The Crystallography of the Bainite in a Low-carbon Low-alloy High Strength Steel

By Yasuya OHMORI**

Synopsis

The bainite that forms in a low-carbon low-alloy steel at the temperatures as low as the Ms point exhibits the (111)\textsubscript{c} // (110)\textsubscript{f} habit, but involves fine cementite laths within the ferrite in a fashion similar to a high carbon lower bainite. The crystallographic aspects of such bainite have been investigated by means of transmission electron microscopy.

The ferrite/cementite orientation relationship is that of Isaichev, and the habit plane and the possible growth direction of the ferrite laths are the (011)\textsubscript{c} // (010)\textsubscript{p} and the (111)\textsubscript{c} // [010]\textsubscript{p} respectively. While the habit plane of the cementite laths is close to the (510)\textsubscript{p} // (101)\textsubscript{c}. It is confirmed that the ferrite laths consisted of much finer sub-laths whose habit plane lies close to that of the cementite laths, suggesting that the cementite laths are formed at the ferrite sub-lath/austenite interphase boundaries. It is shown that such crystallographic results can be explained in a way similar to the analysis done by Kelly for the martensite formation in a Mn-Cr-Ni austenitic steel.

I. Introduction

The previous experiment\textsuperscript{1)} has proved that the bainite in low-carbon low-alloy steels exhibits the (111)\textsubscript{c} // (110)\textsubscript{f} habit similar to that in low carbon lath martensite, but can be divided into three distinct types by the morphology of cementite precipitation. As the bainite formed at the temperatures around the Ms point, B-III\textsuperscript{1)} involves the fine cementite laths similar in appearance to those in high carbon lower bainite, some workers have classified it as a lower bainite.\textsuperscript{2,3)}

The shape of this bainitic ferrite, however, was definitely not plate-like but is lath-like, and was different from the lower bainite in this respect.\textsuperscript{19)} It was also confirmed that the cementite in this bainite was related to the ferrite with the Isaichev\textsuperscript{4)} (or the Bagaryatski\textsuperscript{5)} orientation relationship, but still further information is necessary to achieve the crystallographic analysis using the phenomenological theory of martensite.\textsuperscript{6-9)}

The aim of the present investigation is to determine the mutual relationship between the bainite habit and that of the cementite laths in addition to the ferrite/cementite orientation relationship, and to reveal the mechanism of this bainite formation.

II. Experimental Methods

The chemical composition of the steel investigated is given in Table 1. The steel was prepared by a 1 t high-frequency induction furnace, and was rolled into plates 7 mm thick. They were austenitized at 1200°C in argon for 15 min, transformed isothermally in the range between 400°C and 450°C, and then quenched into iced brine. The foils for transmission electron microscopy were prepared by electropolishing in a chromic-phosphoric acid electrolyte using the Bollmann technique.\textsuperscript{10)} The observation was carried out in a Hitachi HU-200 microscope operated at 200 kV.

III. Experimental Results

A typical bainite formed at 400°C is shown in Photo. 1. It can be seen that the numerous cementite laths within a ferrite grain exhibit a specific growth direction. Since in some cases both cementite and ferrite reflections were obtained simultaneously in a selected area electron diffraction pattern, the trace analysis to determine the relationship between both habits was possible to achieve by taking a specific variant of the ferrite/cementite orientation relationship. Figure 1 is the stereographic projection showing such an analysis and gives the following relationship:

The ferrite habit plane: \((011)_{f} // (010)_{c}\)

The possible ferrite growth direction: \([111]_{f} // [010]_{c}\)

The cementite habit plane: \((501)_{c} // (101)_{f}\)

The possible cementite growth direction: \([010]_{c} // [111]_{f}\)

(The growth directions are compatible with the \([111]_{f} // [010]_{c}\) as can be seen in Fig. 1, but can not be determined uniquely.) An example of such analysis is illustrated in Photo. 2. The bright field

<table>
<thead>
<tr>
<th>C</th>
<th>Si</th>
<th>Mn</th>
<th>P</th>
<th>S</th>
<th>Cu</th>
<th>Ni</th>
<th>Cr</th>
<th>Mo</th>
<th>V</th>
<th>sol. Al</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.12</td>
<td>0.30</td>
<td>0.84</td>
<td>0.004</td>
<td>0.005</td>
<td>0.30</td>
<td>1.11</td>
<td>0.53</td>
<td>0.47</td>
<td>0.03</td>
<td>0.030</td>
</tr>
</tbody>
</table>

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image, the dark field image using the (121)_c reflection, the associated electron diffraction pattern, and its schematic representation are in Photos. 2 (a) to (d) respectively. The stereographic projection of this pattern, Fig. 2, indicates that the cementite can be related to the ferrite by the Isaichev orientation relationship: 4

\[ \{\overline{1}1\overline{1}\}_a // \{010\}_c \\
\{10\overline{1}\}_a // \{10\overline{3}\}_c \]

and that the trace normals to the bainite and cementite laths lie close to the \(\{10\overline{1}\}_a // \{10\overline{3}\}_c\) plane and the \(\{011\}_a // \{301\}_c\) plane respectively. It can also be seen that the possible growth direction for either the bainite or the cementite laths is close to the \(\{010\}_c // \{\overline{1}1\overline{1}\}_a\) axis.

Photograph 3 (a) shows similar bainite laths with their habit plane exactly parallel to the incident electron beam direction. This can be confirmed by the fact that no boundary fringes arising from the bainite lath interfaces inclined to the beam direction can be observed. The associated diffraction pattern and its schematic representation, Photos. 3 (b) and (c), indicate that the ferrite habit plane lies parallel to the \(\{\overline{1}1\overline{1}\}_a // \{10\overline{3}\}_c\) plane, and that the growth direction is possibly the \(\{\overline{1}1\overline{1}\}_a // \{010\}_c\) axis. Since the \(\{010\}_c\) cementite growth direction differs only 30° from the electron beam direction, the shape of the cementite laths may not be well defined, being in keeping with the observation in Photo. 3 (a). Photograph 4 (a) is another example of the bainite whose lath boundaries cannot be clearly observed, suggesting that the habit
plane of the bainite is almost parallel to the foil surface. The diffraction pattern, Photo. 4 (b), and its schematic representation, Photo. 4 (c), support this and demonstrate that the incident beam direction is inclining only 10° to the habit plane normal and that the cementite growth direction is exactly parallel to the [010], // [111], axis.

In order to achieve the precise determination of the cementite / ferrite orientation relationship, it is significant to measure the angle separating the cementite and ferrite reflections. This is because the angle between the reflections around the incident beam direction can be determined within the accuracy of 1°, whereas the errors arising out of the rotation around the axis involved in the plane normal to the beam direction can be about 10° at most. Photographs 5 (a) and (b) are the selected area electron diffraction pattern from a similar bainite and its schematic representation respectively. The 3.5° separation between the [001], and [112], axes can be seen in the pattern, and this agrees with the Isaichev orientation relationship,41 being incompatible with that of Bagaryatskii.43

The direct determination of the austenite / ferrite orientation relationship was impossible to achieve in this steel where no retained austenite existed. However the close examination of the orientation relationship between the bainite laths within a bunch which formed as two different variants of the ferrite / austenite relationship will reveal whether they are in keeping with the Kurdjumov–Sachs relationship10 or not. Namely in the Kurdjumov–Sachs relationship10 the ferrite laths of the same habit (the growth direction and the habit plane) will exhibit either the parallel or the exact twin relationship. The results of analysis are shown in Table 2, and it can be seen that the orientation relationship is slightly deviated from that of Kurdjumov–Sachs.10

Occasionally it was observed that the ferrite laths consisted of much finer parallel laths (this will be referred to as ‘‘sub-lath’’ hereafter) of the habit plane.
3.5' Photo. 5. The selected area electron diffraction pattern from the bainite formed at 400°C for 200 sec
(a) The diffraction pattern
(b) Its schematic representation

Table 2. The angles between the reflections from the ferrite laths in two different variants

<table>
<thead>
<tr>
<th>Film No.</th>
<th>Reflecting zone axis</th>
<th>Planes</th>
<th>The observed angle</th>
<th>The angle expected from K-S relationship</th>
</tr>
</thead>
<tbody>
<tr>
<td>E2499</td>
<td>(730)$<em>{1/2}$ // (210)$</em>{1/2}$</td>
<td>(231)$<em>{1/2}$ &amp; (123)$</em>{1/2}$</td>
<td>3°</td>
<td>0°</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(323)$<em>{1/2}$ &amp; (002)$</em>{1/2}$</td>
<td>8°</td>
<td>5°</td>
</tr>
<tr>
<td>E2518</td>
<td>(110)$<em>{1/2}$ // (115)$</em>{1/2}$</td>
<td>(110)$<em>{1/2}$ &amp; (110)$</em>{1/2}$</td>
<td>3°</td>
<td>0°</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(002)$<em>{1/2}$ &amp; (321)$</em>{1/2}$</td>
<td>14.5°</td>
<td>10.9°</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(002)$<em>{1/2}$ &amp; (231)$</em>{1/2}$</td>
<td>7°</td>
<td>10.9°</td>
</tr>
</tbody>
</table>

inclined to the \{111\}$_r$ lath habit. Photographs 6 (a) and (b) are the bright and the dark field images at such an area, and the dark field image was revealed by using both the cementite and the ferrite reflections of a specific variant. It is interesting to note that the cementite laths are aligning almost parallel to these ferrite sub-laths.

IV. Crystallographic Analysis and Discussions

The ferrite of this bainite exhibits the \{111\}$_a$\{110\}$_a$ habit, and this is exactly similar to that of either the low carbon martensite or the martensite formed in the austenite with low stacking fault energy such as Mn–Ni–Cr austenitic stainless steel. Kelly\textsuperscript{11} has already analysed the crystallography of the martensite formation in the Mn–Ni–Cr austenitic stainless steel using the Bowles-Mackenzie theories\textsuperscript{8–10} in terms of formation of the hexagonal \(\varepsilon\)-martensite bands and the subsequent \(\alpha'\)-martensite transformation between them. Namely the width of the final ferrite laths is restricted within the band of the \(\varepsilon\)-martensite laths on the \{111\}_r planes. The essence of this theory is to assume the 1/6 \langle112\>_r partial dislocations for the lattice invariant shear, and the calculations except the orientation relationship between austenite and ferrite had been carried out by Wechsler et al.\textsuperscript{12} Although Breedis and Kaufman\textsuperscript{13} criticized the \(\gamma\rightarrow\varepsilon\rightarrow\alpha'\) reaction path for the low carbon lath martensite formation in view of the free energy of each phase, Grunes et al.\textsuperscript{14} have pointed out the danger of accepting equilibrium thermodynamic calculations applied to metastable martensite reactions.

In addition to such criticism, the formation of the \(\varepsilon\)-bands which constriuct the lath habit is not the requisite reaction in the Kelly's analysis,\textsuperscript{11} and this can be replaced as well by the bands of stacking faults on the \{111\}_r plane, if they can restrict the \(\gamma\rightarrow\alpha'\) reaction to within themselves. Thus the present analysis will be carried out in this line. (The following calculations correspond to the K-degenerate state with Aa habit type in the reference (12).)

Input data

(i) The lattice parameters for austenite and ferrite are assumed to be equal to those of pure iron:

\[ a_0 = 3.5852 \text{ Å} \]
\[ a = 2.8664 \text{ Å} \]

(ii) The lattice correspondence:

\[
\begin{pmatrix}
1 & -1 & 0 \\
1 & 1 & 0 \\
0 & 0 & 1
\end{pmatrix}
\]
(iii) The lattice invariant shear:
\[ \{112\}_r \{111\}_r \]

(iv) The dilatation parameter:
\[ \alpha = 1.000000 \]

Output data
(i) The invariant line:
\[ X_1 = \begin{pmatrix} -0.746303 \\ 0.086317 \\ 0.659986 \end{pmatrix} \]

(ii) The invariant normal:
\[ n'_1 = (0.814641, 0.240690, 0.527665) \]

(iii) The shape strain:
\[ (r S_f) = \begin{pmatrix} 1.114464, -0.029454, 0.133287 \\ 0.026716, 1.130209, 0.013181 \\ -0.188905, -0.013920, 0.788210 \end{pmatrix} \]

(iv) The habit plane:
\[ \phi'_1 = (0.477636, -0.621134, 0.621334) \]

(v) The magnitude of the shape strain and its direction:
\[ m_1 = 0.226696 \]
\[ d_1 = \begin{pmatrix} 0.577791 \\ -0.415490 \\ -0.702509 \end{pmatrix} \]

(vi) The angle of the lattice invariant shear:
6°49'

(vii) The austenite/ferrite orientation relationship:
\[ \{111\}_f \ 3°44' \text{ from } \{011\}_a \\
\{101\}_f \ 34' \text{ from } \{111\}_a \]

The austenite/ferrite orientation relationship obtained from this calculation is not that of Kurdjumov-Sachs(10) but rotates about 3.7° around the close packed \{101\}_f // [111]_s direction as shown above. This relationship, however, is very close to the Nishiyama relationship(11) and contradicts with Kelly’s calculation.\(^{11}\) It seems significant that the [111]_s growth direction of the ferrite laths is only 6° from the invariant line.

Table 3. The angles between the reflections obtained by the calculated ferrite/austenite relationship

<table>
<thead>
<tr>
<th>Reflecting zone axis</th>
<th>Planes</th>
<th>The angle expected from the calculated relationship</th>
</tr>
</thead>
<tbody>
<tr>
<td>(735)<em>{a1} // (210)</em>{s2}</td>
<td>(231)<em>{a1} &amp; (123)</em>{a1}, (321)<em>{a1} &amp; (002)</em>{a1}</td>
<td>3°</td>
</tr>
<tr>
<td>(110)<em>{a1} // (115)</em>{s2}</td>
<td>(110)<em>{a1} &amp; (110)</em>{a1}, (002)<em>{a1} &amp; (321)</em>{a1}, (002)<em>{a1} &amp; (231)</em>{a1}</td>
<td>3°, 15.5°, 6°</td>
</tr>
</tbody>
</table>

Using this austenite/ferrite orientation relationship, the angles separating the reflections from a bundle of the ferrite laths shown in Table 2 were calculated, and are illustrated in Table 3. It can be seen that, although they are not the positive evidence for the calculated orientation relationship, at least it is compatible with the observed diffraction patterns. The magnitude of the shape strain and the angle of the lattice invariant shear in this case are quite small as have already been shown by Wechsler et al.,\(^{12}\) and it is reasonable to imagine this reaction to occur.

The calculated habit plane of the ferrite is about 73° from the apparent \{111\}_f habit plane, and this is in keeping with the observation in Photo, 6 where the ferrite laths are consisted of the parallel “sub-laths”. It should be noted that the cementite laths are almost parallel to these ferrite sub-laths, suggesting that the cementite laths were formed at the austenite/ferrite interfaces.

In order to make a comprehensive interpretation of such bainite formation, the austenite/ferrite orientation relationship was projected on a stereograph with the observed ferrite/cementite orientation relationship superposed as shown in Fig. 3. It can be seen that the cementite laths exhibit the (301), habit which lies close to the ferrite sub-laths.

Figure 4 is the schematic representation of the process of the bainite reaction which can be expected from the above crystallographic consideration; i.e., (a) the first stage of the transformation is the ferrite sub-lath formation within the densely faulted austenite (the width of the ferrite sub-laths will be restricted to within the densely faulted region parallel to a \{111\}_f plane\(^*\)), (b) the second stage is the coalescence of the sub-laths leading to the sidewise growth, (c) then the

\* Such as assumption is probably reasonable because of the fact that the partial dislocations which produce the lattice invariant shear are available within the densely faulted area.

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third is the precipitation of the cementite laths at the ferrite sub-lath/austenite interface in contact with austenite, resulting in the Isaichev orientation relationship\(^4\) between ferrite and cementite, and (d) the final stage is the successive formation of such ferrite sub-laths and cementite laths which will produce the bainite lath(B–III) involving the parallel cementite laths within the ferrite.

Although the process of such bainite formation can clearly be seen in Photo, 6, in order to achieve a much more detailed and comprehensive explanation for the frequently observed structures, the sectioning of Fig. 4 (d) is quite useful. For instance, the sectioning (A) in Fig. 4 (d) will give the structure similar in appearance to Photo. 1, while the sectionings (B) and (C) will result in those in Photos. 2 and 3 respectively. Photograph 4 can as well be explained in terms of the sectioning (D).

The mechanism of the cementite precipitation is basically similar to that for the lower bainite where the cementite platelets are thought to form at the ferrite/austenite interphase boundaries.\(^{14,17}\) As suggested by Hultgren,\(^{18}\) austenite will be enriched with carbon during the ferrite formation. At the temperatures as low as the Ms point, however, the carbon atoms will be built up in the vicinity of the ferrite sub-laths in austenite and will precipitate at these interfaces. Thus the local lowering of the carbon concentration in the austenite at the interfaces will provide the driving force for the further formation of the ferrite sub-laths. The habit plane of the cementite laths probably lies close to one of the low surface energy planes between ferrite and cementite, and should be almost parallel to the ferrite/austenite interface. It should be noted that such a situation has really been satisfied in the present observations where the habit plane of the cementite laths is close to the (501)\(a\) // (101)\(a\) plane, and is in keeping with the model described above.

V. Conclusions

The bainite which forms at the vicinity of the Ms temperature in a low-carbon low-alloy steel was investigated by means of transmission electron microscopy and phenomenological analysis has been made following the Bowles–Mackenzie theory.\(^5\)\(^\sim\)\(^8\) The results obtained are given as:

(i) The bainite involving the parallel array of cementite laths is in the shape of lath, and the crystallographic relationships are:

- The ferrite habit plane: \((011)_a // (103)_a\)
- The possible ferrite growth direction: \([111]_a // [010]_a\)
- The cementite habit plane: \((501)_a // (101)_a\)
- The possible cementite growth direction: \([111]_a // [010]_a\)

(ii) The bainite laths are consisted of the much thinner ferrite sub-laths and the cementite laths parallel to these sub-laths.

(iii) The crystallography of this bainite formation can be explained in terms of the phenomenological theory of martensite in a fashion similar to that by Kelly\(^11\) for a Mn–Cr–Ni austenitic stainless steel.

(iv) The cementite is thought to form at the ferrite sub-lath/austenite interphase boundaries within the austenite, resulting in the Isaichev orientation relationship.\(^4\)

Acknowledgements

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REFERENCES


