The Crystallography of the Lower Bainite Transformation in a Plain Carbon Steel*

By Yasuya OHMORI**

Synopsis

The isothermal decomposition of a 0.69% plain carbon austenite into lower bainite was investigated by means of both transmission electron microscopy and two surface trace analysis on suitably prepared specimens.

The habit plane of the bainite plates lay close to the $(496)_f$ which was almost parallel to the $(\bar{1}22)_b$. The cementite observed in ferrite was in the shape of the platelets which were aligned on a specific ferrite plane, and was related to ferrite with the Isaichev orientation relationship. The cementite habit plane was close to the $(213)_b/[(201)_c$ which was about 55° from the bainite habit plane.

Assuming that the lattice invariant shear occurred on the $(1\bar{1}1)_f$ slip plane in the $[\bar{1}01]_f$ direction, the observed habit plane was predicted from the phenomenological theory of martensite; this lead to the ferrite/austenite orientation relationship close to the Kurdjumov-Sachs relationship.

The specific variant of ferrite/cementite orientation relationships observed in the present study was also predicted provided that the austenite lattice transforms into the cementite at the austenite/ferrite interface with the movement of the dislocations introduced by the lattice invariant shear.

I. Introduction

Since Davenport and Bain¹⁾ first observed bainite in plain carbon and low alloy steels, the bainite reaction has been studied extensively. Most of such literatures, however, concern the kinetic aspects or the cementite precipitation in bainite, and little is known about its crystallography. This is because it is difficult to devise a steel which will partially transform to lower bainite, retaining the untransformed austenite at room temperature.²⁾

Recently Srinivasan and Wayman³⁾ surmounted this difficulty by choosing the alloy of composition Fe-7.9%Cr-1.11%C in which M_s temperature was below 0°C , and determined the ferrite/austenite orientation relationship and the habit plane of bainite simultaneously. They analysed the crystallographic results following the phenomenological theory of martensite.

In hypo-eutectoid plain carbon steels, however, as the austenite is not stable below room temperature, it is not possible to determine the ferrite/austenite orientation relationship directly. In this case, the information described below can still be obtained.

(1) Assuming that the habit plane of bainite is unique, the habit plane in austenite can be estimated by measuring the interplanar angles between the bainite plates by means of two surface trace analysis.

(2) The ferrite/cementite orientation relationship can be measured directly by electron diffraction.

(3) If the habit planes of both bainite and cementite are shown in the same stereogram by choosing a specific ferrite/cementite orientation relationship, the crystallographic relationships between them can be revealed.

The aim of the present study was to analyse the experimental results following the Bowles-Mackenzie theory⁴⁾⁻⁶⁾ with particular emphasis on the cementite precipitation in the hope that some features of the lower bainite transformation would come out.

II. Experimental Procedure

1. Specimen Preparation

The commercial plain carbon steel of composition 0.69%C-0.28%Si-0.67%Mn was received as a plate of $7 \times 100 \times 200 \text{ mm}^3$. This plate was hot-rolled into a final thickness of 3 mm sheet and machined into the specimens of $1.5 \times 20 \times 20 \text{ mm}^3$. After austenitizing for 5 min at 1200°C in an argon atmosphere, these specimens were quenched into an alloy bath kept at 300°C for various times to transform partially into lower bainite, and they were subsequently quenched into iced brine to suppress further transformation of the austenite into bainite.

2. Optical Microscopy

Since very little austenite was retained at room temperature, the direct determination of the orientation of an austenite grain by means of X-ray technique was impossible. The interplanar angles between the bainite plates, however, can be measured by the trace analysis on two surfaces inclined nearly at right angles to one another. By assuming the bainite habit plane in austenite is unique, comparison of a set of the observed interplanar angles with those calculated for various planes in austenite will make it possible to anticipate the habit plane.

3. Electron Microscopy

In electron microscopy, both two stage replica and thin foil techniques were used. Replicas were taken from the etched specimens which had transformed partially into bainite (the untransformed austenite having decomposed into martensite during subsequent quench). In this way, the bainite/austenite (*i.e.* bainite/martensite) interface was put to observation as it had advanced.

The determinations of the cementite/ferrite orientation relationship and the habit planes of cementite and bainite were carried out by means of transmission electron microscopy. For this purpose, sheet samples were chemically polished down to about 0.1 mm in a solution of 73% H_2O , 25% H_2O_2 , and 2% HF ,⁷⁾ and the final polishing was achieved by the Bollmann technique⁸⁾ using the chromic acid-phosphoric acid electrolyte.

* Received September 5, 1970.

** Central Research Laboratories, Sumitomo Metal Industries, Ltd., Amagasaki 660.

Replicas and thin-foils were examined in a JEM-5Y microscope operating at 100 kV and a HU-200 microscope operating at 200 kV respectively.

III. Experimental Results

Photograph 1 shows the composite optical micrograph of typical bainite plates on two adjacent surfaces inclined at about 90° to one another, and it can be seen that the lower bainite is in the shape of plates. The interplanar angles between the plates on such micrographs were compared with those between like planes in austenite lattice. In this analysis, the uniqueness of the bainite habit plane was assumed. The best fit with the experimental values was found to be $(0.368355, 0.773545, 0.515697)_f$ as shown in Table 1. The error involved in this analysis would be less than 3° , for 3° tilt of the calculated plane gave a completely different set of the interplanar angles from the experimental values.

The structure observed in a replica is shown in Photo. 2. This is typical of a lower bainite and consists of the ferrite plates which were filled with the cementite platelets precipitated on a specific ferrite plane. It should be noted that the cementite was formed at the ferrite/austenite boundary and was not proceeded by the formation of ferrite.

Photograph 3 (a) shows the transmission electron micrograph of the lower bainite plate with its habit plane being nearly parallel to the foil surface, and the parallel rows of cementite platelets can be clearly seen. The electron diffraction pattern associated with Photo. 3 (a) and its schematic representation are in Photos. 3 (b) and (c), and the reflecting zone axis in this case is $[4\bar{5}2]_b$. The stereographic analysis of the diffraction pattern (Fig. 1 (p. 98)) shows that the orientation relationship is close to that of Bagaryatskii;⁹⁾

$$(100)_c // (110)_b$$

$$(010)_c // (\bar{1}11)_b$$

$$(001)_c // (\bar{1}12)_b$$

and that the great circle that is the cementite trace

Photo. 1. Two surface composite optical micrograph of lower bainite

normal passes through $(\bar{2}31)_b$, which is close to $(\bar{2}01)_c$. In this diffraction pattern, however, the $(123)_b$ plane is not 7.5° from the $(111)_c$ plane, but 5° apart on the reflecting zone. As a result, the Bagaryatskii orientation relationship⁹⁾ is not exactly satisfied.

The shape of the cementite particles, although it appeared to be lath-like in many cases, was confirmed to be platelets in observing the bainite in the direction nearly perpendicular to the cementite habit plane as shown in Photo. 4 (a). The diffraction pattern and its schematic representation are in Photos. 4 (b) and (c). The dark field micrograph using the $(121)_c$ reflection revealed that all the cementite platelets were in the same orientation (Photo. 4 (d)). This diffraction pattern also gives the orientation relationship close to that of Bagaryatskii⁹⁾ (Photo. 4 (c)). In this case, however, the $(12\bar{1})_c$ and $(110)_b$ cannot be separated, and the $(112)_b$ is about 0.7° apart from the $(001)_c$. This also indicates that the cementite/ferrite orientation relationship slightly deviates from that of Bagaryatskii.⁹⁾ In Photo. 4 (b), the streaks of the cementite reflections parallel to the $[001]_c$ direction are

Table 1. Determination of the habit plane of lower bainite by the interplanar angle measurements between plates

Calculated values for $(0.368355, 0.773545, 0.515697)_f$ (degrees)	Experimental values (degrees)
12.0	
21.0	
29.1	27.1, 28.3
32.4	
42.8	
43.2	
48.5	46.6
53.2	52.6, 53.0, 53.5
60.4	57.6, 58.5
62.1	62.0
72.3	71.9
74.6	74.9
77.4	77.2
78.6	79.5, 79.6, 79.8
82.2	82.8
85.5

Photo. 2. Bainite/austenite interface

Bagaryatskii⁹⁾ or the Isaichev orientation relationship.¹⁰⁾ Much better agreement can be obtained by the Isaichev orientation relationship,¹⁰⁾ i.e.,

$$\begin{aligned} (010)_c // (\bar{1}\bar{1}\bar{1})_b \\ (103)_c // (101)_b. \end{aligned}$$

As previously mentioned, the habit plane of the bainite in austenite could be determined, but it is equally important to obtain the relationship between the bainite and the cementite habits. Therefore, simultaneous trace analyses for both were carried out in the same $(011)_b$ stereogram by transforming the coordinates so as to achieve the following ferrite/cementite orientation relationship;

Fig. 1. Stereographic analysis of the diffraction pattern shown in Photo. 3 (a)

$$\begin{aligned} (010)_c // (\bar{1}\bar{1}\bar{1})_b \\ (103)_c // (011)_b. \end{aligned}$$

In Fig. 2, it can be seen that the bainite habit plane lies close to the $(\bar{1}22)_b$, while the cementite habit is almost parallel to the $(213)_b$. As the angle separating the $(213)_b$ and the $(\bar{1}22)_b$ is 57.7° , the cementite habit plane inclines about 55° to the bainite habit plane.

Photo. 5. (a) An example of the diffraction patterns showing the Isaichev orientation relationship
(b) Its schematic representation

Table 2. Comparison of the experimental and theoretical separations of the reflections of cementite and ferrite

Plate number	Reflecting zone axis	Approximate orientation relationship	Planes	Angles (degrees)		
				Exp.	Theor.	
					Bag.	Isai.
EO1460	$[4\bar{5}2]_b$	$(100)_c // (110)_b$	$(111)_c$ & $(123)_b$	5.0	7.5	5.0
		$(010)_c // (\bar{1}\bar{1}\bar{1})_b$	$(2\bar{1}\bar{1})_c$ & $(32\bar{1})_b$	9.0	12.0	9.0
		$(001)_c // (\bar{1}\bar{1}\bar{2})_b$				
EO1663	$[\bar{1}13]_b$	$(100)_c // (011)_b$	$(\bar{1}\bar{2}1)_c$ & $(\bar{1}\bar{1}0)_b$	0	1.5	0
		$(010)_c // (\bar{1}\bar{1}\bar{1})_b$	$(001)_c$ & $(2\bar{1}\bar{1})_b$	0.7	0	1.0
		$(001)_c // (2\bar{1}\bar{1})_b$				
EO1681	$[3\bar{3}\bar{1}]_b$	$(100)_c // (110)_b$	$(100)_c$ & $(110)_b$	3.0	0	3.4
		$(010)_c // (\bar{1}\bar{1}\bar{1})_b$	$(313)_c$ & $(323)_b$	3.0	5.5	2.5
		$(001)_c // (\bar{1}\bar{1}\bar{2})_b$				
EO1679	$[3\bar{9}\bar{1}]_b$	$(100)_c // (10\bar{1})_b$	$(\bar{2}10)_c$ & $(\bar{2}\bar{1}3)_b$	11.5	9.5	11.5
		$(010)_c // (\bar{1}\bar{1}\bar{1})_b$	$(\bar{1}\bar{2}2)_c$ & $(103)_b$	5.0	3.0	5.0
		$(001)_c // (\bar{1}\bar{2}\bar{1})_b$

Fig. 2. The habit planes of the lower bainite plates and cementite platelets

IV. Crystallographic Analysis and Discussion

1. The Habit Plane of the Lower Bainite

The lower bainite which was formed at 300°C in the 0.69% carbon steel was plate-like, and the direction cosines of the habit plane normal were (0.368355, 0.773545, 0.515697)_f which nearly correspond to the rational (496)_f. It is interesting to note that this plane lies only 1°12' from the habit plane of the lower bainite in a high purity 0.81% C-Fe binary alloy, its direction cosines being (0.35398, 0.76991, 0.53099)_f.¹¹⁾ Therefore, it seems likely that the lower bainite in the present alloy formed in the same way as that in the pure Fe-C alloy.

2. Application of the Bowles-Mackenzie Theory¹²⁾

Although the Bowles-Mackenzie theory was developed initially for martensite transformation, it is now widely accepted that it is also valid for lower bainite transformation. However, as can be seen in the analysis by Bowles and Kennon,¹³⁾ the present habit plane is not to be predicted if a twinning shear on (101)_f // (112)_b is taken as the inhomogeneous shear, but they did suggest that lower bainite habit could be determined by adopting the hypothesis that the direction of the lattice invariant shear is the [110]_f and the shear plane is any plane in the zone of this direction.

The present analysis has followed the same line of argument, then the variant of the Bain correspondences was;

$$(b\bar{c}f) = \begin{bmatrix} 1\bar{1}0 \\ 110 \\ 001 \end{bmatrix}.$$

Since the present habit plane is very close to that of Fe-C alloy, it will be possible to analyse the results by

assuming a double shear on the (1 $\bar{1}$ 1)_f and (101)_f as having been done in the previous analysis.¹¹⁾ The close examination of the Bowles-Kennon analysis,¹³⁾ however, indicates that a good agreement with the experimental values can also be given by choosing a single slip on the (1 $\bar{1}$ 1)_f with $\theta^2 = \delta^2(a/a_0)^2 = 0.63$, where δ is the isotropic dilatation, a and a_0 are the lattice parameters of the bainite and the austenite respectively, and using the following lattice invariant shear elements;

$$\underline{d}_2 = \frac{1}{\sqrt{2}}[\bar{1}01]_f, \quad \underline{p}'_2 = \frac{1}{\sqrt{3}}(1\bar{1}1)_f.$$

The hypothesis of this slip is consistent with the present experiment in which no evidence of twinning was observed. The results of the matrix calculations are given as;

$$X_1 = \begin{bmatrix} -0.757644 \\ -0.115228 \\ 0.642416 \end{bmatrix},$$

the invariant line,

$$n'_1 = (0.509902, 0.692820, 0.509902)_f,$$

the invariant normal,

$$(f\bar{s}f) = \begin{bmatrix} 1.108545, & -0.060886, & 0.117093 \\ 0.045560, & 1.116594, & 0.074646 \\ -0.170449, & -0.097531, & 0.781484 \end{bmatrix},$$

the shape strain, and

$$\underline{p}'_1 = (0.331253, 0.780205, 0.530615)_f,$$

the habit plane.

This is only 2°23' away from the experimental habit plane. The magnitude and the direction of the shape strain are;

$$m_1 = 0.285052$$

$$\underline{d}_1 = \begin{bmatrix} 0.150418 \\ 0.511818 \\ -0.845824 \end{bmatrix}_f$$

and the angle of the inhomogeneous shear is obtained to be 4°16'. These values are not unreasonable compared with those obtained by Srinivasan and Wayman³⁾ for the lower bainite in the Fe-Cr-C alloy.

The angles between the (111)_f and the (011)_b, and between the [101]_f and the [1 $\bar{1}$ 1]_b were calculated to be 0.53° and 1.68° respectively and this is close enough to the Kurdjumow-Sachs orientation relationship¹⁴⁾ and is in good agreement with the numerous observations which showed the lower bainite being related to the parent austenite with the Kurdjumow-Sachs orientation relationship.

This orientation relationship is demonstrated in a stereogram (Fig. 3) where the habit plane, and the direction and plane of the lattice invariant shear are shown simultaneously. It can be seen that the bainite habit plane lies close to the (122)_b and this is keeping with the results obtained by the single surface trace analysis (see Fig. 2).

It is interesting to note that the present calculations

should be considered. If we examine the similarity between austenite and cementite lattices, it can be seen that the stacking of the $(111)_f$ austenite planes is A, B, C, A, B, C, . . . , whereas the $(100)_c$ cementite plane is A, B, A, B, A, B, Therefore the sweeps of the $\frac{1}{6}[\bar{1}12]_f$ partial dislocations on every successive two $(1\bar{1}1)_f$ layers will produce a crystal structure similar to that of cementite.

It is interesting to note that the Burgers vector and the slip plane of the dislocations introduced as the inhomogeneous shear are $\frac{1}{2}[\bar{1}01]_f$ and $(1\bar{1}1)_f$. This $\frac{1}{2}[\bar{1}01]_f$ dislocation can split into the two $\frac{1}{6}[\bar{2}\bar{1}1]_f$ and $\frac{1}{6}[\bar{1}\bar{1}2]_f$ partials on the $(1\bar{1}1)_f$ inhomogeneous shear plane with the stacking fault between them, and the cementite in the former orientation relationship with the habit close to the $(1\bar{1}1)_f$ should be obtained.

However, as the dimensional misfit between the $(1\bar{1}1)_f$ and the $(100)_c$ is rather large along the $[121]_f$ direction, the surface energy on the cementite/austenite interface can be reduced by rotating the cementite habit plane about the $[101]_f/[010]_c$, resulting in the $(213)_b/(201)_c$ habit (see Fig. 2).

The streaks of the cementite reflections in the $[001]_c$ direction show that the cementite is either very thin in this direction or some faults exist on the $(001)_c$ plane. Since the cementite habit plane was close to the $(201)_c$, it would not be thin in the $[001]_c$ direction, but it seems likely that the stacking faults in cementite produced the elongation of the reciprocal lattices.

As described above in some detail, the results of the present study can be interpreted consistently with the crystallography and support the validity of the phenomenological theory of martensite for analysing bainite.

V. Conclusions

The formation of the lower bainite in a plain carbon steel was investigated mainly by means of transmission electron microscopy, and the following conclusions were drawn.

(1) The habit plane of the lower bainite is irrational and is nearly parallel to the $(496)_f/(\bar{1}22)_b$.

(2) The cementite is related to ferrite with a specific variant of the Isaichev orientation relationship¹⁰⁾ rather than that due to Bagaryatskii.⁹⁾

(3) The habit plane of cementite platelets lies

close to the $(213)_b/(201)_c$ and is about 55° from that of the bainite.

(4) These crystallographic results can be explained in terms of the phenomenological theory of martensite assuming that the inhomogeneous shear occurs on the $(1\bar{1}1)_f$ slip plane with the $[\bar{1}01]_f$ shear direction.

(5) The ferrite/cementite orientation relationship can also be predicted if the cementite lattice is formed in austenite epitaxially on the ferrite surface by the movements of dislocations which are introduced by the inhomogeneous shear.

Acknowledgements

The author is indebted to Dr. M. Sumitomo for allowing him to publish this study and wishes to thank Dr. E. Miyoshi and Dr. T. Kunitake for their encouragements through the course of this work. Thanks are also due to Dr. T. Shiraiwa for providing the facility of electron microscopy.

REFERENCES

- 1) E. S. Davenport and E. C. Bain: *Trans. AIME*, **90** (1930), 117.
- 2) D. N. Shackleton and P. M. Kelly: *Acta Met.*, **15** (1967), 979.
- 3) G. R. Srinivasan and C. M. Wayman: *Acta Met.*, **16** (1968), 621.
- 4) J. S. Bowles and J. K. Mackenzie: *Acta Met.*, **2** (1954), 129.
- 5) J. K. Mackenzie and J. S. Bowles: *Acta Met.*, **2** (1954), 138.
- 6) J. S. Bowles and J. K. Mackenzie: *Acta Met.*, **2** (1954), 224.
- 7) F. Terasaki and A. Yoshikawa: *Kinzoku Butsuri*, **9** (1963), 125.
- 8) W. Bollmann: *Phys. Review*, **103** (1956), 1588.
- 9) A. Bagaryatskii: *Dokl. Akad. Nauk S.S.S.R.*, **73** (1950), 1161.
- 10) I. V. Isaichev: *Zhur. Tekhn. Fiziki*, **17** (1947), 835.
- 11) Y. Ohmori: Ph. D. Thesis, University of Cambridge, (1969).
- 12) C. M. Wayman: Introduction to the Crystallography of Martensitic Transformations, (1964), MacMillan.
- 13) J. S. Bowles and N. F. Kennon: *J. Aust. Inst. Metals*, **5** (1960), 106.
- 14) G. V. Kurdjumov and G. Sachs: *Z. Phys.*, **64** (1930), 325.
- 15) F. B. Pickering: Symposium "Transformation and Hardenability in Steels" Michigan (1967), 109.
- 16) K. W. Andrews: *Acta Met.*, **11** (1963), 939.
- 17) W. Pitsch: *Arch. Eisenhütt.*, **34** (1963), 641.
- 18) C. Zener: *Trans. AIME*, **167** (1946), 550.