Available online at www.sciencedirect.com

SciVerse ScienceDirect

Acta Materialia 60 (2012) 7265–7274

Acta MATERIALIA

www.elsevier.com/locate/actamat

Effect of carbon content on variant pairing of martensite in Fe–C alloys

A. Stormvinter [a,*], G. Miyamoto [b], T. Furuhara [b], P. Hedström [a], A. Borgenstam [a]

[a] Department of Materials Science and Engineering, KTH Royal Institute of Technology, Stockholm, Sweden
[b] Institute for Materials Research, Tohoku University, Sendai, Japan

Received 2 July 2012; received in revised form 12 September 2012; accepted 16 September 2012
Available online 13 October 2012

Abstract

The effect of carbon content on the variant pairing tendency of martensite formed in Fe–C alloys is investigated by means of electron backscattered diffraction analysis. The method used is based on experimentally determined orientation relationships between austenite and martensite. The results show that the carbon content has a strong effect on the martensite variant pairing tendency. This observed change in variant pairing tendency is discussed in relation to the well-known morphological transition from lath to plate martensite in Fe–C alloys and the formation of packets and plate groups. The results indicate that quantitative analysis of variant pairing, as demonstrated here, may facilitate martensite characterization in Fe–C alloys as well as in other alloy systems.

Keywords: Carbon content; Crystallography; Electron backscattered diffraction; Fe–C alloy; Martensite

1. Introduction

The superior hardness of martensitic steels can be attributed to their complex microstructure, which is known to vary with composition, especially with carbon content. For Fe–C alloys lath martensite forms in the composition range 0–0.6 mass%[1] C, whereas acicular plate martensite becomes the dominant morphology above 1.0C [1]. In the composition range of 0.6–1.0C, a mixed regime of lath and plate martensite has been reported, where the fraction of plate martensite increases with increasing carbon content [1–3]. This is a commonly accepted view of martensite formation in ferrous alloys. On the other hand, there have been numerous works on ferrous martensite that illustrate the complexity of martensitic microstructures. For instance, Maki et al. [4] have shown that the character of lath martensite changes with the carbon content, and Greninger and Troiano [5] have observed a change in the morphological appearance of plate martensite in Fe–C alloys. They reported that truly plate-like martensite units, with clearly visible midribs and that are formed in zigzag patterns, were found in alloys containing 1.5–1.8C. Below this composition range they observed a sudden change in the morphological appearance of the plate martensite units: two plate-like units seemed to be emanating from a point and grow with an obtuse angle with much less prominent midribs. This morphology has since been described as butterfly martensite [6,7] and the former as lenticular martensite [6].

It has also been shown several times [8–13] that, during martensitic transformation, there exists a lattice orientation relationship (OR) between the austenite (parent) and martensite (product) phases. For instance, Kurdjumow and Sachs [8] studied a carbon steel by X-ray pole figure analysis and suggested the well-known K-S OR. The K-S OR predicts that 24 unique crystallographic martensite variants may develop from a single parent grain, when annealing twins are disregarded. For lath martensite, these 24 unique martensite variants may in turn be divided into four groups, which consist of six martensite variants with a common parallel relationship of close-packed planes. These four groups have been named as "packets" [14–16] and martensite variants within one packet have nearly the same habit plane. By

* Corresponding author.
E-mail address: stormvin@kth.se (A. Stormvinter).
[1] All compositions will be given in mass% hereafter.

1359-6454/$36.00
http://dx.doi.org/10.1016/j.actamat.2012.09.046

adopting the nomenclature used by Morito et al. [14], the four packets are made up of the following variant groups: V1–V6, V7–V12, V13–V18 and V19–V24. The packet may be further subdivided into three "blocks", where each block consists of two martensite variants with a low misorientation. For instance, the three blocks of packet V1–V6 are: V1/V4, V2/V5 and V3/V6 [14]. The unique variants, e.g. V1, have been named as sub-blocks and are in fact the morphological units that contain several individual laths. A lath has been described as a needle-like martensite unit, a few microns long and less than a micron thick [17]. The substructure of the laths consists of dislocations, which are a result of the accommodation deformation due to the large shape strain [18]. Adjacent laths may have a misorientation of a few degrees, but are in principal the same crystallographic martensite variant [19]. Lath morphology may be regarded as a hierarchic structure: parent grain–packet–block–sub-block–individual lath, where the individual lath can be considered as the basic building block of the microstructure.

In the case of plate martensite, which is found in high-carbon steels with low martensite start temperature, it is not at all evident if there exists a hierarchic structure, similar to that of lath martensite. When studied by optical microscopy (OM), plate martensite appears as individual units of various sizes [2]. The unit size is limited by the parent grain size and by the preceding martensite plates, which inhibit the growth of a fresh unit. Some characteristic features of plate martensite are: (i) midrib, (ii) transformation twins, (iii) deformation twins, (iv) dislocation arrays and (v) transverse microcracks [1,20]. Characterization works performed on the plate martensite have commonly addressed the irrational habit planes [5,11,21–23]. A number of studies have also addressed the variant pairing tendency [24–26]. Such works on variant pairing have been reviewed more recently by McDougall and Wayman [27] in a comprehensive monograph on ferrous martensite. One study on variant pairing was conducted by Okamoto et al. [26], who characterized martensite formed in an Fe–30.70Ni–0.28C alloy. By following Okamoto et al. [26], it may be concluded that a nucleation event in ferrous alloys that forms plate martensite will result in the growth of a "plate group" [24], which consists of four unique crystallographic martensite variants. The principal plate group, which is referred as PG "1" in Table 2, becomes V1, V16, V17 and V6 by adopting the nomenclature previously used in Ref. [14]. In total, six unique plate groups may form from a single parent austenite grain, when annealing twins are disregarded.

Recently, Miyamoto et al. [28] have proposed a method, based on electron backscattered diffraction (EBSD), to accurately determine the OR between martensite and the parent austenite. The method is capable of accurately determining the OR without the presence of retained austenite, and hence may be applicable to all types of martensite. Takayama et al. [29] applied this method to obtain the OR of a low-carbon steel, Fe–0.15C–1.5Mn–0.2Si, and subsequently analyzed the effect of transformation temperature on the variant pairing of bainitic ferrite and lath martensite. Their work, performed by using EBSD, proposed a novel approach for characterizing martensite, i.e. martensite–martensite boundaries were characterized both by misorientation angle and by misorientation axis. Previous works on variant selection using EBSD [14,19,30] were primarily based on misorientation profiles.

However, to the authors' knowledge no systematic investigation of the effect of carbon content on variant pairing tendency of ferrous martensite in Fe–C alloys, covering the full practical range of carbon contents, has been reported to date. Such an investigation is undertaken in the present work, as the variant pairing tendency could aid in the understanding of martensite formation and might also provide a means for quantitative martensite characterization in Fe–C alloys as well as in other alloying systems.

2. Experimental

In the present work, high-purity binary alloys, with nominal compositions of 0.35C, 0.75C, 1.05C and 1.80C, together with an interstitial-free (IF) steel are used. The complete chemical compositions of the alloys, together with the prior austenite grain size (PAGS), are listed in Table 1.

The specimens are cut using a wire electrical discharge machine and then austenitized for 10–30 min at 1373–1473 K under a vacuum. This heat treatment procedure produces a relatively large PAGS, which is desirable in an attempt to isolate the effect of carbon content on the martensitic microstructure, since it is known that a relatively small PAGS affects the martensite start temperature [31] as well as the packet- and block sizes [32]. After heat treatment, the specimens are directly quenched into iced brine at 273 K. Specimens with 1.05C and 1.80C are subsequently cooled in liquid nitrogen for 1 h to reduce the amount of retained austenite. Sample preparation is done by mechanical polishing.

The OM study is made on polished cross-sections in the as-quenched condition after etching with 3% Nital. No traces of diffusion-controlled transformation products are observed in any specimen and it can thus be concluded that the quenching process is rapid enough. Moreover, it is concluded that decarburization affected less than 100 μm of the surface layer, since the martensitic microstructure was found to be rather homogeneous beyond that depth.

Specimens prepared for EBSD received a vibration-assisted final polishing (VibroMet2) for 1.8 ks to improve the surface finish and to remove the damaged layer caused

Table 1
Chemical composition and prior austenite grain size of the Fe–C alloys.

C	Mn	B	Fe	Calc. Ms (K)	PAGS (μm)
0.0023	1.48	0.0027	Bal.	726	320
0.345	0.02	–	Bal.	672	200
0.74	<0.003	–	Bal.	531	370
1.06	<0.003	–	Bal.	472	300
1.80	0.004	–	Bal.	363	250