Dilatometric Analysis of Continuous Cooling Bainite Transformation in Low Carbon Microalloyed Steel

Liangyun Lan

ABSTRACT

The effect of reheat temperature on the continuous cooling bainite transformation in a low carbon microalloyed steel was investigated using a dilatometer based on welding thermal simulation process. At a given cooling rate, the fine grained heat affected zone with reheat temperature of 1050 °C has the lowest bainite start and finish temperatures and highest transformation reaction rate among the sub-zones of heat affected zone.

INTRODUCTION

Dilatometric test is one of the most powerful techniques in material solid-state phase transformation study [1]. There are many research works have reported the effect of reheat temperature (i.e. austenite grain size) on the bainite transformation kinetics under the conditions of isothermal or continuous cooling [2-6]. However, the results seem to be some controversy about the austenite grain size effect. For example, as regards continuous cooling transformation, the austenite grain size has no appreciable effect on the bainite transformation temperature because of its displacive mechanism proposed by Yamamoto et al. [4]. By contrast, Lee et al. [5] concluded that the bainite start (Bs) and finish (Bf) temperatures decrease as the austenite grain size reduces and the transformation rate of upper bainite increases with a decrease in austenite grain size for a low alloy steel.

Although the reheat temperature seems to have only trivial effect on the phase transformation compared with the cooling rate [7], it is evident that this trivial effect also results in the marked difference in mechanical properties of products, especially for welding consumable [8]. Besides, the uneven peak temperature in the heat affected zone (HAZ) may be associated with the formation of the hydrogen cold cracking because the hydrogen can be easy to dissolve in austenite and the cooling rate in the HAZ is independent of the distance from the heat source [9, 10]. Therefore, as mentioned above, it is extremely necessary to investigate and ascertain...
the effect of reheat temperature on the continuous cooling phase transformation of the high strength weldable steel in detail.

EXPERIMENTAL PROCESS

The composition of the low carbon multi-microalloyed steel used in this study is 0.053C-0.22Si-1.65Mn-0.02Al-0.02(Cr+Cu+Mo)-0.07(Nb+V+Ti) (wt. %). The specimens cut from the hot rolled steel plate were machined into cylindrical shape with the dimension of φ3×10mm for dilatometric tests. To simulate roughly the welding thermal cycle process in different sub-zones of the HAZ, including coarse grained HAZ (CGHAZ), fine grained HAZ (FGHAZ) and supercritically HAZ (SCHAZ), the peak temperature was determined at 1300, 1050, and 850 °C, respectively. The whole heat treatment process carried out using a Formastor-FII machine was as follows. Each of specimens was austenitized at a peak temperature for 5 s with the heating rate of 10℃/s. And then two-stage cooling process was applied to cool it down to room temperature. The first stage cooling rate was chosen as 10, 25, 40 ℃/s until the temperature fell to 800 °C, and the corresponding second stage cooling rate after 800 °C was set to 0.5, 3, 10 ℃/s, respectively. The microstructures of the dilatometric specimens were observed using an optical microscope after mechanical polishing and etching with 3% nital etchant.

RESULTS AND DISCUSSION

Fig. 1a shows the relative change of length of dilatometric specimens with the second stage cooling rate of 3℃/s. The Bs and Bf temperatures can be defined as the temperatures corresponding to the points first deviating from the thermal expansion lines of fully austenite or bainite, respectively, because of the volume expansion associated with the bainite formation, as illustrated with the black curve of the SCHAZ (Fig. 1a). It is evident that the reheat temperature influences the bainite reaction behavior at a given cooling rate. The variation of Bs and Bf temperatures with the reheat temperature and cooling rate are shown in Fig. 1b. The Bs temperature decreases significantly with the increase in cooling rate at any the same reheat temperature. However, the Bf temperatures of specimens with the cooling rate of 0.5 °C/s seems to be even lower than those with the cooling rate of 3 °C/s, which is mainly due to slow transformation kinetics and carbon enrichment in residual austenite retarding the transformation [11]. Thus, the microstructure of the SCHAZ with 0.5 °C/s cooling rate consists of massive ferrite, granular bainite and martensite-austenite constituents, as shown in the Fig. 2a.

Figure 1. Dilatometric results showing (a) relative change of length as a function of temperature at a second-stage cooling rate of 3℃/s and (b) the variations of the B_s/B_f temperatures with reheat temperature and cooling rate.
The $B_s$ and $B_f$ temperatures of the FGHAZ specimens are distinctly lower than those of other specimens at a given cooling rate condition and the difference in the $B_s$ temperature become larger with the increase in cooling rate (Fig. 1b). It can be also found that the $B_s$ and $B_f$ temperatures decrease as the austenite grain size reduces comparing between the FGHAZ and CGHAZ specimens at a given cooling rate condition. This effect of austenite grain size is similar to its relationship with martensitic transformation start ($M_s$) temperature [5]. The fine austenite grain size depresses the $M_s$ temperature, which is mainly attributed to the Hall-Petch strengthening of the austenite resulting from high dislocation density and dislocation pile-ups in fine austenite grains [12]. The nucleation mechanism of lath bainite is consistent with the martensite nucleation because it is generally supposed to occur via formation of a small volume with BCC structure bounded by dislocations [13, 14]. Therefore, it can be inferred that fine austenite grains retard the nucleation of bainite by impeding the mobility of dislocation, which reasonably illustrates the present phenomenon because the lath bainite forms in the FGHAZ when cooling rate is $3^\circ$C/s (Fig. 2b).

In addition, it is very interesting that there is an advanced situ observation experiment on the variation in the amount of austenite during real welding process to support the above conclusion [15]. It can be found that the amount of austenite decreases gradually from FGHAZ to CGHAZ within a certain range during the cooling according to Ref.15. This observation result strongly proves that the reheat temperature in the HAZ plays a vital role in influencing the bainite transformation critical temperature, especially for the $B_f$ temperature, because the cooling rate is the same in the HAZ [9]. Furthermore, the higher amount of retained austenite in the FGHAZ, to some extent, explains the enrichment of hydrogen near to the welding fusion line because the hydrogen can be ejected from the weld metal into the sub-zones where the austenite decomposition is retarded [10, 16].
Figure 2. Optical images showing microstructures under different processes. Reheat temperature and the second stage cooling rate are (a) 850 °C, 0.5 °C/s, (b) 1050 °C, 3 °C/s, (c) 1300 °C, 0.5 °C/s, (d) 1300 °C, 10 °C/s, respectively.

The volume fraction of phase transformed \( f_v(T) \) can be calculated by Eq. (1) according to the classic level rule based on the dilatometric curves [5], as shown in the Fig.1a.

\[
f_v(T) = \frac{\Delta L(T) - \Delta L_a(T)}{\Delta L_a(T) - \Delta L_s(T)}
\]

where \( \Delta L(T) \) is the actual value of relative length of the specimen at a temperature T, and \( \Delta L_a(T) \) and \( \Delta L_s(T) \) can be obtained by extrapolating the linear thermal expansion curve of the fully austenite and bainite to T, respectively.

The variation of bainite transformation rate with cooling temperature is shown in Fig. 3. The peak transformation rate increases notably from 2.8×10^-4 to 9.8×10^-3 mm/s and corresponding temperature shifts from 503 to 423 °C with the increase in cooling rate when the reheat temperature is 1300 °C (Fig. 3a). This shift of peak transformation rate is due to different transformation mechanisms at different cooling rates [17], which can be explained based on the microstructural morphology. Granular bainite occurs at the cooling rate of 0.5 °C/s (Fig. 2c), while the lath bainite forms when the cooling rate is 10 °C/s (Fig. 2d), which reveals that the lath bainite formed must be more inclined to the displacive mechanism with one dimension growth and the formation of granular bainite is influenced by the carbon diffusion from ferrite to the martensite-austenite constituent [14, 17].

Typically, Fig. 3b shows that the FGHAZ has the highest peak transformation rates among these three sub-zones at a given cooling rate condition. It is evident that fine austenite grain size can enhance the transformation rate as well as decrease the
corresponding temperature of peak transformation rate although the reheat temperature has much lower effect on the bainite transformation compared with the cooling rate. Table 1 shows the variations in peak transformation rate, corresponding volume fraction transformed and overall reaction time with reheat temperature at the cooling rate of 3℃/s. Obviously, all peak transformation rates occur at about a half volume fraction transformed, but the overall bainite reaction rate of the FGHAZ specimen is accelerated by not only the improvement of peak transformation rate but also the decrease in reaction time.

**TABLE 1. VARIATIONS IN THE PEAK TRANSFORMATION RATE, CORRESPONDING VOLUME FRACTION TRANSFORMED AND OVERALL REACTION TIME WITH REHEAT TEMPERATURE AT THE COOLING RATE OF 3℃/S.**

<table>
<thead>
<tr>
<th>Reheat temperature (℃)</th>
<th>850</th>
<th>1050</th>
<th>1300</th>
</tr>
</thead>
<tbody>
<tr>
<td>Peak transformation rate (mm/s)</td>
<td>0.002</td>
<td>0.004</td>
<td>0.002</td>
</tr>
<tr>
<td></td>
<td>1</td>
<td>9</td>
<td>8</td>
</tr>
<tr>
<td>Volume fraction transformed (%)</td>
<td>0.502</td>
<td>0.494</td>
<td>0.523</td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>8</td>
<td>8</td>
</tr>
<tr>
<td>Overall reaction time (s)</td>
<td>43.0</td>
<td>32.3</td>
<td>37.0</td>
</tr>
</tbody>
</table>

**SUMMARY**

Dilatometric test was employed to analyze the bainite transformation during the simulated welding HAZ thermal cycles in consideration of reheat temperature. The Bs and Bf temperatures of the FGHAZ are lower than those in other sub-zones, and the difference becomes larger with the increase in cooling rate. The overall bainite reaction rate of the FGHAZ is accelerated not only because of the improvement of peak transformation rate but also due to the decrease in reaction time. This result confirms the order of austenite decomposition in different sub-zones of HAZ, which may help to further understand the formation mechanism of welding hydrogen induced cold crack.

**REFERENCES**