Influence of Prior Carbide or Ferrite Precipitation upon Incubation Period for Bainitic Transformation*

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Synopsis

The influence of prior carbide or ferrite precipitation on the incubation period for bainitic transformation was studied using a hyper- (SUJ 2) and hypo-eutectoid (SMCM 8) steel.

The main results obtained are as follows:

1. The incubation period for upper bainitic transformation is remarkably shortened by the prior carbide precipitation, while that for pearlitic transformation is slightly affected.
2. The incubation period for upper bainitic transformation is also remarkably shortened as the carbon content in the austenite is decreased.
3. The incubation period for upper bainitic transformation is prolonged by the prior ferrite precipitation.
4. The incubation period for lower bainitic transformation is shortened by prior ferrite precipitation.

I. Introduction

The isothermal transformation diagram (TTT diagram) and continuous cooling transformation diagram (CCT diagram) are widely utilized for its convenience of knowing the transformation behavior of steel. These diagrams have been known to be varied considerably by alloying elements and heat treatment conditions. For the proper use of these diagrams, the full understanding of incubation period for pearlitic and bainitic transformation is quite important. For instance, a change in cooling rate during continuous cooling results in a different transformation behavior from that shown by the CCT diagram. Therefore, to predict an accurate transformation behavior, the consumption of incubation period for each of pearlitic and bainitic transformation must be incorporated into the CCT diagram.

In the present investigation, the influence of prior carbide or ferrite precipitation upon the incubation period for bainitic transformation was studied using a hyper- (SUJ 2) and a hypo-eutectoid (SMCM 8) steels.

II. Experimental Procedure

The chemical composition of the steels used are shown in Table 1. In SUJ 2 steel, specimens of 4 mm φ × 40 mm were cut from a wire rod after a spheroidizing annealing (the average diameter of spheroidal carbide was about 0.5 μ). In SMCM 8 steel, specimens of 3 mm φ × 10 mm were cut from a wire rod annealed at 900°C.

Figure 1 shows heat treatment diagrams with which the incubation period for isothermal transformation was determined. In Process 1, specimens austenitized in charcoal to prevent decarburization were isothermally held at various temperatures for various length of time in a lead bath and quenched in 5% brine. From hardness measurement and structural observation, the incubation period at various temperatures was determined. In Process 2, specimens austenitized likewise were first held in a lead bath kept at a temperature \( T_2 \) for various length of time so as to precipitate carbide at the grain boundaries of austenite, immediately quenched into another bath for isothermal holding and finally quenched in 5% brine to determine the incubation period.

Table 1. Chemical compositions of steels (wt%)

<table>
<thead>
<tr>
<th>Steel</th>
<th>C</th>
<th>Si</th>
<th>Mn</th>
<th>P</th>
<th>S</th>
<th>Cu</th>
<th>Ni</th>
<th>Cr</th>
<th>Mo</th>
<th>Al</th>
</tr>
</thead>
<tbody>
<tr>
<td>SUJ 2</td>
<td>0.98</td>
<td>0.24</td>
<td>0.41</td>
<td>0.017</td>
<td>0.009</td>
<td>0.20</td>
<td>0.05</td>
<td>1.37</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>SMCM 8</td>
<td>0.40</td>
<td>0.30</td>
<td>0.71</td>
<td>0.016</td>
<td>0.006</td>
<td>0.13</td>
<td>1.79</td>
<td>0.78</td>
<td>0.24</td>
<td>0.027</td>
</tr>
</tbody>
</table>

Fig. 1. Schematic diagram showing heat treatment to examine incubation period for transformation in SUJ 2 and SMCM 8 steels

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In Processes 3 and 5, the incubation period of isothermal transformation was determined by the change in thermal expansion, using Formaster $F$, and in Processes 4 and 6, incubation period was determined after prior ferrite or carbide formation.

For the optical microscope observation, 5% nitral or 5% picral was employed as the etching solution.

III. Experimental Results and Discussion

1. Effect of Prior Carbide Precipitation upon the Incubation Period for Upper Bainitic Transformation

Figure 2 shows the isothermal transformation diagram of SUJ 2 steel where the incubation periods were measured for specimens austenitized at 1050°C (austenite single phase) for 30 min and immediately quenched to each temperature. The transformation completion lines in this diagram are drawn using the reported data. For the temperature range where a transformation of carbide occurs prior to pearlitic or bainitic transformation, the incubation period was defined as the length of time at which respective transformation starts. (The incubation period for pearlitic transformation is hereinafter abbreviated as pearlitic incubation period or P.I.P., and that for bainitic transformation as bainitic incubation period or B.I.P.) The carbide precipitates around the austenite grain boundaries prior to the formation of pearlite from the austenite grain boundaries (see Photo. 1). In the bainitic transformation, there are two cases. The one is where precipitation of carbide first occurs around the austenite grain boundaries and then the bainite forms along the carbides (see Photo. 2 (a)). The other, which is occasionally observed, is where the precipitation of carbide prior to the transformation is not so evident (see Photo. 2 (b)).

The specimens austenitized at 1050°C for 30 min (same as the above) were quenched to 760°C, just above the $A_t$ temperature ($A_t$ is 750°C in this steel), and held at this temperature for 0, 5 and 30 sec, respectively, according to Process 2. Then these were immediately quenched to various temperatures between $A_t$ and 400°C and held at these temperatures to measure incubation period for pearlitic or bainitic transformation (hereinafter called the upper bainitic incubation period or abbreviated as upper B.I.P.). The measured incubation periods are plotted in Fig. 3. It should be noted that the holding at 760°C does not consume P.I.P. since it is above the $A_t$ temperature. However, a precipitation of carbide starts after holding at 760°C for 7 sec.

The curve of 0 sec holding at 760°C in Fig. 3 is the same as the curve in Fig. 2. 5 sec holding at 760°C did not show any significant influence on both the P.I.P. and upper B.I.P. 30 sec holding, however, significantly shortened the upper B.I.P., and slightly shortened the P.I.P. It has to be noted that 5 sec holding at 760°C does not cause any precipitation of carbide, while 30 sec causes a considerable amount of the carbide precipitation. That is, the precipitation of carbide (hereinafter called primary carbide) de-
increases the carbon concentration in the austenite, and remarkably shortens the upper B.I.P., but does not much affect the P.I.P. The fact that the incubation period for pearlitic transformation of a steel containing Cr is not affected so much by the prior isothermal holding, is considered due to a negligible change in the concentration of alloying elements (in this case Cr) in the austenite, since the stage now in consideration is just the initial stage in which the special carbide reaction does not occur yet.

In order to find the influence of consumption of the P.I.P. on the B.I.P., the specimens austenitized likewise were quenched to 760°, 650° and 550°C and held at these temperatures for 30, 10 and 30 sec, respectively. Those specimens were immediately quenched to 450°C and the B.I.P. was measured. The results obtained are shown in Fig. 4. The holding at 550°C for 30 sec must consume some of the B.I.P., since 550°C is below \( A_N \), the maximum temperature at which consumption of B.I.P. can occur (in this case \( A_N \) was estimated to be 590°C from the TTT diagram). However, this consumption of incubation period is negligibly small when it is compared with the B.I.P. at 550°C (10⁴ sec).

As seen in Fig. 4, the B.I.P. at 450°C is shortened by every prior holding. The shortening effect is largest for the holding at 760°C for 30 sec and the holding at 650°C for 10 sec and 550°C for 30 sec follow. Comparing the same holding time, 30 sec, at 550° and 760°C, the latter shortened the B.I.P. more than the former. This can be explained from the optical microscope observation that the amount of primary precipitated carbide is larger in the latter case than the former. As it is noted from Fig. 2, both the holding at 650°C for 10 sec and the holding at 550°C for 30 sec are equivalent to the 80% consumption of P.I.P., while the former shortened the B.I.P. more than the latter, in spite of the shorter holding time. This indicates that the consumption of the P.I.P. does not largely influence the B.I.P., but B.I.P. is rather influenced by the amount of primary precipitated carbide. Since the holding at 650°C for 10 sec produces more carbide than holding at 550°C for 30 sec, it shortens B.I.P. more than the latter. As discussed above, Fig. 4 also indicates that the B.I.P. is shortened by the increase in the amount of primary precipitated carbide which is equivalent to decrease the carbon content in the austenite.

Figure 5 shows the influence of the amount of retained (undissolved) carbide, which was changed by changing the austenitizing temperature, on the pearlitic and upper bainitic transformations. Here, the carbide is completely dissolved when it is austenitized at 1050°C and half dissolved when austenitized at 840°C, as seen in Photo. 3. As seen in Fig. 5, the specimen austenitized at 840°C showed a slightly

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**Fig. 3.** Influence of holding time at 760°C on the incubation period for isothermal transformation of SUJ 2 steel, austenitized at 1050°C for 30 min

**Fig. 4.** Influence of holdings at 760°C for 30 sec, 650°C for 10 sec, and 550°C for 30 sec on the incubation period for isothermal bainitic transformation of SUJ 2 steel at 450°C, austenitized at 1050°C for 30 min

**Fig. 5.** Influence of austenitizing temperature on the incubation period for pearlitic and bainitic transformations of SUJ 2 steel

**Photo. 3.** Microstructure of SUJ 2 steel quenched into 5% brine from austenitizing at 840°C for 30 min. Etched in 5% picral. (×800)
shorter P.I.P. than that at 1 050°C, while the upper B.I.P. of the former is substantially shorter than that of the latter. It is likely that the carbon content in austenite increases with the increase in the amount of undissolved carbide which decreases the upper B.I.P.

Murakami and Imai,1) Wever and Rose,2) and Imai3,4) have reported various factors which affect the isothermal transformation diagram. According to them, the carbide forming elements such as Cr, Mo, V, Ti and Nb remarkably prolong the P.I.P. by stabilizing the super cooled austenite and preventing the diffusion of carbon. However, these carbide forming elements do not remarkably prolong the B.I.P. Furthermore, when the austenite grain size becomes larger, the P.I.P. becomes longer, while the B.I.P. hardly changes. Since the nucleation of pearlite starts around the austenite grain boundaries, they have explained that the above phenomenon is due to the reduction of grain boundary area per unit volume of austenite with the increase in the austenite grain size. Both this fact and the present results shown in Fig. 5 suggest that the factors which influence the P.I.P. are the austenite grain size and the content of alloy elements in the austenite. However, the carbon content in the austenite slightly influence the P.I.P. Since P.I.P. and B.I.P. show different behaviors for the prior holding and austenitizing temperature, the nucleation mechanisms of pearlite and bainite are considered to be different.

Formerly, the nucleus of pearlite was considered to be the cementite5) and later it was proposed that ferrite6,7) can be the nucleus of pearlite as well as the cementite. Recently, it is considered that nucleus of pearlite will be the ferrite in hypo-eutectoid steels and cementite in hyper-eutectoid steels.8) The nucleus of bainite is generally considered as ferrite.9,10) Since SUJ 2 steel is a hyper-eutectoid steel, the nucleus of the pearlite is considered to be cementite and that of the upper bainite is ferrite. Therefore, the suppression of the upper bainitic transformation in this steel by the increase in carbon content in the austenite will be due to the suppression of the ferrite formation which serves as the nucleus of bainite formation. However, the nucleation mechanisms are not clear yet and this matter is left for a future study.

2. Influence of Prior Carbide Formation upon Incubation Period for Lower Bainitic Transformation

Figure 6 shows the incubation periods of bainitic transformation in SUJ 2 steel measured at 400°C, 350°C and 300°C after austenitized at 1 000°C for 10 min and those measured at 400°C, 350°C and 300°C after formation of carbides by holding at 760°C for 60 sec following the same austenitizing treatment. As seen from Fig. 6, the incubation periods of both the upper and lower bainitic transformations are substantially accelerated by the prior carbide formation.

3. Influence of Prior Ferrite Formation upon Incubation Period for Bainitic Transformation

Figure 7 shows the TTT diagram of SNCM 8 steel austenitized at 860°C for 10 min. The transformation completion lines in this diagram are drawn using the reported data.11) The specimens austenitized at 860°C for 10 min were quenched to 630°C and held at this temperature for 0, 300, 900 and 3 600 sec, respectively. Then the specimens were quenched to 450°C, 400°C and 350°C to measure the B.I.P. The results obtained are shown in Fig. 8. As is seen, the B.I.P. at 450°C and 400°C becomes longer as the holding time at 630°C becomes longer. The influence of holding at 630°C appears larger on the B.I.P. at 450°C than that at 400°C, and the B.I.P. at 350°C is slightly shortened by the holding at 630°C. That is, the direction of the prior holding effect is reversed at the boundary of about 370°C. On the other hand, by the holding at 630°C, the precipitation of ferrite starts at 350 sec and the pearlitic transformation starts at 8 000 sec, as shown in Fig. 6. As the holding time at 630°C becomes longer, the amount of ferrite increases and decreases the carbon content in the austenite.

Bainite has been generally classified into two types according to the transformation temperature; upper and lower.12,13) The temperature 370°C at which the influence of holding at 630°C on the B.I.P. is reversed, as shown in Fig. 7, may correspond to the temperature which divides the bainite into the upper
and lower ones. From Figs. 6 and 7, it is considered that the increase in carbon content in the austenite by the precipitation of ferrite will prolong the upper B.I.P. and shorten the lower B.I.P.

Higgins and Axom\(^1\) have reported that, in En 26 steel, the bainitic transformation at 320°C is accelerated by the precipitation of ferrite. This coincides with the present results at 350°C, although Higgins and Axom did not report the transformation products at 320°C.

The opposite influences upon the upper and lower bainitic transformations are presumably due to the difference in their nucleation mechanism. This may be understood by assuming that the nucleus of the upper bainite is ferrite and the formation of which is retarded with the increase in the carbon content in the austenite. All the results shown in Figs. 3 to 8 indicate that the incubation period of the upper bainite is shorter when the carbon content of the austenite is lower. Thus the lower carbon content makes it easier to form the nucleus of the upper bainite. On the other hand, the lower bainitic transformation is influenced little by the carbon content of the austenite but is largely shortened by the prior precipitation of either ferrite or carbide. For the nucleation mechanism of bainitic transformation, there have been many proposals.\(^2\) However, further consideration is still needed.

**IV. Conclusions**

In the present investigation, the influence of carbon content in the austenite on the incubation period for bainitic transformation was studied using a hyper- and a hypo-eutectoid steels. In a hypo-eutectoid steel, the carbon content was changed by changing the amount of primary precipitated carbide or changing the amount of dissolved carbide. In a hypo-eutectoid steel, the carbon content was changed by changing the amount of primary precipitated ferrite. The main results obtained are as follows:

1. The incubation periods for upper and lower bainitic transformations are remarkably shortened by the prior carbide precipitation, while that for pearlitic transformation is hardly affected.

2. The incubation period for upper bainitic transformation is remarkably shortened by the increase in the amount of undissolved carbide by lowering austenitizing temperature.

3. By the prior ferrite precipitation, the incubation period for upper bainitic transformation is prolonged, while that for lower bainitic transformation is shortened.

**Acknowledgements**

The authors would like to thank Mr. T. Aizawa, Researcher in the Research Division of Aichi Seiko Co, Ltd., for his assistance in this study.

**REFERENCES**