Microstructural Characterization of Bainitic Steel Submitted to Torsion Testing and Interrupted Accelerated Cooling

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HSLA low-carbon bainitic steel containing B was submitted to torsion tests to simulate controlled rolling, followed by interrupted accelerated cooling. Microstructural characteristics and the mechanisms for the refinement of structure were evaluated using light microscopy, scanning electron microscopy, transmission electron microscopy, and Vickers hardness testing. The final microstructure was found to contain complex mixture of granular bainite, small islands of MA constituent, bainitic ferrite, and polygonal ferrite. Increasing the cooling rate or decreasing the finish cooling temperature resulted in a decrease in the volume fraction and average size of the MA islands and the polygonal ferrite. A finish cooling temperature of 400°C produced a microstructure consisting of fine laths of bainitic ferrite with an interlath MA constituent. A quantitative relationship between the accelerated cooling variables and the ferrite grain size was developed. © Elsevier Science Inc., 2000. All rights reserved.

INTRODUCTION

In the last 2 decades there have been considerable advances in the theory and practice of accelerated cooling after controlled rolling. Several investigations have been conducted with the objective of studying the influence of cooling variables on the microstructure and mechanical properties of High-Strength Low-Alloy (HSLA) low-carbon bainitic steels [1–6]. The study of the microstructural characteristics of these steels has been carried out using the classification system developed for bainitic and ferritic microstructures by Krauss and Thompson [7]. Most of the bainitic microstructures observed in the low-carbon microalloyed steels can be well described as bainitic ferrite (acicular ferrite) and granular bainite [with discreet islands of MA (martensite and/or residual austenite)].

The MA islands formed in granular bainite during the continuous cooling of steels have a strong effect on the mechanical properties [8]. This constituent leads to increases in the tensile strength but a deterioration in the impact toughness. It also has a small effect on the yield strength. For these reasons, it is very important to understand the influence of cooling variables on the formation of MA islands in the granular bainite.

In the present work, an alternative method, based on hot torsion testing to simulate controlled rolling and on gas-accelerated cooling, was used to study the influence of cooling rate (CR) and finish cooling temperature (T_{FC}) on the microstructure of HSLA low-carbon bainitic steel recently developed by the metallurgical industry. The microstructure refinement mechanism and the MA islands (granular or equiaxed mor-
phology) formation mechanism are discussed. A quantitative relationship between these cooling variables and the ferrite grain size was obtained by multiple regression analysis.

**EXPERIMENTAL PROCEDURE**

The chemical composition of the steel used in this investigation is given in Table 1. Tubular torsion specimens, having a gauge length of 16.5mm, 6.5mm outer, and 2mm inner diameter, were used to study microstructural characteristics after interrupted accelerated cooling. A thermocouple, connected to an interface card installed in a personal computer, was placed inside the specimen, allowing control of the thermal profiles during thermomechanical processing and data collection of the cooling curves.

The specimens were deformed using a nine-pass torsion test. They were reheated to 1200°C for 15 min and, while cooling down at a rate of 1°C/s, they were submitted to five passes at temperatures above the nonrecrystallization temperature \( T_{nr} = 970°C \), followed by four passes below this temperature. A strain per pass of \( \varepsilon = 0.2 \) and a strain rate of \( \dot{\varepsilon} = 2 \, s^{-1} \) were used. Details of the temperature of each pass during the hot torsion experiments are given in Fig. 1.

The continuous cooling transformation (CCT) diagram of this steel (Fig. 2) was determined by thermal analysis of the cooling curves from deformed austenite according to the nine-pass torsion test schedule described above [9]. This diagram was utilized in the selection of the cooling rates and finish cooling temperatures used after the thermomechanical processing, and are also indicated in Fig. 1. The cooling rates measured correspond to average values for the temperature range of 800 to 500°C.

The cooling rate and the finish cooling temperature after deformation were controlled by means of a cooling device using helium and a control panel, which permitted close regulation of the helium flow rate [10].

Samples for metallographic observation and Vickers hardness (VH) measurements (4.905N load) were sectioned longitudinally, producing a plane tangential to the gauge length to the torsion specimens. Two percent nital and LePera’s etchants [11] were used to examine the microstructures. The samples were observed by light microscopy (LM) and scanning electron microscopy (SEM). Volume fractions and dimensions analyses of the constituents were performed using computerized image analysis, IMAGE PRO-PLUS™, from light microscopy. More detailed microstructural characterization, for selected cooling rates and finish cooling temperatures, was conducted using transmission electron microscopy (TEM) of thin foils in a bright-field mode.

**RESULTS AND DISCUSSION**

**MICROSTRUCTURE**

Figure 3 shows the microstructure corresponding to a specimen quenched after the last pass of the nine-pass test. Elongated austenite grains are observed, revealing that accumulation of deformation has taken place during hot working in the low-temperature range. The elongated grains have, in the plane of observation, an approximate aspect ratio of 4:1, given an average value of 40 μm.

<table>
<thead>
<tr>
<th>C</th>
<th>Mn</th>
<th>Si</th>
<th>P</th>
<th>Al</th>
<th>Nb</th>
<th>V</th>
<th>Ti</th>
<th>Ni</th>
<th>B</th>
<th>S</th>
<th>N</th>
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<td>0.08</td>
<td>1.70</td>
<td>0.25</td>
<td>0.021</td>
<td>0.029</td>
<td>0.033</td>
<td>0.058</td>
<td>0.026</td>
<td>0.17</td>
<td>0.0024</td>
<td>0.002</td>
<td>0.0048</td>
</tr>
</tbody>
</table>
The combined effects of cooling rate and finish cooling temperature on the microstructure are illustrated in Figs. 4 (LM photomicrographs) and 5 (SEM photomicrographs). It can be seen from Figs. 4(a) and 5(a) that the microstructure associated with the highest finish cooling temperature ($T_{FC} = 650^\circ C$) exhibits a mixture of fine polygonal ferrite (with a volume fraction $\approx 12\%$), granular bainite, and small islands of the MA constituent. The MA constituent has a granular or equiaxed morphology (volume fraction $= 4.5\%$ and with islands...
of average size less the 2μm). By contrast, the microstructures associated with the next lower finish cooling temperature (T_{FC} = 500°C) [Figs. 4(b) and 5(b)] consist of granular bainite and bainitic ferrite. A small amount of polygonal ferrite is also in evidence in these microstructures.

In the case of the two higher finish cooling temperatures (T_{FC} = 650°C and T_{FC} = 600°C), the MA islands are distributed practically uniformly throughout the bainite matrix (Fig. 6). This figure, a compilation of binary images in which the MA islands appear white, shows that the increase in cooling rate or decrease in finish cooling temperature implies a decrease in the volume fraction and the average size of the MA islands.

Figures 4(c)–(d) and 5(c)–(d) show that, for the lowest finish cooling temperature, T_{FC} = 400°C, the microstructure is essentially bainitic, with fine laths of bainitic ferrite and interlath MA constituent. It can be seen from Fig. 5(c), CR = 6.3°C/s, that the microstructure contains a small amount of polygonal ferrite. Figure 7(a)–(d), TEM micrographs of samples cooled at rates of 6.3°C/s and 33°C/s for T_{FC} = 400°C, shows that the width of the bainitic ferrite laths decreases with increasing cooling rate, and that the widths can be as narrow as 0.2μm. No evident interlath carbides were observed in this steel under present conditions. The refinement of bainitic ferrite by increasing the cooling rate could be due to the following: when the cooling rate increases, the reduction in the bainite transformation start temperature, B_s, leads to an increase in the driving force (the difference in free energy between the austenite phase and the ferrite phase) for the nucleation rate of subunits of ferrite and, consequently, to a decrease in the width of the bainitic ferrite laths. The increase in the

![Fig. 4. Light photomicrographs of samples cooled at different rates and with different finish cooling temperatures: (a) 6.3°C/s, 650°C; (b) 13.3°C/s, 500°C; (c) 6.3°C/s, 400°C; (d) 33°C/s, 400°C.](image-url)
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cooling rate leads to a continuous increase in the Vickers hardness from 262 to 320.

The analysis of the optical, SEM, and TEM photomicrographs reveals that the cooling variable of greater influence on the bainite morphology is the finish cooling temperature. When the finish cooling temperature decreases from 650 to 400°C, it can be observed that the ferrite crystals change from their granular morphology with the presence MA islands (by default, these islands have granular or equiaxed shapes resolvable in light micrographs) to finer ferrite crystals with laths morphology (MA constituent is retained between the ferrite laths with acicular morphology).

Figures 8(a)–(b) and 9(a)–(b) show the influence of the cooling rate on the volume fraction and average size of the MA islands and the polygonal ferrite, associated with the various finish cooling temperatures, respectively. The results show that the increase in the cooling rate or the decrease in the finish temperature leads to a decrease in the volume fraction and the average size of the MA islands and the polygonal ferrite. For $T_{FC} = 400^\circ$C no MA islands were detected.

FERRITE GRAIN SIZE

A quantitative relationship between the cooling variables and the ferrite grain size was obtained by means of multiple regression analysis. The statistical treatment was carried out by taking the cooling rate and the finish cooling temperature as independent variables. The following equation was obtained:

$$d_\alpha = 0.12(CR)^{-0.27}(T_{FC})^{0.67} \quad R = 97.2\% \quad (1)$$

where $R$ is the multiple correlation coefficient, $d_\alpha$ is ferrite grain size. The values enclosed in the parentheses indicate 95% of
confidence level. Figure 10 shows that the correspondence between measured and predicted [Eq. (1)] ferrite grain size is quite close, and discrepancies observed are very small.

The effectiveness of cooling rate on the ferrite grain size appears to be reduced as the finish cooling temperature is decreased. The grain size is reduced from 5.6 to 3.7 μm for an increase in the cooling rate from 6.3 to 33°C/s for $T_{FC} = 650°C$. Under the same conditions for $T_{FC} = 500°C$, $d_a$ is reduced from 4.6 to 3.2 μm. From Eq. (1), when the cooling rate increases tenfold, the ferrite grain size is reduced to almost half (0.54).

**MA CONSTITUENT**

The formation of MA islands is a process controlled by carbon diffusion. Therefore, it
was expected that both the cooling rate and finish cooling temperature would influence the average size and volume fraction of the MA islands. The displacive model has been proposed and accepted [12–15] for the kinetics of bainite transformation. In this model the nucleation of ferrite occurs by a diffusional mechanism, and longitudinal growth takes place by a displacive mechanism. The growth of ferrite laths (or plates) is controlled by the repeated nucleation of subunits (individual ferrite laths), and its nucleation rate strongly depends on the driving force for the phase transformation reaction. Diffusionless growth requires that transformation occurs at a temperature be-

![Fig. 7. TEM photomicrographs of samples cooled at different rates but with the same finish cooling temperature: (a) 6.3°C/s, 400°C; (b) 33°C/s, 400°C.](image)

![Fig. 8. Influence of cooling rate on: (a) the volume fraction of the MA islands (f_{MA}); (b) the average size of the MA islands (d_{MA}).](image)

![Fig. 9. Influence of cooling rate on: (a) the volume fraction of the polygonal ferrite (f_{PF}); (b) the average size of the polygonal ferrite (d_{PF}).](image)
low $T_o$, when the free energy of bainite becomes less than that of austenite of the same composition. The $T_o$ curve defines temperatures at which austenite and ferrite of the same composition have equal free energy (Fig. 11). While the austenite–bainite transformation proceeds, any excess carbon is rejected into the residual austenite. When carbon-enriched residual austenite is continuously cooled to a temperature below the martensite transformation start temperature ($M_s$), it will transform to an MA constituent.

An increase in the cooling rate causes a decrease in the bainite transformation start temperature ($B_s$) (Fig. 2) and, consequently, an increase in the difference of free energy between austenite and bainite, as shown in Fig. 11. The free energy of the austenite will rise from $\gamma_1$ to $\gamma_2$, and the $T_o$ curve shifts from $T_{o1}$ to $T_{o2}$. This results in an increased amount of bainite and in a smaller amount of retained austenite, which subsequently transform into MA islands. This can explain why the amount of the MA islands decreases when the cooling rate increases.

The finish cooling temperature also influences the dimensions and volume fraction of MA islands. For a given cooling rate and for a higher finish cooling temperatures (e.g., 600°C), bainite has not yet started to form, or is only in the very initial stages of development. During the subsequent slow cooling in air (1°C/s), the sample remains for a long enough time at temperatures where diffusion of carbon atoms over long distances is still possible. The bainite transformation, already initiated during accelerated cooling, can then continue until zones of stable carbon-enriched austenite are formed, which will become lower temperature MA islands. When the finish cooling temperature is smaller, the formation of bainite is already at an advanced stage at the point of interruption of the accelerated cooling, and is brought to completion during the subsequent air cooling. In this case, the sample remains a very small time at temperatures where diffusion of carbon atoms over long distances is still possible. During the austenite–bainite transformation the carbon is rejected into the adjacent residual austenite, reducing the volume fraction and the size of the MA islands.

**CONCLUSIONS**

The effects of interrupted accelerated cooling on the microstructural characteristics of the HSLA low-carbon bainitic steel were
studied, and the following conclusions were reached.

For the conditions of accelerated cooling applied in the present work, the final microstructure consists of a complex mixture of granular bainite, small MA islands, bainitic ferrite, and polygonal ferrite. For \( T_{FC} = 400^\circ C \), the microstructure is essentially bainitic, with fine laths of bainitic ferrite with an interlath MA constituent. No evident interlath carbides could be observed in this steel.

The increase in the cooling rate or the decrease in the finish cooling temperature results in decreasing volume fraction and average size of the MA islands and the polygonal ferrite.

A quantitative relationship between the cooling variables and ferrite grain size is proposed. The empirical equation shows that the cooling rate has a stronger influence than the finish cooling temperature on the ferrite grain size.

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References


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