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The analysis of bainitic ferrite microstructure in microalloyed plate steels through quantitative characterization of intervariant boundaries

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ABSTRACT

Electron backscatter diffraction (EBSD) measurements were performed to investigate the bainitic ferrite microstructure in low-carbon, microalloyed steels with varying C and Mn contents. Fully austenitized samples were isothermally heat treated at temperatures ranging from 450 to 550 °C to form bainitic ferrite. The bainitic ferrite microstructures and boundary characteristics obtained from the EBSD measurements were analyzed based on an inferred Kurdjumov-Sachs (K-S) orientation relationship. The heat treated samples exhibit a microstructure composed of laths and the lath aspect ratio tends to increase at lower isothermal heat treatment temperatures. High fractions of boundary misorientation angles below 5° are observed, which are due to lath boundaries in the microstructure. Additionally, misorientations of approximately 7°, 53° and 60° are observed, which are related to the sub-block, packet, and block boundaries, respectively. With decreasing isothermal heat treatment temperature, there is an increase of block boundaries; these boundaries are intervariant boundaries between different blocks within a packet, most of which have the misorientation angle of 60°. The specimens with a higher carbon level contained increased length of block boundaries, whereas the addition of Mn moderated the dependence of block boundary length on the heat treatment temperature within the experimental temperature range. Meanwhile, the length of intervariant boundaries of both packet and sub-block character did not vary much with heat treatment temperature and alloy composition.

1. Introduction

Steels for linepipe applications are designed to obtain a combination of high strength, exceptional toughness and suitable weldability. The application of low temperature transformation products, such as bainitic ferrite and martensite, to the microstructure of linepipe steels provides an opportunity to increase their strength. Bainitic microstructures have been commonly used in recently developed linepipe steels to obtain mechanical properties prescribed by American Petroleum Institute (API) product specification levels such as X70 and X80 [1,2].

Bainite exhibits complex substructures [3,4]. Similar to martensite microstructures, one of the characteristics of the bainitic ferrite phase transformation is believed to be the lattice correspondence between prior austenite and the bainitic ferrite [4–7]. The associated crystallographic orientation relationship between the two phases makes it possible to analyze the complex substructure of the bainite.

Both the Kurdjumov–Sachs (K–S) and Nishiyama–Wasserman (N–W) orientation relationships are frequently used to describe the austenite to bainitic ferrite crystallographic relationship [8–13]. Furuhara et al. [9] used the K-S orientation relationship for analysis of upper bainite in Fe-9Ni alloys with varying carbon content, and other studies have considered the K-S orientation relationship for the analysis of bainitic ferrite microstructures in steels of differing composition [10,11]. Meanwhile, Gong et al. [12] and Beladi et al. [13] applied the N-W orientation relationship to EBSD results obtained from a high-carbon, vanadium-containing nanobainitic steel. Experimentally measured orientation relationships between prior austenite and bainitic ferrite estimated using the angles between close-packed planes and close-packed directions of the two phases deviated similarly from both the K-S and N-W orientation relationships [7]. As discussed below, the K-S orientation relationship was applicable in the present study.

The crystallographic details related to the 24 variants of the K-S

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Table 1
Twenty-four variants based on the K-S orientation relationship and the intervariant boundary characteristics [10,14,15].

Var. No.	Plane Parallel	Direction Parallel	Close-packed Plane (CPP) Group	Bain Group / Correspondence	Misorientation from V1	Boundary Type
V1	$(111)_\gamma//(011)_\alpha$	$[\bar{1}01]_\gamma//[\bar{1}\,\bar{1}\,1]_\alpha$	CPP1	B1 / $[001]_\gamma$	–	–
V2		$[\bar{1}01]_\gamma//[\bar{1}\,1\,\bar{1}]_\alpha$		B2 / $[0,0,1]_\gamma$	60.00°/$[11\bar{1}]$	Block
V3		$[01\bar{1}]_\gamma$ // $[\bar{1}\,\bar{1}\,1]_\alpha$		B3/$[010]_\gamma$	60.00°/$[011]$	Block
V4		$[01\bar{1}]_\gamma//[\bar{1}\,1\,\bar{1}]_\alpha$		B1 / $[001]_\gamma$	10.53°/$[0\bar{1}\,\bar{1}]$	Sub-block
V5		$[1\bar{1}0]_\gamma//[\bar{1}\,\bar{1}\,1]_\alpha$		B2 / $[0,0,1]_\gamma$	60.00°/$[0\bar{1}\,\bar{1}]$	Block
V6		$[1\bar{1}0]_\gamma$ // $[\bar{1}\,1\,\bar{1}]_\alpha$		B3 / $[010]_\gamma$	49.47° / $[011]$	Block
V7	$(1\bar{1}\,1)_\gamma//(011)_\alpha$	$[10\bar{1}]_\gamma$ // $[\bar{1}\,\bar{1}\,1]_\alpha$	CPP2	B2 / $[0,0,1]_\gamma$	49.47° / $[\bar{1}\,\bar{1}\,1]$	Packet
V8		$[10\bar{1}]_\gamma$ // $[\bar{1}\,1\,\bar{1}]_\alpha$		B1 / $[001]_\gamma$	10.53° / $[11\bar{1}]$	Packet
V9		$[\bar{1}\,\bar{1}\,0]_\gamma$ // $[\bar{1}\,\bar{1}\,1]_\alpha$		B3 / $[010]_\gamma$	50.51° / $[\bar{1}03\bar{1}3]$	Packet
V10		$[\bar{1}\,\bar{1}\,0]_\gamma$ // $[\bar{1}\,1\,\bar{1}]_\alpha$		B2 / $[0,0,1]_\gamma$	50.51° / $[\bar{7}\bar{5}5]$	Packet
V11		$[011]_\gamma$ // $[\bar{1}\,\bar{1}\,1]_\alpha$		B1 / $[001]_\gamma$	14.88° / [1,5,13]	Packet
V12		$[011]_\gamma$ // $[\bar{1}\,1\,\bar{1}]_\alpha$		B3 / $[010]_\gamma$	57.21° / $[\bar{3}56]$	Packet
V13	$(\bar{1}11)_\gamma//(011)_\alpha$	$[0\bar{1}1]_\gamma$ // $[\bar{1}\,\bar{1}\,1]_\alpha$	CPP3	B1 / $[001]_\gamma$	14.88° / $[51\bar{3}\bar{1}]$	Packet
V14		$[0\bar{1}1]_\gamma$ // $[\bar{1}\,1\,\bar{1}]_\alpha$		B3 / $[010]_\gamma$	50.51° / $[\bar{5}5\bar{7}]$	Packet
V15		$[\bar{1}01]_\gamma$ // $[\bar{1}\,\bar{1}\,1]_\alpha$		B2 / $[0,0,1]_\gamma$	57.21° / $[\bar{6}\bar{2}5]$	Packet
V16		$[\bar{1}01]_\gamma$ // $[\bar{1}\,1\,\bar{1}]_\alpha$		B1 / $[001]_\gamma$	20.61° / $[11\bar{1}\bar{6}]$	Packet
V17		$[0,1,1]_\gamma$ // $[\bar{1}\,\bar{1}\,1]_\alpha$		B3 / $[010]_\gamma$	51.73° / $[\bar{1}16\bar{1}]$	Packet
V18		$[0,1,1]_\gamma$ // $[\bar{1}\,1\,\bar{1}]_\alpha$		B2 / $[0,0,1]_\gamma$	47.11° / $[\bar{2}4\bar{1}021]$	Packet
V19	$(11\bar{1})_\gamma//(011)_\alpha$	$[\bar{1}10]_\gamma$ // $[\bar{1}\,\bar{1}\,1]_\alpha$	CPP4	B3 / $[010]_\gamma$	50.51° / $[\bar{3}\ 13\ 10]$	Packet
V20		$[\bar{1}10]_\gamma$ // $[\bar{1}\,1\,\bar{1}]_\alpha$		B2 / $[0,0,1]_\gamma$	57.21° / $[36\bar{5}]$	Packet
V21		$[0\bar{1}\,\bar{1}]_\gamma$ // $[\bar{1}\,\bar{1}\,1]_\alpha$		B1 / $[001]_\gamma$	20.61° / $[30\bar{1}]$	Packet
V22		$[0\bar{1}\,\bar{1}]_\gamma$ // $[\bar{1}\,1\,\bar{1}]_\alpha$		B3 / $[010]_\gamma$	47.11° / $[\bar{1}0\ 21\ 24]$	Packet
V23		$[0,1,1]_\gamma$ // $[\bar{1}\,\bar{1}\,1]_\alpha$		B2 / $[0,0,1]_\gamma$	57.21° / $[\bar{2}5\bar{6}]$]	Packet
V24		$[0,1,1]_\gamma$ // $[\bar{1}\,1\,\bar{1}]_\alpha$		B1 / $[001]_\gamma$	21.06° / $[9\bar{4}0]$	Packet

Table 2.
Chemical compositions of experimental Base, HiC and HiMn alloys. The amount of N and B is in ppm and that of other elements are in weight percent.

Steel	C	Mn	Si	Cr	Ti	Nb	N	B
Base	0.040	1.71	0.148	0.27	0.015	0.039	36	16
HiC	0.099	1.53	0.144	0.30	0.016	0.040	32	12
HiMn	0.041	2.50	0.155	0.29	0.015	0.042	37	18

orientation relationship are summarized in Table 1 [10,14,15]. There are four independent fcc close-packed plane (CPP) groups ($(111)_\gamma$, $(1\bar{1}\,1)_\gamma$, $(\bar{1}11)_\gamma$, and $(11\bar{1}\,)_\gamma$) which can be parallel to the bcc $(011)_\alpha$ plane. In a single CPP group, three fcc close-packed directions ($[\bar{1}11]_\gamma$, $[01\bar{1}]_\gamma$, and $[1\bar{1}0]_\gamma$) are available, one of which is parallel to a bcc close-packed direction ($[\bar{1}\,\bar{1}\,1]_\alpha$ or $[\bar{1}\,1\,\bar{1}]_\alpha$) in the CPP. The combination of four fcc CPP groups, three fcc directions, and two bcc directions yields a maximum of 24 available variants of the crystallographic orientation. Misorientation characteristics between the variants can also be calculated from their crystallographic orientation relationship. The misorientation angle and rotation axis for each variant with respect to the V1 variant are provided in Table 1.

The hierarchy of bainitic ferrite microstructures within a single prior austenite grain can be explained based on the variant orientation characteristics. For the K-S orientation relationship, a single prior austenite grain is divided into packets, each of which belongs to a single CPP group with six available variants, implying that the CPP planes of the six bcc variants in a single packet are nearly parallel to a single CPP plane of the parent austenite grain. There are three blocks available in a single packet depending on the Bain group, where each block includes two variants sharing both CPP and Bain groups *e.g.* V1 and V4, called sub-blocks. Sub-blocks are further divided into the smallest morphological unit in the bainitic ferrite, the laths.

The boundaries between variants from different CPP groups are *packet* boundaries, *i.e.*, V1/V7 to V1/V24. The *block* boundaries can be defined as the boundaries between two variants belonging to different Bain groups within a single CPP group such as V1/V2, V1/V3, V1/V5, and V1/V6. The *block* and *packet* boundaries generally have high misorientation angles. The misorientation angle between the laths of different variants in a single block is 10.53°, corresponding to the V1/V4 intervariant boundary, which is referred to as a *sub-block* boundary. It is worth mentioning that there may also be adjacent laths corresponding to the same variant in a single block (*e.g.* V1/V1) but from different nuclei. The *ideal* misorientation angle between the same variants is zero, but real microstructures do not correspond perfectly to the idealized pole or misorientation distributions. Experimental observations [16,17] reveal that there are small misorientation angles (below 5°) between laths of the same variant *i.e.* V1/V1. Considering the small (sub-micron) lath width, the smallest crystallographic unit practically detectable by EBSD observation in a bainitic ferrite microstructure is a sub-block.

The crystallographic sub-units in bainite are known to affect the mechanical properties of bainitic steels. Brozzo et al. [18] showed that the cleavage fracture resistance of low-carbon bainitic steels was mainly dependent on the average packet size, and yield strength was more dependent on the substructures within the packets. Rancel et al. [19] also concluded that bainitic packet size governs cleavage crack propagation.

With the development of electron backscatter diffraction (EBSD) techniques for crystallographic observation, several investigations of the complex substructure in bainitic ferrite have been performed in different steels [8–13,19–22]. Rancel et al. [19] reported that the bainite packet size of medium carbon steel increased with increasing austenitization temperature due to the increase of prior austenite grain size. Furuhara et al. [9] examined the microstructure of upper bainite in a series of Fe-9Ni alloys. The study concluded that while the bainite packet size does not vary much with carbon content at relatively high isothermal heat treatment (IHT) temperatures within the range of temperatures where bainite forms, it tends to decrease with increasing carbon content at lower IHT temperatures. On the other hand, block width increases with increasing carbon content and IHT temperature.