transformation has the following characteristics.

(1) Bainite transformation is a process of nucleation and growth

Upper bainite ferrite nuclei has generally preferentially formed on lean carbon austenite grain boundaries, and lower bainite ferrite nuclei can be formed in austenite grains due to large undercooling. These are directly related to the final morphology of the upper and lower bainite.

(2) The formation of ferrite in bainiteis carried out according to the martensitic transformation mechanism

Ferrite and austenite in bainite maintain a coherent relationship and grow along the edge of the parent austenite specific crystal plane by cutting edges (Caballero et al., 2013). Ferrite in bainite maintains austenite phase relationship with parent austenite.

Bainitic ferrite nucleation by martensitic transformation mechanism: the existence of carbon atoms in the supercooled austenite diffusion redistribution, resulting in carbon-lean and carbon-rich regions, assuming isothermal temperature is T1, when the carbon content in the zone is lower than a certain threshold C1 (corresponding to Ms = T1), and the Ms point is higher than T1. At this time, the lean carbon zone forms ferrite through the martensite transformation mechanism at T1.

(3) The distribution of carbides in bainite is related to the formation temperature

3.2. Heat treatment process selection

During the preparation of the metallographic sample, the sample is first ground on a grinder, the cross section of the sample is rectangular, and the four corners need to be knocked out to avoid breaking the polishing cloth, and then the test surface is exposed successively by sandpaper polishing. Followed by mechanical polishing with a metallographic polishing machine, the grinding surface becomes a scratch-free smooth mirror
surface. Then the entire sample is dry to prevent oxidation of the polishing surface, and finally the test if the sample is observed under a metallographic microscope, if it is found that the surface deformation layer seriously affects the clarity of the microstructure, the deformation layer may be removed by repeated polishing and etching.

Controlled cooling after rolling process is generally divided into three phases, it includes the beginning of rolling austenite deformation to ferrite transformation temperature between the start of Ar3 cooling, the Ar3 temperature to the austenite phase transformation complete the entire phase change process and austenite transformation were completed to room temperature cooling. Specimens were etched with nitric acid alcohol and observed by metallographic microscope. The focal length and contrast have adjusted appropriately. Micro-areas without dark spots or scratches were photographed and each area should be photographed at several locations. In this paper, two samples (1 #, 3 # steel) were chosen to do isothermal quenching.

### Table 2. Isothermal quenching process table

<table>
<thead>
<tr>
<th>NO.</th>
<th>Austenitized temperature + time</th>
<th>Isothermal temperature (°C)</th>
<th>Bainite transformation time spent</th>
<th>Selected time</th>
</tr>
</thead>
<tbody>
<tr>
<td>1#</td>
<td>960°C+30min</td>
<td>375°C</td>
<td>52min</td>
<td>52min</td>
</tr>
<tr>
<td></td>
<td></td>
<td>355°C</td>
<td>72min</td>
<td>180min</td>
</tr>
<tr>
<td></td>
<td></td>
<td>300°C</td>
<td>6h</td>
<td>10min</td>
</tr>
<tr>
<td>3#</td>
<td>900°C+30min</td>
<td>275°C</td>
<td>13h</td>
<td>40min</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>72min</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>180min</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>6h</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>9h</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>13h</td>
</tr>
</tbody>
</table>

### Table 3.1 # steel duplex treatment + isothermal quenching process table

<table>
<thead>
<tr>
<th>Austenitizing temperature (°C)</th>
<th>Biphasic zone (treatment temperature (°C))</th>
<th>Biphasic zone (treatment time)</th>
<th>Isothermal quenching temperature (°C)</th>
<th>Isothermal quenching time</th>
</tr>
</thead>
<tbody>
<tr>
<td>960</td>
<td>780</td>
<td>2min</td>
<td>320</td>
<td>180min</td>
</tr>
<tr>
<td>820</td>
<td>2min</td>
<td>320</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>4min</td>
<td>350</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>10min</td>
<td>350</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>10h</td>
<td>320</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

### 4. Test content and result analysis

#### 4.1. Test Results

The microstructure of the low carbon bainitic steel after isothermal treatment was observed. The bainitic steel for testing is austenitized at 960 °C for 30 minutes and then isothermally heated in a box furnace for a different time. The water has cooled to room temperature and the microstructure is as shown in Figure 3.
Figure 3. Microstructure after Q & P heat treatment with quenching temperature of 780 °C, temperature of 320 °C and temperature of 350 °C, time of 120s and 240s for 1# steel

It can be seen from the comparison of the above figure that the dual phase isothermal time has a great influence on the microstructure. It can be seen the same isothermal quenching conditions, the dual phase isothermal time is long, then the inside of some of the granularity of the microstructure becomes finer, because the same austempering conditions, it is most likely the isothermal phase of the dual-phase effect,. The original transformation, which may be granular pearlite or melted fragmented lamellar pearlite, become more and become finer. Because the ferrite particles are air-cooled post-formation phase, the first phase in the two-phase melting, with a long time isothermal melting the more ferrite, the remaining ferrite particles are smaller, and the austenite carbon content is lower, the hardness after isothermal quenching is lower.

Figure 4. Microstructure after Q & P heat treatment with quenching temperature of 355°C, time of 10min, 40min, 72min and 180min for 1# steel
According to this principle, it is predicted that there will be one lowest point of hardness value as the processing time of the dual-phase zone increases. After this minimum point, the hardness will increase, even exceeding the hardness of bainite obtained by austenitizing and isothermal quenching.

Figure 5. Microstructure after Q & P heat treatment with quenching temperature of 275°C and 300°C, time of 13h and 6h for 3# steel

4.2 Results and discussion

The austenite volume fraction and the austenite carbon content show a complex change independent of the quenching temperature when the dosing temperature is 355 °C. The kinetic calculations of carbon partitioning at 355 °C indicate that the carbon is redistributed from martensite to austenite into the final stage after isothermal treatment of 120 seconds (Speer et al., 2017). Therefore, the simulation results show that the carbon content and the austenite volume fraction in the sample are similar to those of the direct quenching under the conditions of 3 seconds and 10 seconds. The hardness of the dual-phase zone + isothermal quenching decreases, and the isothermal time with the dual-phase zone is longer, the lower hardness may be due to the incomplete dissolution of the cementite, which is hard and brittle. Therefore, with the isothermal time the cementite dissolves longer, the hardness decreases. However, the pearlite structure of ferrite + cementite is lower than the lower bainite formed by austenitizing + isothermal quenching. According to this principle, it is predicted that there will be one lowest point of hardness value as the processing time of the dual phase zone increases, and the hardness will increase even beyond the hardness of bainite obtained by austenitizing and isothermal quenching.

<table>
<thead>
<tr>
<th>NO.</th>
<th>Heat treatment process</th>
<th>hardness</th>
<th>Result analysis</th>
</tr>
</thead>
<tbody>
<tr>
<td>1#</td>
<td>355-72min</td>
<td>403</td>
<td>The hardness of the dual-phase zone + isothermal quenching decreases, and the isothermal time with the dual-phase zone is longer, the lower hardness may be due to the incomplete dissolution of the cementite, which is hard and brittle. Therefore, with the isothermal time the cementite dissolves longer, the hardness decreases. However, the pearlite structure of ferrite + cementite is lower than the lower bainite formed by austenitizing + isothermal quenching.</td>
</tr>
<tr>
<td></td>
<td>355-180min</td>
<td>401</td>
<td></td>
</tr>
<tr>
<td></td>
<td>375-52min</td>
<td>391</td>
<td></td>
</tr>
<tr>
<td></td>
<td>375-180min</td>
<td>403</td>
<td></td>
</tr>
<tr>
<td></td>
<td>780-2min+320-180min</td>
<td>356</td>
<td></td>
</tr>
<tr>
<td></td>
<td>780-2min+350-180min</td>
<td>357</td>
<td></td>
</tr>
<tr>
<td></td>
<td>780-4min+320-180min</td>
<td>284</td>
<td></td>
</tr>
<tr>
<td></td>
<td>780-4min+350-180min</td>
<td>292</td>
<td></td>
</tr>
<tr>
<td>3#</td>
<td>275-13h</td>
<td>522</td>
<td>The high hardness of 3# is due to the fine and even bainite structure, and the smaller structure of 275-13h, similar to the fine grain strengthening.</td>
</tr>
<tr>
<td></td>
<td>300-6h</td>
<td>504</td>
<td></td>
</tr>
</tbody>
</table>

Figure 6. Experimental results
After 13h of dispensing time, all samples showed a decrease in the volume fraction of austenite and a significant increase in the carbon content in the retained austenite. The reason for this behavior is austenitic decomposition in bainite (Xie et al., 2014). Bainite forms continuous nucleation and diffusion-free growth through bainitic ferrite sheets, and soon after, excess carbon is distributed toward the surrounding austenite. Each bainitic ferrite plate continues to grow until it is prevented by the strength of the complete austenite (Han et al., 2017). The cementite then precipitates between the bainitic ferrite plate and the carbon-rich austenite. However, since the steel is alloyed with a considerable amount of aluminum, the precipitation of carbides between the bainitic ferrite plates may be suppressed.

4.3. Microalloy element effect

Microalloying element Nb can effectively control the austenitizing, recrystallization, grain growth and elemental migration of TRIP steel. It can also control the hot rolling, critical zone annealing, isothermal and strain transformation in the bainite forming temperature range. All kinds of phase transitions affect the transformation of austenite into ferrite and bainite and the retained austenite volume fraction and stability, which all contribute to the good mechanical properties of TRIP steel. Niobium in solid solution delayed the static and dynamic crystallization and the transformation of austenite to ferrite during hot deformation.

Mo is a ferrite-forming element and decreases the bainite onset temperature. Adding Mo to Nb-containing steels further enhances strength and toughness together with reduced Si content, with Mo playing an important solute dragging effect, carbide precipitation is postponed. In addition, Mo strongly delays the transformation of austenite to ferrite and pearlite. Cu and Ni are austenite-stabilizing elements. The content of retained austenite in the alloy with addition of Cu and Cu + Ni greatly increases, the elongation reaches 34% ~ 38%, and the tensile strength reaches 800 ~ 850MPa. Common TRIP steel alloy elements are V, P, Ni, etc. Other viewpoints of alloying elements researchers are not exactly the same, so the literature on the role of trace alloying elements can only as a reference.

5. Conclusions

TRIP steel is a kind of high-strength steel with high strength and plasticity. And its application prospect as automobile steel is very broad. At present, it has been very active in research on TRIP effect, compositional design, formability, weldability, platability and dynamic mechanical properties, and it has achieved remarkable results. In addition, TRIP steel has been applied in research of composition and microstructure design made significant progress. Among them, the excellent mechanical properties of TRIP steel come from the martensite strengthening, the TRIP effect (amount and time). The martensitic transformation kinetics is the key to control the matching between the two. At present, there are mainly three types of phase transition thermodynamic and kinetic models based on stress-assisted, strain-induced, and heat-induced martensitic transformation.

For low-carbon steel, if the transformation temperature is relatively high, the diffusion ability of carbon atoms is relatively strong. In the formation of ferrite in bainite, carbon atoms can be ferrite through the ferrite-austenite interface to austenite to diffuse to obtain carbide-free bainite composed of strip-like ferrite. If the transformation temperature is lower, the transformation temperature is in the range of upper bainite, and carbon atoms are not diffused from austenite through the ferrite-austenite interface at this time. Therefore, feathery bainite with discontinuous cementite distributed between ferrite bars was obtained. Unlike silicon, aluminum does not have the effect of solid solution strengthening. The replacement of part of silicon with aluminum will result in the loss of strength, and it should be compensated by other measures to increase the strength.

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References


