EFFECT OF HOLDING TEMPERATURE TO BAINITE TRANSFORMATION IN CR MO STEEL

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ABSTRACT

The effect of holding temperature to variant selection mechanism during bainite transformation was investigated in 2Cr-1Mo steel. The behavior of transformation has been studied by using high temperature laser scanning confocal microscopy, LSCM via in situ observation. The specimen was heat treated to 1350℃ and hold for 60s before being cooled to 560℃and 580℃. At both conditions, each specimen was isothermally transformed for 1 hour and cooled to room temperature. The heat treated specimen was then analyzed by using electron backscattered diffraction, EBSD method. As a result, variant preferential selection is more prominent in higher holding temperature which coarsened the block and packet boundary is connected with low misorientation angle variant.

Keyword : Variant analysis, Bainite, Phase transformation, Heat affected zone (HAZ), Cr-Mo steel

INTRODUCTION

Bainite has become more important in steel technology nowadays due to the hope in getting the best balance between strength and ductility (Barbacki,1995; Bhadeshia,1992) . The crystallography of bainite is said to nearly resemble the traits of lath martensite in terms of orientation and packet formation, which is the lath martensite in low carbon steel, a prior austenite grain is divided into packets, lath in the same habit plane with respect to its matrix, and each packet is divided into blocks [3)]. It is reported that, these three level hierarchy consist in its morphology played a crucial role in improving the toughness of bainitic steel (Kawata et al,2006;Hiromoto et al,2006). To date, there were several researches done to analyze the transformation of upper bainite by means of EBSD method. However, until now the in situ observation of the bainite transformation in a single prior austenite grain which associated with variant analysis of crystallographic packets has scarcely been studied.

In the present study, in situ observation of phase transformation is conducted using LSCM to grasp the block formation sequences in a single prior austenite grain and variant analysis then will be done in accordance to the information. The focus of variant analysis here is on the orientation relationships of each blocks formed in different holding temperature. Thus, the effect of the temperature on the variant selection mechanism can be identified.

EXPERIMENTAL METHODS

The Cr-Mo steel (Fe−0.14%C−2.14%Cr−0.86%Mo wt%) was used in the present study. By using the high temperature LSCM, the specimen with 5 mm in diameter and 1 mm in thickness, was placed in an alumina crucible and held in a platinum holder inside the furnace. Under controllable condition, the specimens then were austenized at 1350℃ for 60s. After that, each specimen was cooled to 580℃ and 580℃ at -15℃/s and held at this temperature for 3600s before being cooled to room temperature. The phase transformation during this process was displayed on a monitor and simultaneously recorded along with the image at a rate of 30 frames/s. An elaborate description of LSCM was detailed in the previous researches(Komizo et al,2011). The heat treated specimens were measured for the crystal orientation at room temperature and analyzed by SEM/EBSD. The accelerating voltage of SEM (JEOL JSM-6400) was set at 20kV, an electron beam diameter was about 0.2 μm and the step size was 0.8. Both analysis results were then compared to each other in order to study the behavior of bainite transformation.

RESULT

Isothermal Bainite Transformation Behavior

Holding temperature at 560℃

Figure 1 showed the isothermal transformation behavior observed at 560℃ holding temperature. Generally, the transformation from austenite to bainite started merely after 16s of incubation period and reached to saturated condition after 3567s.

The area marked in red color showed the analyzed area and arrows with numbers describing the transformation sequences. The first bainitic ferrite block, Q1 as shown in Fig.1(b) transformed after 25s. It was nucleated from inside the grain and slowly grew in elongated directions until being stifled by the opposite grain boundary. 10s after the first nucleation, there was a nucleation observed at the similar site but grew in the opposite directions in straight line compared to the previous one. Figure 1(c) showed the nucleation site for the next formed block, Q2 49s after an incubation period. Here, it is interesting to note that, except Q4, all of the bainitic ferrite blocks in this analyzed grain nucleated from the same grain boundary. In the case of Q4, it is suggested that the transformation occurred in neighboring grain becomes a factor for the nucleation in order to accommodate a strain involved during transformation. The transformation in analyzed grain ceased 138s later on.

Holding temperature at 580℃

Figure 2 showed the isothermal transformation behavior observed at 580℃ holding temperature. It is clear that, the specimen exhibits almost similar characteristics when it being held at 560℃. However, when it comes to the kinetics of transformation, current holding temperature observed to be slower and reached to saturated conditions in shorter incubation period. As shown in figure 2(a) and 2(f), the transformation started after 5s and ceased after 941s of incubation period.

The area marked in red color in Fig.2(g) showing the analysis area and the arrows with numbers appeared in figure 2(a)-(d) describing the transformation in sequences. The first block, T1 nucleated from grain boundary after 17s incubated, later on grew slowly in elongated and width directions simultaneously. As the transformation proceed, the second, T2 and third block, T3 observed to be nucleated at the same grain boundary after 25s and 28s respectively. The transformation observed to be ceased after 93s of incubation period.

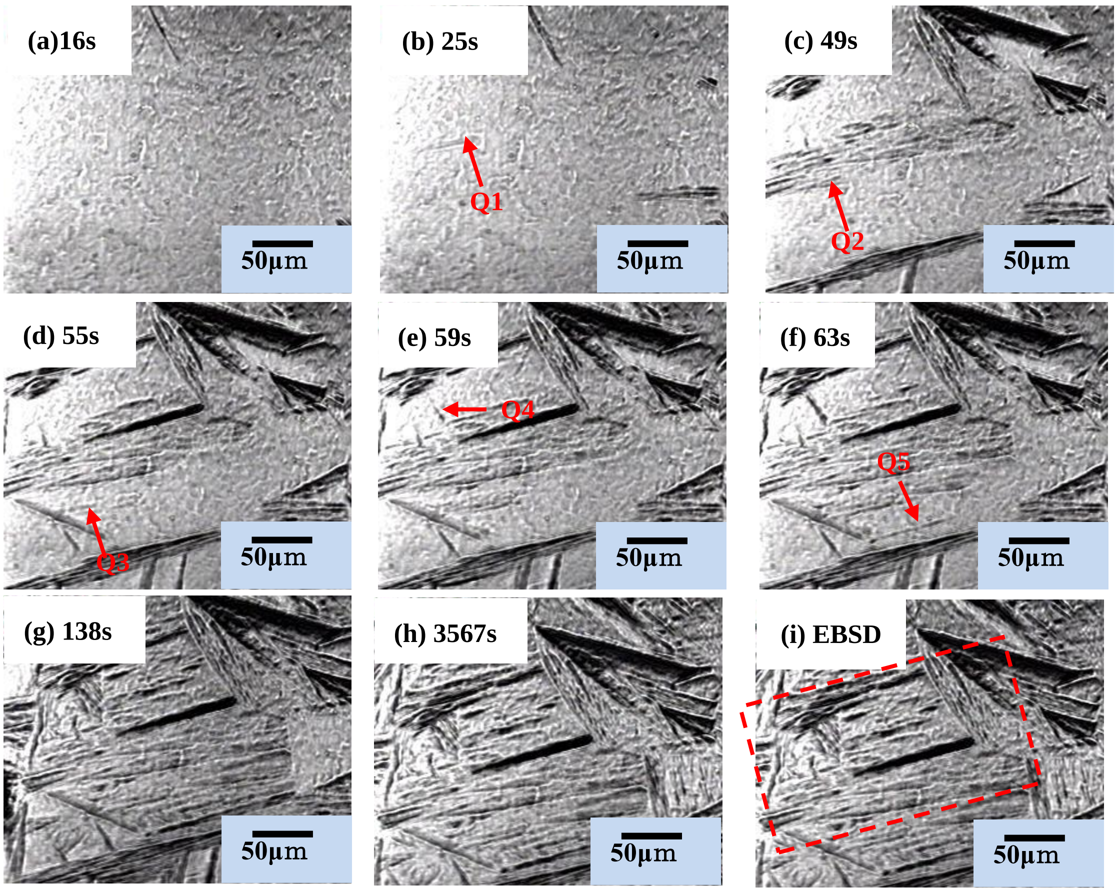


Figure 1. Isothermal transformation behavior of Cr-Mo steel at 560℃ x 1 hour, (a) transformation started after 16s incubation period, (b)-(f) nucleation and growth of bainitic ferrite lath showed in sequences marked as Q1,Q2,Q3,Q4 and Q5 which nucleated after displayed incubation period,(g) transformation for analyzed grain ceased after 138s, (h) transformation at whole grain ceased after 3567s, (i) analyzed grain.

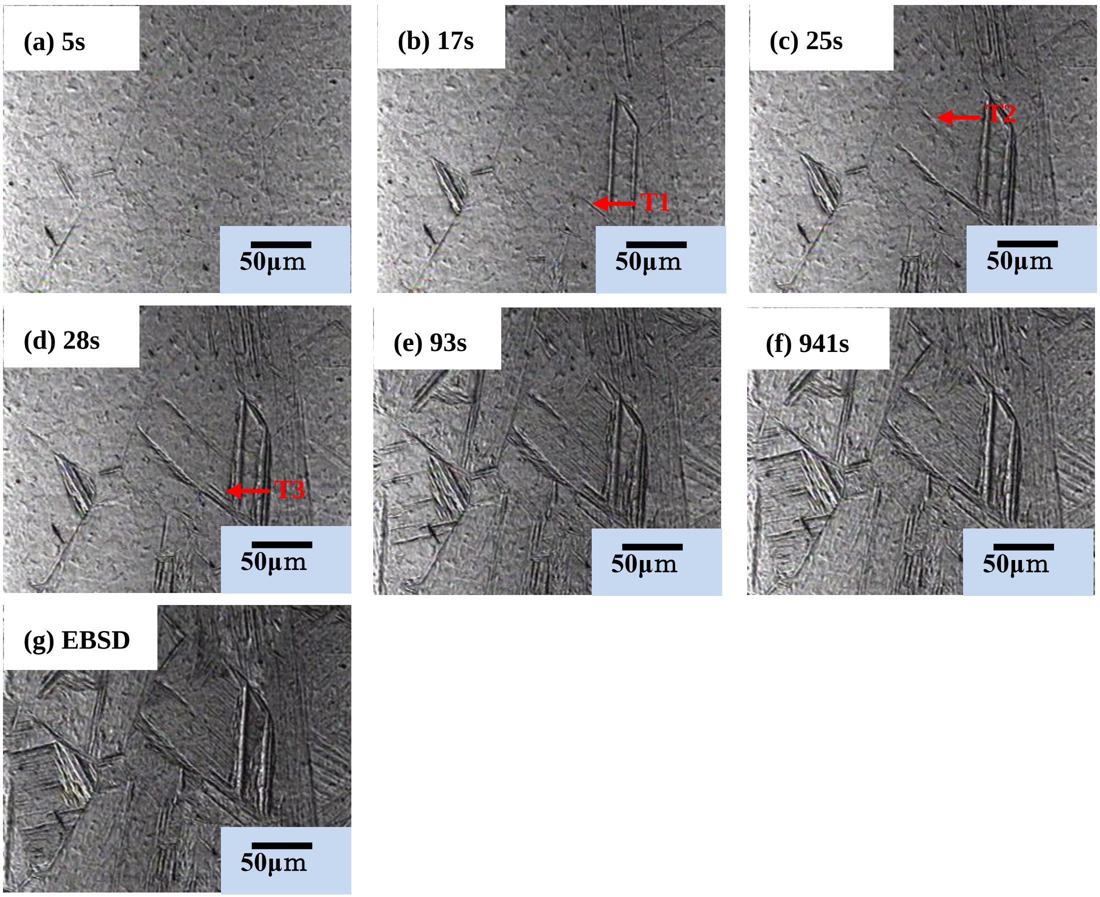
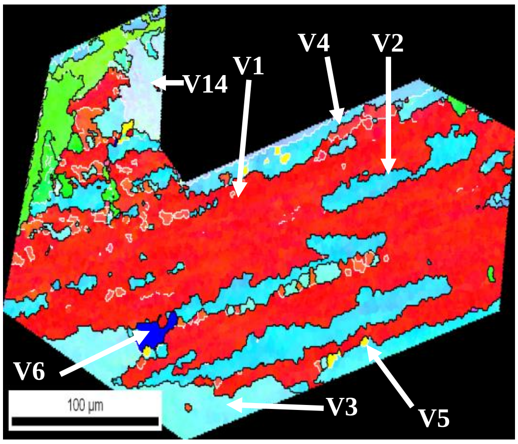
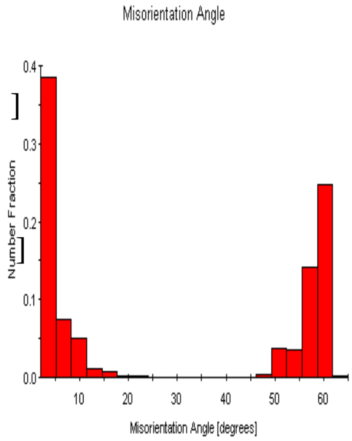


Figure 2. Isothermal transformation behavior of Cr-Mo steel at 580℃ x 1 hour, (a) transformation started after 5s of incubation period, (b)-(d) nucleation and growth of bainitic ferrite block showed in sequences marked as T1,T2 and T3 which nucleated after displayed incubation period, (e) transformation for analyzed grain ceased after 93s, (f) transformation at whole grain ceased after 941s, (g) analyzed grain

Variant Analysis

In this study, the crystal orientation of the bainitic ferrite was measured by EBSD and determination of variants done at the same area by using a pole figure method. Fig.3 showed the crystal orientation for specimens which transformed under the isothermal conditions. Figure 3(a) and (c) are the inverse pole figure, IPF of the bainitic ferrite and figure 3(b) and (d) are describing the fraction numbers of misorientation angle illustrated in graphs subject to Fig.3(a) and (c) respectively. The different colors used to distinguish between different variants. As shown in figure 3(a) for 560℃ holding temperature, V1 with red in color seen to be a dominant variant. However, there was also formation of V2 within the V1, which contributed for about 47.9% of the high angle misorientation graph. It is known that, the relationships between these two variants, V1 and V2 are CSL Σ3. From the in situ observation by LSCM, it is clear that, the transformation ceased after 3567s of holding times, and the transformation said to become incomplete transformation(Ohmori,1990), so that, the untransformed austenite were remaining in between of bainitic ferrite blocks. Thus, the formation of V2 in between of V1 blocks is suggested to be occurred during the continuos cooling after 1 hour holding time. However, there is no such evidence regarding this matter to prove the differences that maybe exist in microstructure crystallography between bainitic ferrite transformed isothermally and athermally except the visual observation during LSCM. In addition, the formation of variant boundaries, V1 and V3 with high misorientation angle, recorded as 60°and variants which having a CSL Σ11 relationship such as V1 and V6, and V2 and V3 also contributes to the fraction of high misorientation angle graph. Anyhow, the transformation of V1 was dominant in contributing the fraction of low misorientation angle showed in Figure 3(b). Moreover, there were a formations of specific variant pairs formed during transformation such as V1 and V4, V2 and V5 and V3 and V6. All of these pairs having a low misorientation angle, 10.5°. Thereon, when the transformation temperature was increased to be 580℃, the formation of V1 was clearly dominated the grain. This phenomenon likely because of the tendency to form the specific variant and finally coarsened the blocks. This result is in line with the result by Furuhara et al (2006), who suggested that coarser blocks formed with increasing of transformation temperature.

<table>
<tr><th>Inverse Pole Figure (IPF)</th><th>Misorientation Angle
Fraction of Low and High Angle
[in percentage]</th></tr>
<tr><td>
</td><td>(b)
Low angle [<15°]
= 52.1%

High angle [>15°]
=47.9%

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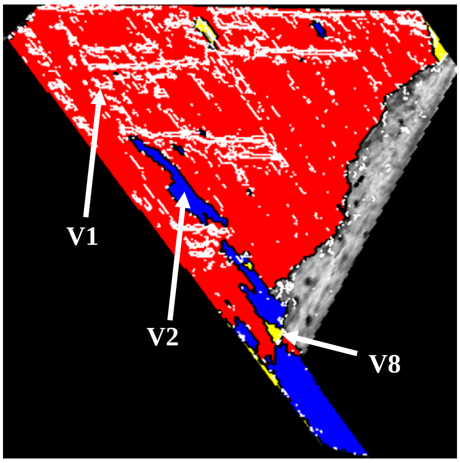
<tr><td>
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Low angle [<15°]
= 77.4%

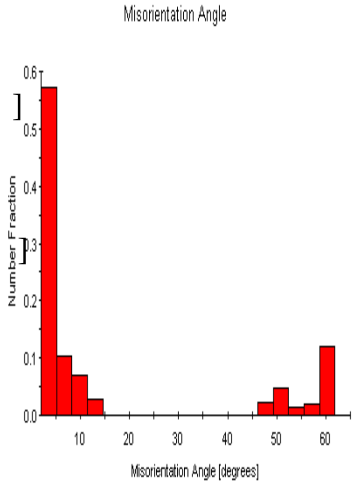
High angle [>15°]
=22.6%

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Figure 3. Variant determination and distribution of low angle and high angle misoriention in each conditions, (a),(b) 560℃, (c),(d) 580℃

Morphology of Blocks and Packets

The so called BP Map and CP Map was used to clarify the relationships of determined variant in Fig.3 with correspondence bain strain and related closed packed plane(Zhang et al,2012). As for BP Map, there are 3 bain group in the grain and illustrated in 3 different colors, red, green and blue which refers to 3 $\langle 001 \rangle \gamma$ directions. Likewise for CP Map, there are ideally 4 packets in the grain subject to the parallel close packed planes $\{011\}\alpha // \{111\}\gamma$ in line to K-S orientation relationships and these 4 planes illustrated in 4 different colors, red, green, blue and yellow.

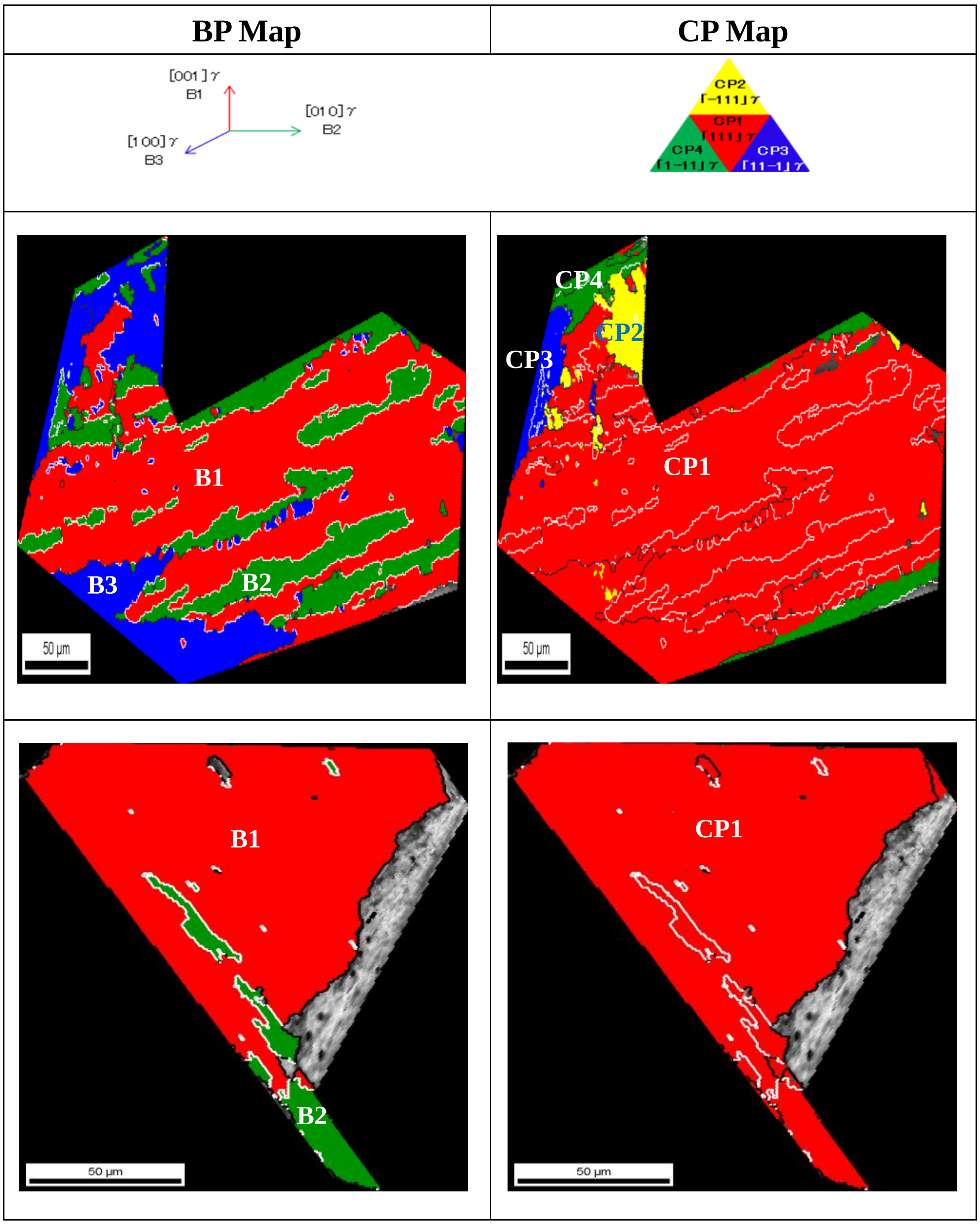

Figure 4. BP Map and CP Map for each conditions, (a), (b) 560℃, (c),(d) 580℃

Figure 4 illustrated the BP and CP Map. The BP map showed that there is no variants with high misorientation angle formed within the same correspondence bain area. This is can be confirmed easily in the analysis, wherein there is no any black or white line contains in the area represents by red, green or blue colors which refers to <001>γ directions. Here, black line refers to high misorientation angle and white line refers to twinning relationships. However, from the result of CP Map analysis, the formation of high misorientation angle and twinning relationship variants in the same packet area could be observed clearly by seeing to the black and white line. Same as BP Map, black line refers to high misorientation angle and white line refers to twinning relationships.

Then, by comparing both map, it is can be concluded that, the packet boundary is connected with low misorientation angle variants which belong to the same bain group.

Correlation Between Block Formation Sequences and Variant

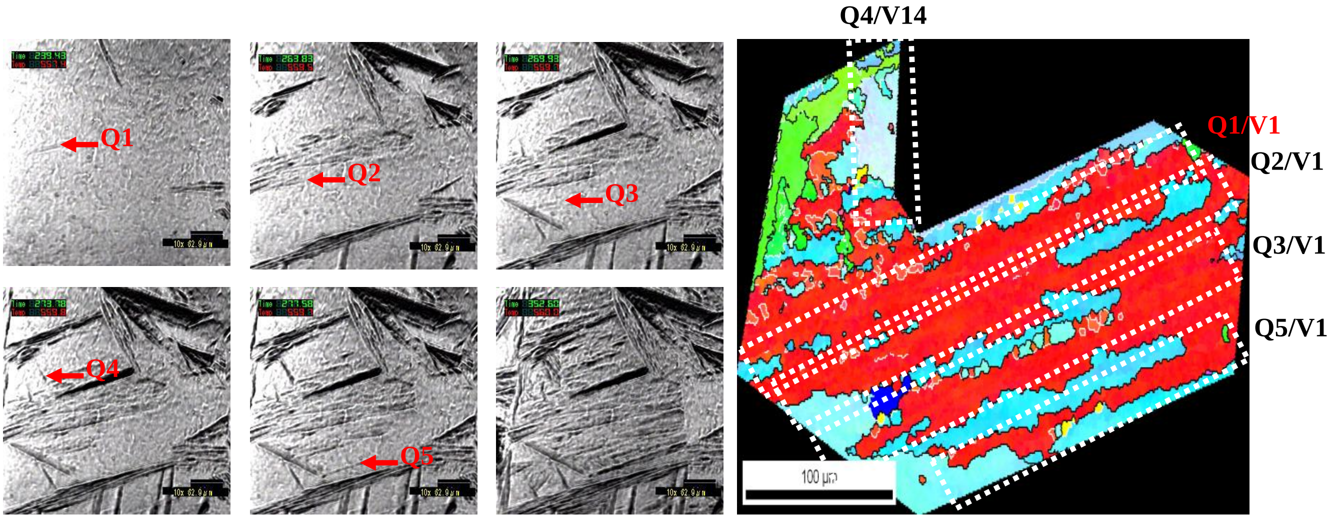

Figure 5. Correlations between transformation sequences by LSCM to be matched with variants formed in the grain for the case of 560℃ holding temperature

Figure 5 shows the correlations between transformation sequences and formation of variants in the grain for the case of isothermal transformation, 560℃ holding temperature. By comparing both LSCM and EBSD analysis results, the first block, Q1 could be matched to V1 which red in color. Then, after some while, the blocks which transformed simultaneously and both of them were marked as Q2, one was nucleated from the same grain boundary of Q1 and another one was classified as secondary block since it was nucleated from primary block, also identified as V1. The same thing goes to Q3 and Q4 where both of them were identified as V1. This phenomenon might be occurred due to preferential variant selection mechanism where, the tendency to form specific variant which in turn caused a formation of coarser block. This phenomenon also can be related to plastic deformation in austenite phase in order to relax the strain during formation of bainitic ferrite.

Subsequently, Figure 6 below showed the correlations between transformation sequences and formation of variants in the grain which underwent an isothermal transformation at 580℃ holding temperature. The first block, T1 can be matched as V2 and caused a twinning to become V1 during the growth process. After that, the second block, T2 transformed followed by T3 after a while. T2 was recognized as V1 and T3 was V2 which causing a twinning to become V1 during growth process. Then, the growth process continued and developed to form a coarse packet.

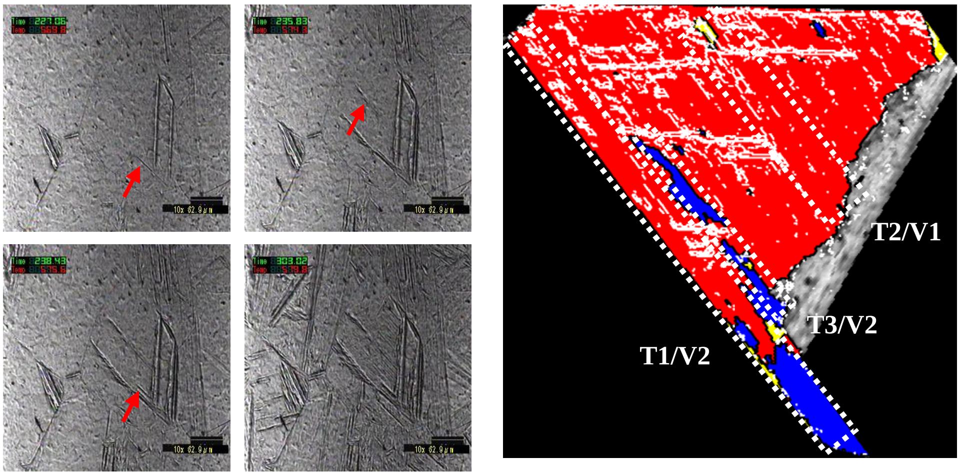

Figure 6. Correlations between transformation sequences by LSCM to be matched with variants formed in the grain for the case of 580°C holding temperature

DISCUSSION

Table 1 is a summarized data for incubation times, start and finish for every transformation temperature and its relationship with an average block size. From the data, it can be concluded that the transformation temperature has a linear relationship with the average block size, in which the higher the transformation temperature resulting higher value of the average block size. This result is in line with the results reported by Furuhara et al(2006), suggesting that finer microstructure of bainitic ferrite can be obtained in a lower transformation temperature. Figure 7 shows the fraction of variants which having a CSL relationship and also the line graph showing the tendency in forming high misorientation angle in each mentioned temperatures. From these two results, it seems like there is a close relationship between decreasing of CSL Σ3/high angle and increasing of average block size with increasing of transformation temperature. The formation of different texture in low and high temperature suggesting that, isothermal bainite transformation drives by two mechanisms: the plastic-accommodation which normally occurs in high temperature and self-accommodation in low temperature.

The variant analysis result has revealed that there is a tendency to form the same orientation of bainitic ferrite block (variant 1 which represented by red color in both cases) in both holding temperature. And, the formation of blocks in one packet observed to be increased by decreasing of transformation temperature. This is suggested that there is a variant selection in nucleation of bainitic ferrite at the austenite grain boundary during isothermal transformation and the effects can be seen more clearly in higher transformation temperature. The cause for this formation of preferred variants is, reductions of boundary energy and strain energy produced during nucleation(Furuhara et al,2006). It is said that, the transformation driving force lowered in the case of high transformation temperature and this is going to strengthen the preferential variant selection for nucleation of bainitic ferrite. High temperature enables the untransformed austenite to deform plasticity by ease in order to accommodate the transformation strain during development of bainitic microstructure which then coarsened the block.

The partitioned of carbon during transformation also gives an impact to the variant selection mechanism. The holding temperature was in fact high, and due to this reason, the carbon has an enough time to partition into austenite and becomes heterogeneous with carbon enriched and carbon depleted regions. It is reported that, the variant selection is strong in heterogeneous nucleation where the subsequent bainitic ferrite initiates from the carbon enriched regions during the transformation development and this criterion can be seen clearly during in situ observation by LSCM especially for the case of 580℃ holding time.

Table 1. Effect of transformation temperature to the average block size

Transformation Temperature, [℃]	Incubation Time [s]		Average Block Size, [μm]
	Transformation Start	Transformation Finished	
560	16	3567	4.04
580	5	941	5.65

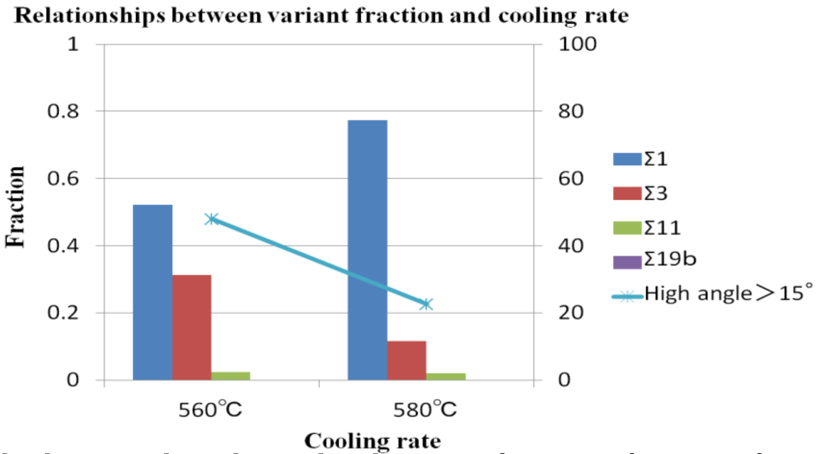

Figure 7. Graph showing the relationship between fraction of variant formation and holding temperature

CONCLUSION

In this study, an observation was concentrated to the transformation of bainite in a single austenite grain and transformation sequence within the grain was analyzed. By using the EBSD method, the orientation relationship of transformed block was analyzed. From the analysis, it can be concluded that:

(1) The nucleation of bainitic ferrite block mainly initiates from austenite grain

boundary.

(2) The formation of same variant and specific variant pairs (V1 and V4, V2 and V5, V3 and V6) proof the mechanism of variant preferential selection during bainite transformation. The mechanism caused the formation of coarser block especially in higher holding temperature.

(3) Packet boundary is connected with low misorientation angle variant belongs to the same bain group. The formation of CSL Σ1(belong to the same bain group) and CSL Σ11 at packet boundaries is an effects of strain accommodation during transformation.

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