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Variant selection in grain boundary nucleation of bainite in Fe-2Mn-C alloys

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ABSTRACT

The effects of transformation temperature and carbon content on variant selection of bainite structure in Fe-2mass%Mn-C alloys with carbon content ranging from 0.2 to 0.75 mass% were investigated at transformation temperatures between 673 and 773 K. Single variant of bainitic ferrite (BF) was nucleated at the austenite grain boundaries in all the alloys transformed at 773 K and the 0.2 mass% C alloy transformed at 673 K. Multiple variants tended to be selected in nucleation at γ grain boundaries with increasing carbon content at 673 K. Variant selection rules in the nucleation of BF at γ grain boundaries were analyzed with respect to (1) a near Kurdjumov-Sachs (K-S) orientation relationship with both sides of austenite grains, parallel relationships of (2) growth direction and (3) habit plane to austenite grain boundary plane, and (4) plastic accommodation of transformation strain. The analyses revealed that rule (1) is the strongest among the rules investigated, and the fraction of BF that satisfies rule (1) is higher at lower carbon content and higher transformation temperature. The fractions of BF that satisfy rule (2) are low under all the conditions investigated, while the effects of rule (3) and (4) increase at higher carbon content. The variant selection rules observed indicate that higher austenite strength with higher carbon alloys results in different variant selection from those that appear in low carbon steel and also result in an enhancement of self-accommodation.

1. Introduction

The bainite structure has been widely used recently for various types of high strength steels, such as transformation induced plasticity (TRIP) steels and low-carbon welding steels for automobiles, buildings, linepipes or ships, and medium carbon spring steels. The good balance of strength and toughness of such steels relies on a fine ferrite structure that contains a high density of dislocations and fine cementite particles.

Bainitic ferrite (BF) holds a near Kurdjumov-Sachs (K-S) orientation relationship (OR) ($(111)_{fcc}//(011)_{bcc}$, $[-101]_{fcc}//[-1-11]_{bcc}$) with the prior austenite (γ) [1,2]. As a result, twenty-four equivalent orientations (variants) of BF can be formed in a single γ grain. The twenty-four K–S variants and inter-variant misorientations between variant 1 (V1) and other variants are shown in Table 1 [3–5]. 24 variants are divided into four close-packed planes parallel groups (CP groups), each of which consist of six variants that share the same parallel relation of close-packed planes in the K-S OR. On the other hand, the twenty-four variants are classified into three distinctive groups that share the same Bain lattice correspondence (Bain groups) [6]. The pairing of specific variants results in the division of one prior γ grain by hierarchical structures such as packets and blocks in the upper bainite structure. The upper bainite is defined as lath-shaped bainitic ferrite, according to the classification by Ohmori et al. [7], and is transformed typically at temperatures ranging from 873 to 673 K. The packet is composed of variants that belong to the same CP group and is further subdivided by blocks that consist of lathes with almost the same crystal orientation. It is supposed that the block, packet and prior γ grain boundaries are high-angle, and those boundaries impede slip deformation and crack propagation [8–12]. Therefore, understanding of the complicated crystallographic structure of bainite is a key to control the mechanical properties of bainite steels.

The crystallography of bainite structure has been well characterized using electron backscatter diffraction (EBSD) technique [5,13,14]. Variants belonging to the same CP group have been reported to form adjacently at lower transformation temperatures,

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Table 1
24 variants in the K-S orientation relationship and their numbers for CP and Bain groups.

Variant no.	Plane parallel	Directional parallel	CP group	Bain group	Misorientation from V1 [deg.]
V1	(111)γ//(011)α	[−101]γ//[−1−11]α	CP1	B1	–
V2		[−101]γ//[−11−1]α		B2	60.0
V3		[01−1]γ//[−1−11]α		B3	60.0
V4		[01−1]γ//[−11−1]α		B1	10.5
V5		[1−10]γ//[−1−11]α		B2	60.0
V6		[1−10]γ//[−11−1]α		B3	49.5
V7	(1−11)γ//(011)α	[10−1]γ//[−1−11]α	CP2	B2	49.5
V8		[10−1]γ//[−11−1]α		B1	10.5
V9		[−1−10]γ//[−1−11]α		B3	50.5
V10		[−1−10]γ//[−11−1]α		B2	50.5
V11		[011]γ//[−1−11]α		B1	14.9
V12		[011]γ//[−11−1]α		B3	57.2
V13	(−111)γ//(011)α	[0−11]γ//[−1−11]α	CP3	B1	14.9
V14		[0−11]γ//[−11−1]α		B3	50.5
V15		[−10−1]γ//[−1−11]α		B2	57.2
V16		[−10−1]γ//[−11−1]α		B1	20.6
V17		[110]γ//[−1−11]α		B3	51.7
V18		[110]γ//[−11−1]α		B2	47.1
V19	(11−1)γ//(011)α	[−110]γ//[−1−11]α	CP4	B3	50.5
V20		[−110]γ//[−11−1]α		B2	57.2
V21		[0−1−1]γ//[−1−11]α		B1	20.6
V22		[0−1−1]γ//[−11−1]α		B3	47.1
V23		[101]γ//[−1−11]α		B2	57.2
V24		[101]γ//[−11−1]α		B1	21.1

faster cooling rates or lower carbon contents, which leads to the formation of fine bainite structures [5,13,14]. On the other hand, variants that belong to the same Bain group tend to form as a group at higher transformation temperatures, slower cooling rates or higher carbon contents, which results in the formation of relatively coarse bainite structures with smaller misorientation between intra-Bain variants [5,13,14]. γ grain boundaries are generally the preferential nucleation sites of BF in upper bainite structure; therefore, Furuhara et al. [14] investigated variants of BF nucleated at γ grain boundaries and showed that variant selection is enhanced at higher transformation temperatures due to less driving force, which results in the formation of the coarse bainite structure. Furthermore, they analyzed four variant selection rules for BF nucleation at the γ boundary, as shown in Fig. 1; (rule 1) near the K-S orientation relationship with both sides of the austenite grain, parallel relationships of (rule 2) growth direction and (rule 3) habit plane to the austenite grain boundary plane, and (rule 4) plastic accommodation of transformation strain. They determined that variants of BFs nucleated at γ grain boundaries in an Fe-9Ni-0.15C alloy tend to have smaller misorientation from the K-S OR with respect to the γ grain into which BF does not grow (rule 1), or have growth direction closer to the γ grain boundary plane (rule 3) than the other variants [15]. They supposed that the former and latter rules resulted from lower BF/γ interfacial energy and elimination of the larger grain boundary area during the nucleation of BF, respectively, which resulted in smaller activation energy for nucleation than for other variants [15]. The same variant selection rules were reported in the nucleation of martensite lath at prior γ grain boundaries in an Fe-20Ni-5Mn alloy [16]. It was also presumed that stronger variant selection causes coarsening of BF at higher carbon content due to the smaller driving force [15].

Nakashima [17] recently investigated the block size of the bainite structure in Fe-C-Mn based alloys with equivalent carbon contents (%C+%Mn/6) for hardenability fixed at 0.36% by adjustment of both the carbon and Mn contents to reduce the difference in the driving force for bainite transformation. The block size decreased with an increase in the carbon content, unlike the previous study where the block width increased at higher carbon content in an Fe-9Ni-C alloy [14]. It was thus supposed that the variant selection was weakened by self-accommodation at higher carbon content due to higher γ strength, which resulted in less plastic accommodation in γ. However, the effect of carbon content on the variant selection of BF has not been investigated in detail to date.

Therefore, the present study aims to clarify the effects of carbon content and the transformation temperature on the variant selection of BF in nucleation at γ grain boundaries using Fe-2Mn-C alloys, which are the model alloys of practically important low-alloyed steels.

2. Experimental procedure

Three Fe-2mass%Mn-C alloys containing 0.2, 0.35 and 0.75 mass %C were used in this study. After homogenization at 1453 K for 86.4 ks, the alloys was austenitized at 1273–1523 K for 1.8 ks to obtain a γ grain size of approximately 200 μm, subsequently transformed isothermally in a salt bath at 773 or 673 K for various periods of time to obtain the bainite structure, and then quenched into water. The specimens were cut, and then mechanically and electrochemically polished in a solution of 30 mL $HClO_4$ + 470 mL C_2H_5OH. Microstructural characterization was conducted using optical microscopy (OM) after being etched with 2% Nital solution. EBSD measurements were performed for non-etched specimens in a scanning electron microscope (SEM; JSM-7001F, Jeol) equipped with an EBSD system at an accelerating voltage of 25 keV.

To analyze the variant selection rules at γ grain boundaries, the orientation of a given γ grain boundary was determined from traces on two different planes, as shown in Fig. 2(a) [18]. In this analysis, after measurement of the α orientation map for BF nucleated at prior γ grain boundaries (Fig. 2(b)), a cross-sectional plane perpendicular to both the sample surface and the grain boundary trace was prepared using focused ion beam (FIB) milling. Fig. 2(c) shows that it is possible to determine the γ grain boundary plane from traces on the sample surface and the cross-section made by FIB. The accuracy was confirmed by measuring the orientation of the annealing $\{111\}_{fcc}$ twin boundaries in an austenite-stabilized Fe-25mass%Ni-0.5mass%C alloy. The pole figure in Fig. 3 shows that the errors in the determination of the $\{111\}_{fcc}$ twin plane are within 5° in most cases. In addition, the orientations of parent γ grains are determined from bainite or martensite orientations