Variant Selection of Low Carbon High Alloy Steel in an Austenite Grain during Martensite Transformation

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In this study, the development of a lath martensite structure in low carbon high alloy steel was observed in situ using high-temperature laser scanning confocal microscopy. The crystallography of the martensite structure was analyzed using electron backscatter diffraction patterns. It was observed that martensite transformation starts from the prior austenite grain boundary. Then, the variant (Σ1) of another packet belonging to the same bain correspondence was observed in the early stage of martensite transformation. Another block in the same packet was observed in the next stage of martensite transformation. Finally, transformation occurred among the neighbors of the transformed martensite block.

KEY WORDS: variant selection; martensite transformation; in situ observation; EBSD.

1. Introduction

In recent years, there have been demands for a decrease in the use of alloying elements and an improvement in the mechanical properties of steels. Martensite is a microstructure that is indispensable for the strengthening of steels. Thus, it is necessary to utilize a martensite microstructure to meet these demands and to clarify the transformation behavior of martensite in detail.

Martensite transformation is a diffusionless process and is caused by an atomic correspondence between parent and product lattices. The strain due to martensite transformation is relaxed when an austenite is deformed plastically (Plastic accommodation, PA) or elastically (elastic accommodation, EA), or when different variants are formed (self accommodation, SA). It has been reported that the microstructures of shape memory alloys,3) non-ferrous alloys4) and thin-plate martensite5) are formed during the combination of SA variants. These combinations appear well in a thermoelastic non-ferrous martensite. It is believed that they can relax the transformation stress predicted by the phenomenological theory of martensite crystallography (PTMC). However, ferrous lath martensite is not formed by such combinations. It is observed that lath martensite contains some groups with almost the same habit plane (packet). The packet consists of six types of variants. PTMC analysis reveals that the combination of variants in a sub-block in the block is not advantageous for SA.6) Although various techniques have been used to analyze this structure, the reason as to why a lath martensite microstructure is different from other martensite structures is still unclear. The martensite transformation strain should be relaxed by plastic deformation of the matrix and/or martensite resulting plastic accommodation. Moreover, the formation of variants plays an important role in the formation of a martensite structure.

In recent years, the electron backscatter diffraction (EBSD) technique has been adopted for analyzing the phase transformation of microstructures.5) Subsequently, the crystallography of lath martensite structures was investigated using this technique.4,6–9) The crystal orientation relationship of lath martensite, plastic accommodation in the parent austenite9) and the variant selection in a grain boundary12) have been discussed. The martensite structure after heat treatment has been observed in previous studies.13,14) However, it is necessary to examine microstructure change in situ to understand microstructure evolution at elevated temperatures. The in situ SEM/EBSD technique has recently become popular and has been used for in-situ observations of the solid-phase transformation process of a metal material.13,14) However, it is difficult to observe the high-speed martensite transformation phenomenon during a continuous thermal cycle because of the present low time resolution of this technique. To overcome this problem, we developed a high-speed photography technique using high-temperature laser scanning confocal microscopy (LSCM) and observed the solid-phase transformation in situ during a continuous thermal cycle.15–18)

In this study, the martensite transformation of low carbon high alloy steel was observed in situ by the LSCM technique during a continuous cooling cycle. Then, the crystal orientation in the same areas was measured by EBSD. The transformation model of lath martensite is discussed using the obtained experimental results.
2. Experimental Procedure

In this study, martensite transformation was observed in situ during a continuous cooling cycle by high-temperature LSCM. Figure 1 shows a schematic diagram of the setup of a high-temperature LSCM system. The system consists of an infrared image furnace and a laser scanning confocal microscope. Using a confocal system, only light incident from the focal plane is permitted to reach the photon detector. The image was recorded at a rate of 30 frames/s. The infrared light focus in the furnace covered a volume of diameter 10 mm and height 10 mm. The specimen in the furnace was mirror polished. The specimens were machined to 5 mm in diameter and 1 mm in height, and the observed plane was mirror polished. The specimens were cooled to room temperature after heating to 1485°C as shown in Fig. 2. The martensite transformation during cooling was observed in situ. The rate of cooling from 100°C to room temperature was –0.45°C/s as shown in Fig. 2. The martensite transformation was analyzed. It is well known that there are 24 variants in the case of a K-S orientation relationship (OR).4,7 The crystal orientation relationship based on variant 1 (V1) is shown in Table 2. Figure 3 shows the coincidence grain boundary [Σ1, Σ3 coincidence site lattice (CSL)] for the 24 variants.

Given the three <001> directions, there are three crystallographic variants of the Bain strain. This means that a pack-
et consists of three types of parallel blocks with different orientations. In this study, a Bain map classified by areas having the same orientation was used as the block map. As a packet is a group of parallel laths with the same CP plane, the packet in the martensite structure was identified using the CP map. Moreover, the variant in the martensite structure was analyzed by the pole figure method.

3. Results and Discussion

3.1. In Situ Observation of Martensite Transformation

The $A_s$, $A_f$, and $M_s$ temperatures were measured during the continuous thermal cycles by high-temperature LSCM and were found to be 719°C, 801°C and 131°C, respectively. However, $M_f$ was not determined because it was lower than the room temperature in this experiment.

Figure 4 shows the in situ observation martensite transformation behavior of an austenite grain during the cooling cycle by high-temperature LSCM. As shown in Fig. 4(a), Grain 1 and Grain 2 were observed as austenite grains at 135°C. The surface relief of the martensite structure is shown in Fig. 4(b). At the lower part of Grain 1 in Fig. 4(b), the remained austenite can be clearly observed among the blocks that had transformed earlier (shown as white dotted lines). With decreasing temperature, the formation of the blocks and packets was clearly observed and groups of laths were formed in packets, as shown by the arrows in Fig. 4(c). Finally, the remained austenite in each packet was gradually transformed into martensite laths, as shown in Fig. 4(d).

3.2. Crystal Orientation Relationship between Martensite and Retained Austenite

After cooling to room temperature, the crystal orientation of the martensite in the area in Fig. 4 was measured by EBSD. Figure 5 shows the crystal orientation in Grain 1. Figures 5(a) and 5(b) are orientation maps constructed from the inverse pole figure of the martensite and austenite, respectively. Black lines show boundaries having a misorientation angle greater than 15°. 
tained bulk retained austenite.

From the crystal orientation of retained austenite, OR between the parent (austenite) and transformed phase (martensite) is summarized in Fig. 6. The results show that the CP plane [(111) γ and (011) α'] and CP direction ([101] γ and [-1-11]α') were almost parallel with a decentralization of 3° or less. It can be concluded that the martensite observed here had a K-S relationship 21) with the austenite.

3.3. Microstructure of Martensite on the Sample Surface and in Bulk

Martensite transformation on the surface of specimens was observed by high-temperature LSCM. The martensite structure was influenced by the restraint exerted by the sample surface. The effect of the surface should be examined because the packet parallel to the CP plane can be easily observed. 22) It is known that, the ideal six variants in a packet of lath martensite can relax the shear strain but cannot affect the change in volume.

As there is no restraint in the normal direction of the surface, a packet that can accommodate cubical expansion in this direction might be produced. Thus, the martensite microstructure at the surface was compared with that in the sample.

The Bain map and the CP map for the martensite structure with prior austenite and Grain 1 and Grain 2 observed on both unpolished and polished surfaces of the samples are shown in Fig. 7. The black and white lines indicate high-angle misorientation and the Σ3 twin-grain boundary, respectively. In Fig. 7(b), the red (CP1), yellow (CP2) and green areas (CP4) are adjacent packets, as indicated by the pink circles. It was assumed that these packets were connected by the same Bain group [Fig. 7(a)]. Furthermore, numerous Σ3 twin-grain boundaries were included in the same packet.

The results of the high-temperature LSCM revealed that the block groups [arrows in Fig. 4(c)] that considerably transformed in Grain 1 belong to the same Bain correspondence area [Fig. 7(a)]. Same result was obtained in Grain 2 as shown in Fig. 7(c).

To confirm the surface effect during martensite transformation, the crystal orientation of the martensite structure in the sample that was polished to half its original height was examined [Figs. 7(e) and 7(f)]. The boundary between the two packets, CP3 (blue) and CP4 (green) was connected by the same Bain group B2. The result was similar to that of the surface observation. Furthermore, Fig. 7(e) indicated that adjacent packets were connected by variants belonging to the same Bain group.

The observation of the martensite microstructure in the sample revealed that adjacent packets were connected by the same variants belonging to the same Bain group, which is similar to the results obtained for the surface. In the next section, the variant selection observed in a parent austenite grain (Grain 1) is discussed based on the results of variant analysis of the martensite microstructure.

3.4. Crystal Orientation of the Martensite Microstructure at Room Temperature

Variants of the martensite microstructure in Grain 1 were analyzed in detail by the pole figure method, as shown in Fig. 8. The misorientations of the variants with a twin relationship (Σ3), such as V1-V2, V7-V8, V15-V16, and V23-V24 were observed in Grain 1.

Next, the time series of the variant formation was analyzed to discuss the formation of packets. Figure 9 shows the in situ observation results of the martensite transformation in Grain 1 [the same area in Fig. 4(c)]. The variant analysis clearly indicated that the block marked with the white dotted line in Fig. 9(g) was V16 [Fig. 9(b)]. After V16 was produced, V15-which has a twin relationship with V16-was formed from the remained austenite [Figs. 9(c) and 9(d)].

V8 grew from the grain boundaries and V7 was transformed in an adjacent area. The orientation between V7 and V8 is also a twin relationship. Moreover, V1 was observed as shown in Fig. 9(b). Figure 10 shows the {111} pole figure of the martensite plates. It was observed that the three variants V1, V8 and V7 intersect at the (-1, -1, 1) pole point. In other words, V1 and V7 were rotated by 10.5° (V1-V8) and 60° (V8-V7) from V8, respectively, at the centre of the CP direction [-1, -1, 1]. It has been reported that V1-V8 has a Σ1 relationship and small misorientations in the bainite transformed from the prior austenite grain boundary. 24, 25) Moreover, V1, V7 and V8 have the same relationship of CP plane as austenite. This means that laths with these three types of variants can grow in the same direction, 24) which results in the accommodation of transformation stress and strain.

3.5. Variant Selection Mechanism of Martensite Transformation

The strain due to lath martensite transformation is relaxed by the PA or SA process. When the carbon content is increased, the martensite transformation start temperature is decreased, 19) and PA does not occur readily in the remained austenite. Thus, SA with the formation of different variants is expected in this case. 25) On the other hand, the accommodation of transformation strain by combining variants with small misorientations that belong to different packets has been reported in bainite laths with the same Bain correspondence. 24, 25) In this study, many combinations of variants with the same Bain correspondence were observed. This suggested that variants belonging to the same Bain group were transformed by a similar accommodation mechanism. 26, 27)

Next, a martensite transformation model with respect to the time series was proposed. It was observed that martensite transformation starts from the prior austenite grain boundary and proceeds along the growth direction of the
block initially formed in the prior austenite grain. Then the variant (Σ1) of another packet belonging to the same Bain correspondence was observed in the early stage of martensite transformation. Another block in the same packet was observed in the next stage of martensite transformation. Finally, transformation occurred among the neighbors of the transformed martensite block.

In previous studies, we analyzed the crystallography of martensite and austenite structures by X-ray diffraction using Synchrotron radiation. The austenite phase accommo-
dated by a rotation of less than 3° of the crystallite immediately after martensite transformation. It was believed that the plastic accommodation mechanism of austenite was dominant in the first stage of martensite transformation because a large amount of austenite remained.

A model of lath martensite transformation is proposed from the results as shown in Fig. 11. Initially, in one packet, a block that has a preferred variant from the energy viewpoint is transformed from the austenite grain boundary. Then, the block of another packet appears from another austenite grain boundary. The two blocks collide as shown in Fig. 11(b). It can be considered that an initial block appears from a packet boundary in competition with a formation from a grain boundary. Next a different packet with the same Bain correspondence appears as shown in Fig. 11(c). Another variant of another packet that belongs to the same Bain correspondence is formed from the deformed austenite to immediately relax the transformation strain [Figs. 11(c) and 4(b), 4(c) and 9(b)]. Moreover, because this block has a preferred variant from the energy viewpoint, it is suggested that the other block is formed apart from the first block to relax the transformation stress. Moreover, because this block has a preferred variant from the energy viewpoint, it is suggested that the other block is formed apart from the first block to relax the transformation stress. Finally, transformation occurs immediately after martensite transformation. It was believed that another block immediately relaxes the transformation strain. Moreover, because this block has a preferred variant from the energy viewpoint, it is suggested that the other block is formed apart from the first block to relax the transformation stress.

(2) Another block in the same packet was observed in the next stage of martensite transformation. This suggests that the martensite phase was formed around the initial block as a self-accommodation variant. Finally, transformation occurred among the neighbors of the transformed martensite block.

4. Conclusions

Martensite transformation in low carbon high alloy steel was observed in situ by high-temperature LSCM during continuous cooling, and the crystallography of the martensite structure was analyzed by EBSD. The main conclusions are as follows:

(1) Initially, a block was transformed from the prior austenite grain boundary. Then, a different packet with the same Bain correspondence appeared in the early stage of martensite transformation. It can be assumed that another variant of another packet that belongs to the same Bain correspondence is formed from the deformed austenite to immediately relax the transformation strain. Moreover, because this block has a preferred variant from the energy viewpoint, it is suggested that the other block is formed apart from the first block to relax the transformation stress.

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