

Morphology and Crystallography of Plate-like Lower Bainite in Fe–C Alloys

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Steels can have a variety of microstructures with different mechanical properties by selecting alloying elements and heat treatments. Bainite, which has attracted attention in recent years as a hard microstructure, has several types of microstructures and the microstructure types vary with transformation temperature. In particular, it is known that plate-like bainitic ferrites appear instead of lath-like bainitic ferrites when held between 573 K and the martensitic transformation start temperature. The microstructure change of the plate-like bainite (henceforth plate-like lower bainite) with carbon content or transformation temperature has not been studied systematically. The aim of this study is to characterise the microstructure of the plate-like lower bainite and the effect of carbon on the microstructure using Fe–C alloys.

The compositions of the specimens are from 0.6 to 1.4 mass% C. These specimens were heat-treated at temperatures ranging from 523 K to 573 K after austenitisation, followed by water cooling. These specimens were observed by optical and scanning electron microscopy, and their crystal orientations were analysed using the electron backscatter diffraction analysis method.

Microstructure observations and crystallographic analysis showed that plate-like lower bainite contains a packet and block structure within the prior austenite grains, similar to lath martensite and lath-like bainite. The most frequently observed crystallographic orientation relationship is the one being 20° away from the twin orientation relationship, *i.e.* V1/V6 relationship. The paired variants compose a microstructure unit and the bundled bainitic plates have similar long directions. The morphology of the interface was also found to be different from that of lath martensite and upper bainite. The variant pairing and paired block morphology including interface shapes are considered to be the distinct features of plate-like lower bainite.

Keywords: bainite, microstructure, EBSD, crystallography, steels

1. Introduction

Recently, steel has been required to have even higher strength in the field of transport equipment and buildings. Due to such requirements, the rapid cooling microstructures of steel materials have been focused on. While lath martensite and upper bainite have been applied to commercial steels, platelet bainite (hereafter plate-like lower bainite), which is formed at low temperatures in high carbon steels, has been characterised. However, the focuses were on the internal structure of bainitic plates or orientation relationships between bainitic ferrite and carbide/austenite¹⁻³). Hence, there are few studies on the morphology and orientation relationships between neighbouring bainitic plates⁴⁻⁶).

This article aims to characterise the microstructure of plate-like lower bainite and to clarify the carbon effect in Fe–C alloys using crystallographic analysis methods.

2. Experiment

Three iron-carbon binary alloys as shown in Table 1 were used for the study. These specimens were austenitised by holding at 1273 or 1373 K and were isothermally treated at 523 or 573 K. Finally, the specimens were cooled by water. Optical microscopy was performed on the obtained specimens to confirm that they were fully plate-like lower bainite; the prior austenite grain sizes of the Fe–0.6C, Fe–1.0C and Fe–1.4C specimens were 265, 282 and 308 μm in circular equivalent diameter, respectively. Scanning electron microscope (SEM) observations and crystallographic measurements using an electron backscatter diffraction (EBSD) analysis were carried out on these specimens to

analyse the microstructure. The orientation maps were processed by the so-called austenite reconstruction method, and bainitic ferrite orientations were labelled by their crystallographic variants. The orientation relationships of the variants and the variant grain morphologies were analysed using the variant maps⁷).

Table 1 Chemical compositions of the specimens.

Specimen	Fe	C	Mn	Si	P	S
Fe–0.6C	Bal.	0.61	0.01	0.014	0.001	0.005
Fe–1.0C	Bal.	1.06	<0.003	0.01	<0.002	0.0005
Fe–1.4C	Bal.	1.42	<0.01	<0.01	0.001	0.003

3. Results and Discussion

Figure 1 shows the crystal orientation maps obtained from the EBSD measurements. It can be seen that in all specimens, plate-like single-crystal regions (hereafter bainite plates) are formed side by side. The bainite plates are aligned, which correspond to blocks of lath martensite and upper bainite. The bainite plates clearly show a unit, which is similar to the packet of lath martensite and upper bainite.

Several blocks are bundled and have similar long directions, although the long directions are not the same. In a set of blocks, there are two types of crystal orientations and long directions; the blocks are paired and the paired blocks compose a microstructure unit. The interface of the block pairs is locally flat. The flat faces are connected by smaller side faces, which have a different direction from the flat faces. The variant pairs and interface morphology are not observed in the lath martensite or upper bainite

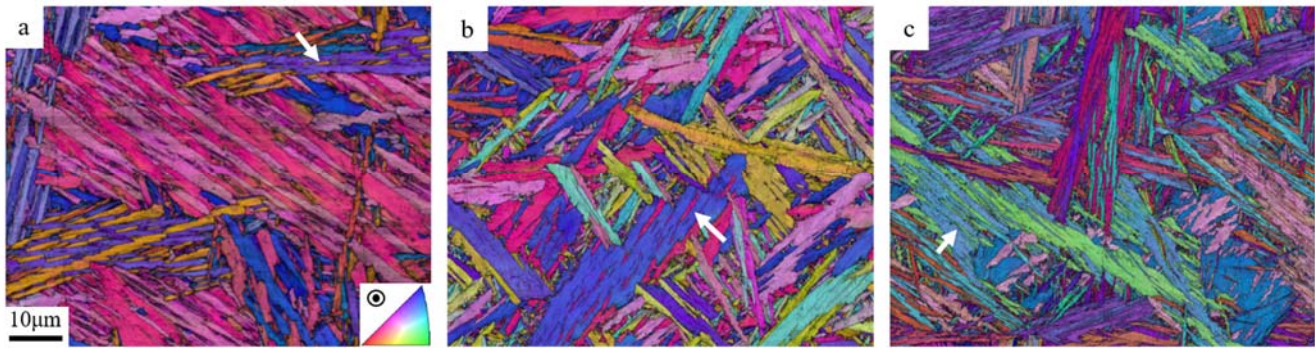


Fig. 1 Crystal orientation maps of (a) Fe-0.6C, (b) Fe-1.0C and (c) Fe-1.4C specimens overlaid with grey-scaled image quality maps. Colours correspond to crystal orientations parallel to the normal direction of the surface.

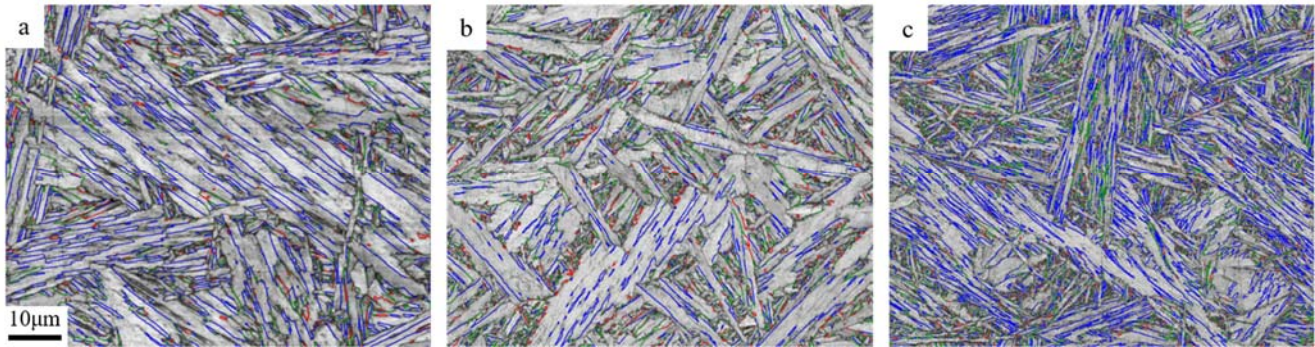


Fig. 2 Grey-scaled image quality maps large-angle block boundaries of (a) Fe-0.6C, (b) Fe-1.0C and (c) Fe-1.4C specimens. Red, green and blue lines indicate V1/V2, V1/(V3 or V5) and V1/V6 block boundaries, respectively.

microstructure. In the block pairs, small and fragmented blocks are observed in larger blocks as shown by the arrows in Fig. 1. The area densities of the small blocks are increased by the carbon addition.

The boundary maps, which correspond to Figs. 1a, 1b, and 1c, are shown in Figs. 2a, 2b, and 2c, respectively. The boundaries indicate three types of block boundaries corresponding to the large-angle block boundaries, and the crystal orientation relationships of the block boundaries are indicated by colours. Red, green and blue lines correspond to V1/V2, V1/(V3 or V5) and V1/V6 relationships according to the variant number in Ref. 8. The V1/V2, V1/(V3 or V5) and V1/V6 relationships correspond to the "near twin" orientation relationships, which are deviated from the twin orientation relationship (60° about [111]) by about 0° , 10° and 20° , respectively. The crystal orientation relationship between these blocks was investigated and revealed that they have a crystallographic orientation relationship of about 20° away from the twin orientation relationship and the paired variants compose a unit, as noted in Refs. 4 and 5. Lath martensite has a similar morphology to plate-like lower bainite, but the characteristic inter-block orientation relationship of lath martensite is close to the twin relationship. The blocks tended to become thinner with increasing solid solute carbon content and decreasing transformation temperature, but there was no significant change in the inter-block orientation relationships. The shape and adjacent tendency of blocks described above can be considered essential features of plate-like lower bainite.

4. Conclusions

The microstructural characteristics of the plate-like lower bainite in high carbon steels with carbon content from 0.6 to 1.4 were analysed from crystallographic viewpoints. From the results, the following were clarified.

1. Plate-like lower bainite has a block and packet structure similar to lath martensite.
2. The blocks in the packet tend to have a crystallographic orientation relationship of about 20° away from the twin orientation relationship, *i.e.* V1/V6.
3. The bundled blocks make up a microstructure unit and the set of blocks is composed of V1 and V6.
4. The block sizes are decreased with increasing carbon content.

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