Bainite Formation in Low Carbon Steel by Thermomechanical Control Process

Long Li

ABSTRACT.

Continuous cooling transformation (CCT) behavior of plain low carbon steel was investigated. Based on the obtained results, allotriomorphic ferrite and high volume fraction of bainite structure has been obtained by controlled deforming in the finish rolling temperature (higher than $A_{e3}$) and controlled cooling. The formation of bainite would lead to an enhanced strength of the low carbon steel and the steel possesses a good combination of strength and ductility.

INTRODUCTION

Grain refinement is an effective way of increasing strength and ductility of metallic materials simultaneously [1-5]. Deformation induced ferrite transformation (DIFT) theory has been accepted to produce ultrafine grained low carbon steels [6-9]. However, high strength steels with ultra-fine ferrite grains are not quite satisfactory in some aspects, e.g. high yield ratio (YR) which means poor formability [3, 4]. Furthermore, it is noted that the heavy deformation must be proposed and the deformation temperature is relatively lower (austenite region near the critical temperature $A_{r3}$) [2-4]. The preferred orientation has also been found in ultrafine grained low carbon steels, which means the deformed structure is dominant [3]. Ref. [4] indicated that the microstructure of the rolled strip with ultrafine ferrite grains was inhomogeneous through the strip thickness. Therefore, compound-strengthening mechanism should be utilized in order to develop high level steel based on low carbon steel.

In recent times, great progress has been made in the research of the bainitic microstructure characteristics and transformation behavior for HSLA [10-12], medium carbon alloyed steels [13] and low carbon micro-alloyed steels [14]. The most popular microstructure in plain low carbon steels is still a mixture of ferrite and pearlite. Since the structure strength of bainite is much higher than that of pearlite, steel strength will be evidently increased through substituting pearlite with bainite in ferrite/pearlite low carbon steels [11]. However, the development of the plain low
carbon steel with a mixed microstructure containing ferrite and bainite is not yet documented well.

Bainite formation was studied by the continuous cooling transformation (CCT) diagram and the optimized thermomechanical control process (TMCP) for a plain low carbon steel in the present work. New low carbon steel with duplex microstructure of ferrite and bainite has been developed through TMCP.

**EXPERIMENTAL**

The material used in the present investigation is a commercial low carbon steel widely applied in industrial fields. Its chemical composition was Fe-0.10C-0.19Si-1.06Mn-0.01P-0.006S-0.006N (wt-%). The steel was prepared in a 50kg vacuum induction furnace. The ingot forged of 50mm×100mm×120mm size was subsequently hot rolled to 10mm-thick plates. Specimens for dilatometric study, 6mm in diameter and 12mm in length, were machined from the plates. The transformation of overcooling austenite was conducted in a Gleeble-1500 thermomechanical simulator. Dilatation curves were obtained by austenitizing the sample at 1000˚C for 3min and the specimens were deformed at 850˚C then continuously cooled at various controlled rates from 1 to 200˚C/s. The dilatometric schedules for determining the CCT diagram in the conditions of deformation are presented in Fig.1 (a).

TMCP was carried out on a φ450mm two-high mill with pipe-cooling facility in laboratory. The intermediate billet was heated to 1200˚C for 2hrs and then start-rolled at higher than 1100˚C and finally rolled to 6.5mm thick plates. Finish rolling temperature (FRT) processed was 850˚C. Table 1 lists the reduction distribution in pass for the hot rolling experiments. After hot rolling, the steel plates were cooled down by accelerated cooling to coiling temperatures (CT) to simulate coiling process, as shown in Fig.1 (b).

<table>
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<th>Table 1. Reduction distribution for the hot rolling experiments of the tested steel.</th>
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<td>Parameter</td>
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<td>Outlet thickness,mm</td>
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<tr>
<td>Rolling temperature,˚C</td>
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<tr>
<td>Reduction,%</td>
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<tr>
<td>True stain</td>
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</table>

Room temperature tensile strength was measured in an Instron testing machine (Model No. 4206) conforming to ASTM standards. Microstructures were examined by LEICA DMIRM optical microscope (OM) and EM-400T transmission electron microscope (TEM). Optical metallographic samples prepared by conventional grinding and polishing techniques were etched in 4% nital. For TEM observation, thin foils were prepared from 300μm thick slices. These slices were mechanically thinned to about ~40μm thickness and then electropolished in a solution of ethanol with 8% perchloric acid at -25˚C in a double jet unit.
RESULTS AND DISCUSSION

Processing

Specimens were austenitized at 1000˚C for 3 min and then continuously cooled to room temperature at a cooling rate of 5˚C/s by using Gleeble-1500 thermo-mechanical simulator, and \( A_\text{e3} \) measured is 710˚C for the tested steel. \( A_\text{e3} \) calculated is 842.8˚C by thermo-calc software. Ref. \cite{15} indicated that the \( A_\text{d3} \) (deformation induced ferrite transformation temperature) can not be above \( A_\text{e3} \). Therefore, the 850˚C of deformation temperature (above \( A_\text{e3} \)) was selected to attain deformation free microstructures.

Transformation of overcooling austenite

Fig.2 shows the corresponding microstructure, which were obtained under the representative cooling rates of 100, 25, 10, and 2˚C/s. Fig.3 shows CCT diagram conducted using the linear cooling rate dilatometric method and metallography.

The CCT diagram shows that the austenite to bainite transformation in the tested steel occurs in cooling rates ranging from 50˚C/s to 10˚C/s. A transformation product containing polygonal ferrite and bainite is obtained at cooling rates between 40˚C/s and 10˚C/s, which is easily reproduced in a modern industrial scale. Cooling rates slower than 10˚C/s would promote the predominant formation of a mixture of polygonal ferrite and pearlite. The pearlite is avoided cooling down at about 10˚C/s and the polygonal ferrite is suppressed if cooling is carried out higher than 40˚C/s. Nevertheless, when the cooling rate is higher than 50˚C/s, the obtained microstructure in the sample is martensite (Fig.3), which is not a desired phase due to its detrimental effect in toughness.
At the cooling rate of 25°C/s, the transformed microstructure (Fig. 2(b)) of the sample was mainly ferrite and bainite, and the formation of pearlite has been totally inhibited along the whole of the transformation. The bainite microstructure was about 40% in volume fraction, which possessed the parallel ferrite with lath structure. In addition, the prior austenite grain boundaries, most of that were covered with a layer of ferrite, could be seen clearly, that of without being elongated means the recrystallization could have occurred at the deformation temperature of 850°C. However intragranular transformation of the austenite takes place, leading to the formation of bainite. With the decrease of the cooling rate down to 10°C/s, the microstructure (Fig. 2(c)) of the specimen was dominated by ferrite, and a little pearlite and bainite can be found. When the cooling rate was reduced to 1°C/s, the transformed product (Fig. 2(d)) mainly consisted of polygonal ferrite a and some pearlite. From Fig. 3, it can be seen that hardness increases with the increase of cooling rate, which resulted from the increase in volume fraction of bainite and the refinement of microstructure or the formation of martensite.

Based on the discussion mentioned above, a certain amount of bainite can be obtained at a cooling rate range from 10 to 50°C/s during the continuous cooling transformation of overcooling austenite for the tested steel. The results also have shown that if the cooling rates required are to avoid the formation of a high volume fraction of ferrite and/or pearlite, the cooling rates have to reach the range of 20~40°C/s where bainite develops.
Thermomechanical control process

Microstructure

Thermomechanical control process was designed with the five-pass deformation and controlled cooling at a cooling rate of 40°C/s. Microstructure of the hot rolled specimens was observed using OM and TEM, as presented in Fig.4. Results show the microstructure is mainly composed of bainite and ferrite (Fig.4 (a)). In the scanning

![Figure 4. Micrographs of the steel by controlled rolling with accelerated cooling](image)

(a) Optical micrograph shows the mixture of polygonal ferrite and bainite; (b) bright field electron micrograph of polygonal ferrite; (c) bright field electron micrograph of lath ferrite; (d) bright field electron micrograph of carbides.

Electron micrograph of the tested steel, a transformation product exists, containing allotriomorphic ferrite, bainite ferrite lath and carbide; along the lath boundaries, few retained austenite or carbide is not seen to be present. Ferrite is somewhat polygonal or like an irregular ferrite mass (Fig.4(b)) and the prior austenite grain boundaries are clearly distinguished and are found to be equiaxed due to recrystallization of austenite during deformation in the last pass of control rolling with FRT of 850°C (higher than the A_ε3). In view of presently available evidence and on the basis of earlier reports [11, 16], the microstructural phase is considered to be the grain boundary allotriomorph of ferrite (F_GBA) in Fig.4. Fig.4 (d) shows the evidence of carbide precipitates in the microstructure of the steel and electron diffraction indicates that the precipitates are Fe₃C structure.

The CCT diagram shows that the formation of polygonal or allotriomorphic ferrite has been suppressed when the cooling rate reaches 40°C/s. However, the
microstructure of the tested steel contains about 15% polygonal ferrite by TMCP (Fig.4 (a)). Since the cooling rate in the core is a little slower than that (40°C/s) of the surface of the steel, a certain amount ferrite can form during TMCP.

Much research work has been done in the phase transformation during hot deformation. DIFT could only occur when the deformation is processed between $A_{c3}$ and $A_{c1}$ [15-18]. In the temperature above $A_{c3}$, although deformation can increase the free energy of austenite, the deformed austenite would change to the un-deformed state through the dynamic recovery and dynamic recrystallization process because that the free energy level of un-deformed austenite is lower than that of ferrite [15]. The temperature range for deformation induced ferrite transformation (DIFT) was also identified by hot rolling tests and the grain boundary allotriomorphic ferrite/bainite was attained in the plain low carbon steel through controlling the deformation schedules in the present work.

**Tensile properties**

Mechanical properties of the steel under investigation, as shown in Table 2, illustrates that the low carbon steel possess a considerably higher strength, compared to conventional hot rolling. It can also be found that the yield strength of the steel can exceed 420MPa with satisfactory elongation and YR when CT was about 500°C and FRT reached 850°C. The experimental results show that the duplex microstructure composed of ferrite and bainite has the optimum strength and ductility. In industrial scale, ultrafine grained low carbon steels have been produced in rolling plants [3,19] and the strength of the steels increased significantly (also shown in Table 2). From the experimental results, it is found that the strength of the ferrite/bainite steel reaches the level of ultrafine grained steel with the similar chemical composition. FRT and CT of the allotriomorphic ferrite/bainite steel are higher than those of the ultrafine grained steel and the reduction is relatively small, which is easily implemented in industrial scale notwithstanding a little bit higher cooling rate.

**Table 2.** Mechanical properties of the tested steel and ultrafine grained steel after thermo-mechanical control process.

<table>
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<tr>
<th></th>
<th>YS(MPa)</th>
<th>UTS(MPa)</th>
<th>%EL</th>
<th>YS/UTS</th>
<th>FRT(°C)</th>
<th>CT(°C)</th>
<th>Cooling rate (°C/s)</th>
<th>True strain</th>
<th>Reference</th>
</tr>
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<tr>
<td></td>
<td>428.1</td>
<td>532.2</td>
<td>26.1</td>
<td>0.80</td>
<td>850</td>
<td>490~510</td>
<td>40</td>
<td>2.0 (total)</td>
<td>—</td>
</tr>
<tr>
<td>420~450</td>
<td>520~550</td>
<td>28~36</td>
<td>0.81~0.82</td>
<td>800</td>
<td>&lt;450</td>
<td>30</td>
<td>2.5 (finishing rolling)</td>
<td>[3][19]</td>
<td></td>
</tr>
</tbody>
</table>
Fig. 5 shows that the tensile results of stress as a function of strain in ultrafine and coarse grained steel. Fig. 5 indicates the absence of significant work hardening after yielding of ultrafine grained steel. This is reflected in the ratio YS/UTS, which is higher than 0.95 (Fig.5), compared with 0.7 for conventional strip and 0.8 for allotriomorphic ferrite/bainite steel. Ultrafine ferrite grains make contribution mainly to the yield strength and the hard bainite will make the tensile strength of the steel increase obviously.

The experimental results demonstrated that for the plain carbon steel, the bainite dominated microstructure can be easily achieved by TMCP, with a controlled rolling in a little above A_e3 temperature and controlled cooling at cooling a cooling rate of 35~40°C/s to CT (bainite transformation region), which could be further optimized by CCT diagram. A duplex ferrite/bainite microstructure (allotriomorphic ferrite/bainite) for plain low carbon steel is formed and the tensile strength can be increased remarkably by the strengthening of bainite, sub-structure (ultrafine ferrite lath) and carbide precipitates resulting in good combination of properties.

**CONCLUSIONS**

1. The increase of cooling rate can cause increase in hardness due to the increase in the volume fraction of bainite and the size of ferrite grains of the experimental steel. A transformation product containing polygonal ferrite and bainite is obtained at cooling rates between 40°C/s and 10°C/s.

2. The temperature range for deformation induced ferrite transformation was also identified by hot rolling tests. Allotriomorphic ferrite/bainite structure has been obtained by controlled deforming temperature with accelerated cooling in plain low carbon steel.

3. The yield strength is over 420MPa and the tensile strength reaches 530MPa in an low carbon steel when the finish rolling temperature is about 850°C (higher than A_e3) and the coiling temperature is around 500°C (at a cooling rate of 35~40°C/s). The strengthening mechanisms of the experimental steel included bainite hardening, fine ferrite lath hardening, and precipitation hardening as well as solution hardening.
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REFERENCES