Isothermal Decomposition Processes of Austenite in Fe-Cr-C Alloy Steels

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The formation mechanism of an unusual structure formed at lower temperatures in the upper C curve where eutectoid reaction occurs in a T-T-T diagram of high Cr steels has been investigated mainly by means of metallographic observations. The morphology of this structure is quite different from those of lamellar eutectoid products, but very similar to that of bainite in optical microscopic levels. TEM observation shows that this structure was consisted of fine lamellar carbides/ferrite aggregates, and grew preferentially in edgewise directions. Dendritic growth of the eutectoid decomposition products led to the morphology similar to bainite. The interlamellar spacings of them were continuously changed with decreasing transformation temperature and exhibited the same inclination as that constructed for pearlite in plain carbon steels. The carbide particles precipitated during the formation of this structure were not cementite but alloy carbides such as $M_2X_C$. This structure, therefore, is a sort of eutectoid transformation products, and the formation mechanism is essentially diffusional and different from that of bainite where both diffusional and shear processes are thought to operate.

Key words: eutectoid reaction, lamellar pearlite, degenerate pearlite, acicular structure, bainite, carbide precipitation, interlamellar spacing, orientation relationship

I. Introduction

When a plain carbon steel is isothermally held at temperatures below $Ae_1$ point, eutectoid structure such as pearlite consisting of cementite lamellae and those of ferrite forms.\(^{(1,2)}\) With lowering the transformation temperature, however, the lamellar growth of cementite is suppressed and the structure in which fine cementite platelets are distributed periodically as bands is formed. This structure is called degenerate pearlite.\(^{(1,3)}\) The decomposition of austenite in the temperature ranges between about 900K and Ms point induces the intermediate transformation product which often exhibits acicular or feather-like morphology in optical microscopy and is called bainite.\(^{(5)}\) These transformations induce different C-curves in a time-temperature-transformation (T-T-T) diagram, i.e., the upper and the lower C-curves, and the microstructures of degenerate pearlite and bainite can be easily distinguished. In the case of high Cr steels, although the isothermal decomposition processes of austenite have been extensively studied experimentally and theoretically,\(^{(6,8)}\) the bainite-like morphology could be often observed to form at lower temperatures in the upper C-curve where eutectoid reaction occurs in a T-T-T diagram.\(^{(9,10)}\) The formation mechanism of the bainite-like structure has not been well understood yet. The reason for the difficulty in specifying the formation mechanism may exist in the fact that the morphology of it is very similar to that of bainite formed in lower C-curve of the same steel. There are, also some arguments on the classification of bainite.\(^{(11,12)}\) The aims of the present study, therefore, are to examine the differences from bainite and to clarify the formation mechanism of this structure.

II. Experimental Procedure

The chemical compositions of the steels used in the present investigation are given in Table 1. These steels were received as hot-rolled cylindrical rods of 20 mm in diameter and 500 mm long. The specimens of 4 mm thick, 10 mm wide and 10 mm long were machined from them and were heat

| Table 1. Chemical compositions of the steels used (mass %) |
|-----------------|-------|-------|-------|-------|-------|-------|-------|-------|-------|
| Mark            | C     | Si    | Mn    | P     | S     | Cr    | Ni    | O     | Al    |
| Steel 1         | 0.20  | 0.02  | 0.001 | 0.001 | 0.001 | 8.20  | 0.02  | 0.005 | 0.0006|
| Steel 2         | 0.38  | 0.02  | 0.001 | 0.001 | 0.001 | 8.20  | 0.02  | 0.004 | 0.0002|

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treated as follows. They were austenitized at 1423K for 1.2ks in a dynamic nitrogen atmosphere and were quenched into either a lead or an alloy bath kept isothermally at various temperatures between 523K and 1073K covered with a layer of active charcoal to prevent decarburization. After holding isothermally for various periods, the specimens were finally quenched into water to suppress further isothermal decomposition. The cross sections of the heat-treated specimens were polished, etched in 3% nital and supplied for the microstructural observations by optical and scanning electron microscopes. T-T-T diagrams for these steels were constructed by an image analyzer equipped with a light microscope. Thin foil specimens for transmission electron microscopy were prepared from 0.5 mm thick disk slit which were sliced from the heat-treated rods of 3 mm in length and diameter. The discs were subsequently thinned and electropolished by a conventional twin-jet polishing method using an electrolyte consisting of 10 vol% perchloric acid, 20 vol% glycerol and 70 vol% ethanol at room temperature and at the current of 45 mA. The foils were examined in a JEM 2000 EX transmission electron microscope operated at 200 kV.

III. Experimental Results

1. T-T-T diagrams

Figure 1 shows the T-T-T diagrams for these steels. As shown in Fig. 1 (a), Steel 1 (0.20 mass%C) has only one C-curve for eutectoid reaction (which will be refered to as the upper C-curve hereafter) in the temperature range above about 848K. The retardation of the transformation at temperatures about 850K may be due to the solute drag-like effects $^{[14]-[16]}$ of strong carbide forming elements such as Cr. The C-curve of bainite, however, could not be detected at temperatures between the lower limit of the upper C-curve and Ms point within the time period examined (up to holding for 86.4ks).

![Fig. 1 T-T-T diagrams for Steel 1 (a) and Steel 2 (b). The numbers within the diagrams indicate the amounts of transformation in percentage and the marks of LP, DP, BL, LB and Ms represent lamellar pearlite, degenerate pearlite, bainite-like structure, lower bainite and martensite starting point, respectively.](image)

![Fig. 2 optical micrographs of Steel 1 formed at temperatures between 1023K and 848K in the upper C-curve. (a) and (b) show LP and DP, respectively, and (c) through (f) show BL. (a) were transformed at 1023K for 1ks, (b) at 948K for 3.6ks, (c) and (d) at 898K for 36ks, (e) and (f) at 848K for 86.4ks, respectively.](image)
because the Ms point is higher than the temperature of bainite forms. In the case of Steel 2 (0.36 mass% C) where the Ms point lies below 623K, two clearly separated C-curves for both eutectoid reaction above 848K (the upper C-curve) and lower bainite at temperatures between 623K and Ms point (which will be referred to as the lower C-curve hereafter) were observed. Since upper bainite forms at temperatures above 623K, it could not be detected in Steel 2 within the time period examined (up to holding for 86.4ks) as in the case of Steel 1. It should be noted that the incubation time for transformation in Steel 2 is much shorter than that of Steel 1 as can be seen in Fig. 1 (b) and that transformation stasis could not be recognized during the formation of bainite-like structure (BL). The above results imply that the transformation products formed in the individual C-curves are significantly different in the formation mechanism.

2. Microstructures

Figure 2 shows the optical micrographs of Steel 1 isothermally transformed in the upper C-curve. Above about 973K where the noses of the C-curves of both steels exist, only lamellar pearlite (LP in Fig. 1) consisting of carbide lamellae and those of ferrite was observed as in Fig. 2 (a). At temperatures between the nose and 923K, LP was gradually collapsed as decreasing transformation temperature and degenerate pearlite (DP in Fig. 1) where the carbide lamellae were broken up into fine platelets as in the case of plain carbon steels was observed (Fig. 2 (b)). Since the formation mechanism of pearlite has been extensively studied in details \cite{1-4}, the characteristics and the formation mechanism of both LP and DP were not discussed in the present study. Figures 2 (c) through (f) show the structures transformed at temperatures between 898K and 848K in the upper C-curve of Steel 1. As shown in Fig. 2 (c), degenerate pearlite (DP) nucleated along the prior austenite grain boundaries. The acicular (or Widmanstatten-like) products subsequently formed from DP colony/austenite interfaces and grew into the parent austenite. The secondary pearlite colonies formed around the acicular products and enclosed them in the following stage of transformation as in Fig. 2 (d). With decreasing the transformation temperature, the amount of pearlite formed along the austenite grain boundaries at the initial stage of transformation was much reduced and the thickness of acicular products decreased significantly as in Fig. 2 (e). In this lower transformation temperature, the initially formed acicular structures were covered by pearlite colonies, and then secondary acicular products formed on both sides of the pearlite colony/austenite interface and grew in a dendritic fashion (Fig. 2 (f)). These structures exhibit a bainite-like morphology (BL) shown in Fig. 2 (f). These processes were repeated until the completion of transformation. It is interesting to note that although BL forms in the upper C-curves (Fig. 1), the morphology of BL is quite different from that of lamellar eutectoid product, but is very similar to that of bainite formed in the lower C-curve in optical microscopic observation. Figure 3 shows the scanning electron micrographs taken from a BL region of Steel 1 isothermally transformed at 898K for 36ks (Fig. 3 (a)), and transformed at 848K for 86.4ks (Fig. 3 (b)) in the upper C-curve. Very coarse and long elongated carbides (white regions) were
observed. These elongated carbides, however, were not continuous but broken up into several fragments. Figure 4 shows the transmission electron micrographs taken from a central region of BL in Steel 1 isothermally transformed at 873K for 86.4ks. Here (a) and (b) are the bright field images, and (c) through (e) show the selected area diffraction pattern for (b), the schematic illustration of (c) and the stereographic analysis, respectively. As can be seen in Fig. 4 (a), there are two rows of very coarse carbides with considerably fine carbide particles between them. The bright field image (b) was taken from a fine carbide particle region. These fine carbide particles were identified as M(Cr, Fe)\(_2\)C\(_6\) by the selected area diffraction pattern shown in Fig. 4 (c) and were related to the ferrite with Kurdjumov-Sachs (K-S) relationship.\(^{17}\) The growth direction of the fine carbide particles was very close to \(<110>_{\text{M}_{23}\text{C}_6} \parallel <111>_{\alpha}\) as shown in Fig. 4 (e). The crystal structure of these coarse carbide particles, however, changed from cementite, M\(_{23}\text{C}_6\) to M(Cr, Fe)\(_2\)C with increasing isothermal holding time. Figure 5 is the dark field image showing M\(_{23}\text{C}_6\) particle distribution taken from the central region of BL in Steel 1 isothermally transformed at 898K for 28.8ks. As shown in Fig. 5, M\(_{23}\text{C}_6\) particles were distributed periodically as bands and were appeared as some parallel rows of M\(_{23}\text{C}_6\) in the high magnification micrograph. Thus, the transformation is thought to proceed by discontinuous precipitation of M\(_{23}\text{C}_6\) and ferrite growth, i. e., interphase boundary precipitation.\(^{18}\) Figure 6 shows TEM micrographs taken from also a sidewise-growth interfaces of a BL region in Steel 1 formed at 898K for 28.8ks.
Here (a) through (e) are the bright field image, the dark field image using a carbide reflection, the selected area diffraction pattern, the schematic illustration of (c) and the stereographic analysis, respectively. Coarse elongated carbides arranged horizontally were M₆C. In the upper side of them, needle-like carbides arranged in a specific direction were observed. The fibrous carbides formed in a Fe-5 %Cr-0.2 %C alloy were observed only at temperatures higher than that of nose of the upper C-curve in the present 8 %Cr alloys. These carbide particles were identified as also M₆C₅ by the selected area diffraction pattern shown in Fig. 6 (c) and were related to the ferrite with K-S relationship. The growth direction of them is also close to $<110>_{M₆C₅} \parallel <111>_{α}$ as shown in Fig. 6 (e). While in the lower side, rows of fine carbide particles also recognized as in Fig. 4. These needle-like and spot-like (or row-like) carbides are probably eutectoid decomposition products but the difference in the detailed growth mechanisms for them is not clear at present. Figure 7 shows the formation processes of BL in Steel 2 at 848K. Here (a) through (c) are the bright field images, (d) and (e) are the selected area diffraction pattern for (c) and the schematic illustration of (d), respectively. The carbide plates formed at the initial stage of transformation were enclosed by ferrite as in Fig. 7 (a). These structures nucleated side-by-side and formed pearlite-like packets as can be seen in (b) and (c). These carbide plates were identified as M₇C₃ by the selected area diffraction pattern shown in Fig. 7 (d). The structure of these carbide lamellae gradually changed to M₆C₅ with increasing isothermal holding time. Figure 8 represents the result of the trace normal analysis for M₆C₅ needles with fixing the K-S orientation relationship. Since these carbides grow preferentially in edgewise direction, the final structure appeared to be acicular as in the case of bainite. The $<110>$ growth direction of M₆C₅ is parallel to the $<111>_{α}$. This direction may correspond to $<110>_{γ}$ in the parent phase.
3. Interlamellar Spacing

Figure 9 shows the interlamellar spacings at various degrees of undercooling in the upper C-curve. The solid line in Fig. 9 is for pearlite in plain carbon steels. The values obtained in the present research for LP and BL at temperatures between 973K and 848K were plotted and can be expressed by a broken line. These lines exhibit the same inclination against the supercooling to one another. This result suggests that BL is not bainite but a sort of eutectoid transformation products.

IV. Discussion

1. Formation mechanism of BL

Although BL forms in the upper C-curves of the T-T-T diagrams (Fig. 1), it comprises lamellar pearlitic structure and interphase boundary precipitation of carbides (Fig. 4 through 8), and the logarithms of interlamellar spacings of them exhibit the same inclination as that constructed for pearlite.
in plain carbon steels (Fig. 9). These results indicate that, although the morphology of BL is similar to that of bainite formed in the lower C-curve of the T-T-T diagram, the formation mechanism of BL is definitely different from that of bainite but very similar to those of eutectoid products. The formation processes of BL can be depicted as in Fig. 10. During the isothermal holding prior to transformation, both interstitial carbon and substitutional Cr atoms which are strong carbide forming elements will segregate to austenite grain boundaries (Fig. 10 (a)). Carbide particles will precipitate there as shown in Fig. 10 (b). The austenite surrounding this carbide nucleus will be depleted in carbon and will precipitate ferrite adjacent to the carbide nucleus as shown in Fig. 10 (c). This process will be repeated side-by-side and will form a colony along the austenite grain boundary. Further growth of eutectoid products will become quite difficult in such a situation because it requires long range diffusion of substitutional elements. In order to proceed further transformation under such a situation, these processes represented in Figs. 10 (b) and (c) will be repeated ((d) and (e)). Then in the regions adjacent to these elongated eutectoid structures, i.e., in both sides of them, the interphase precipitation will occur. If these transformation events mentioned above occur also on the interphase precipitation areas, the dendritic structure consisting of them will be resulted. The kind of carbides to form in this stage of transformation will depend on the transformation temperature. In the case of M_{23}Cr, it was related to the ferrite with K-S relationship and the growth direction of it was close to $<110>M_{23}Cr||<111>_a$ which may correspond to $<110>_a$ in the parent phase. Assuming that the ferrite was related to the austenite with K-S relationship, these carbide should be related to the austenite by the cube-cube relationship. The activation energy to nucleate a carbide on a semicoherent ferrite/austenite interface will be much reduced in comparison with that for the nucleation on an incoherent interface.

2. Differences between BL and bainite

It has been well established that bainite and eutectoid reactions have their own C-curves in T-T-T diagrams of steels. In the case of present high Cr steels, Steel 2 has clearly separated two C-curves as shown in Fig. 1. This is, of course, not a direct evidence indicating that BL is a kind of eutectoid products, but, if the mechanism of BL is the same as that of eutectoid products, it will form in the same C-curve. This indicates that the mechanism of BL formation is different from that of bainite. It has also been well known that the carbide particles precipitated within bainite are specifically cementite and any alloy carbides do not precipitate even in steels containing large amounts of strong carbide forming elements. In the case of present study, however, most of the carbides precipitated in the upper C-curves were M_{23}Cr and only cementite precipitated in the lower C-curve in which bainitic reaction occurs. This indicates that the partition of substitutional atoms during bainite reaction does not occur, but that the substitutional alloying
elements are partitioned at the advancing colony/interphase boundaries during BL formation. The interlamellar spacing of BL changes continuously with decreasing transformation temperature, and has the same inclination as that constructed for pearlite in carbon steels. If BL is formed as the same process as bainite, the interlamellar spacing of it will not lie on this line. From the above facts, it can be concluded that the formation mechanism of BL is similar to lamellar pearlite. This results also indicate that bainite should not be classified only by the morphology of carbide precipitated.

V. Conclusions

The mechanism of the bainite-like structure (BL) formation at lower temperatures in the upper C curve in a T-T-T diagram of 8 mass%Cr steels has been investigated mainly by means of metallographic observations and the following results were obtained.

1. When the Cr steel austenite with a higher carbon content is isothermally decomposed at temperatures between $\text{Ae}_1$ and Ms points, clearly separated two C-curves in a T-T-T diagram are resulted. The upper C-curve arises from a eutectoid reaction, but bainite reaction occurs in the lower C-curve.

2. At lower temperatures in the upper C-curve, the acicular structure forms and grows preferentially in edgewise-growth direction. Dendritic growth of the acicular structure leads to bainite-like structure in morphology.

3. The BL was consisted of fine lamellar structures covered by interphase precipitation products. The carbide particles precipitated in BL are not cementite but mainly $\text{M}_2\text{C}_6$ relating to ferrite with K-S relationship. The growth direction of $\text{M}_2\text{C}_6$ was close to $<110>_{\text{M}_2\text{C}_6} \parallel <111>_{\alpha}$, which may correspond to $<110>_{\alpha}$, in the parent phase.

4. The interlamellar spacing of BL changes with supercooling continuously in a similar manner to that for eutectoid products.

5. The transformation mechanism of BL is the same as that of eutectoid decomposition products. Therefore, BL is quite different from bainite where both diffusional and shear processes are thought to operate.

Acknowledgements

The authors would like to express his sincere thanks to Sumitomo Metal Industries, Ltd. for supplying the materials. Thanks are also due to the members of the Advanced Instrumentation Center, Ehime University, for providing the facility of JEM 2000EX electron microscope.

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