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Morphology Map of Bainites in 2% Si Steels

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Abstract. A metallographic study of isothermal transformation products formed at the early stage of transformation was made in silicon alloyed high-carbon steels (C wt%=0.6, 0.8, 1.1 and 1.4) in the temperature range between 700 and 200 °C. Observations are summarized as a "morphology map" showing the formation temperature-carbon content fields of isothermal transformation products. In all steels investigated, the proeutectoid ferrite, upper bainite and lower bainite are formed at temperatures below the extrapolated A_3 line and above 600 °C, between 550 and 400 °C, and below 350 °C and above the M_s temperature, respectively. The microstructural- B_s temperature and the transition temperature from upper bainite to lower bainite are independent of the bulk carbon content, and around 550 and 350 °C, respectively. It is shown that above results can be explained by a diffusional model for the proeutectoid ferrite formation and a displacive model for the bainite formation.

1. INTRODUCTION

The transformation mechanism of bainite has been a topic of discussion[1], and antipodal models (*diffusional or displacive*) have been proposed. The diffusion controlled reaction model[2] describes the bainitic reaction as an extension of the proeutectoid ferrite reaction. By this model, the bainite must be observed in the stable or metastable ($\alpha + \gamma$) two-phase field in the phase diagram. By a displacive model[3] including the statistical fluctuation of carbon concentration in the austenite, on the other hand, the bainite in an Fe-M-C ternary alloy (M: a substitutional element) should be formed at temperatures below the M_s temperature of an Fe-M binary alloy, which is the alloy with carbon atoms removed from the ternary alloy, and the B_s temperature is independent of the bulk carbon content.

The present results indicate that the bainitic ferrite develops by the displacive mechanism rather than the diffusional mechanism.

2. EXPERIMENTAL

The chemical compositions of the steels used are given in Table 1 along with their M_s temperatures which were determined metallographically. Specimens of 17 × 12 mm in size were cut from hot rolled and grounded plates of 1 mm thickness. Austenitizing was carried out at $A_{cm} + 60$ °C for 10 min under dynamically evacuated conditions. The specimens were quenched in a Pb bath at temperatures between 700 and 600 °C or in an inert $\text{NaNO}_2 - \text{KNO}_3$ bath at temperatures between 550 and 200 °C, transformed for various periods of time, and finally quenched into water. Specimens for light and SEM metallography were etched with 2% nital.

Table 1 Chemical compositions (wt%) and Ms temperatures (°C) of the steels investigated

Steel	C	Si	Mn	P	S	Ms
Fe-2Si-0.3C	0.304	1.99	tr.	0.006	0.001	330
Fe-2Si-0.6C	0.616	2.01	tr.	0.004	0.001	270
Fe-2Si-0.8C	0.789	2.020	tr.	0.003	0.004	240
Fe-2Si-1.1C	1.118	2.089	tr.	0.002	0.003	175
Fe-2Si-1.4C	1.394	2.045	tr.	0.002	0.003	150

3. RESULTS

Figs. 1(a)–(d) show microstructures of isothermal transformation products at relatively early stage of transformation at 600, 500, 400 and 300 °C in the Fe-2Si-0.6C steel. At 600 °C, the pearlite (P) and the proeutectoid ferrite (PF) form as shown in Fig. 1(a). The matrix is martensite formed from untransformed austenite on quenching from the isothermal holding temperature. At 500 and 400 °C (Figs. 1(b) and (c)), the morphology of the product is markedly different from that of the proeutectoid ferrite. The shape of the product resembles a letter "一" of *kanji*. This structure has been called "upper bainite" in other investigation of silicon steels[4]. The 300 °C product (Fig. 1(d)) characterized by a fine line is the "lower bainite" in silicon steels[4]. The same microstructural changes caused by decreasing the isothermal transformation temperature are shown in Figs. 2 to 4 for Fe-2Si-0.8, 1.1 and 1.4%C steels, respectively.

The results of microstructural observation throughout the temperature range 700 to 200 °C are summarized as a "morphology map" in Fig. 5. Marks $\blacklozenge$, $\diamond$, $\circ$ and $\triangle$ in Figs. 5 are placed at temperature–carbon content coordinate at which the pearlite, pearlite + proeutectoid ferrite, upper bainite and lower bainite were detected. As indicated in Fig. 5, it can be seen that (i) the bainite has its own formation temperature range different from that of proeutectoid ferrite, (ii) the microstructural–Bs temperature is about 550 °C and independent of the bulk carbon content, and (iii) the transition of bainite morphology from the upper bainite to the lower bainite occurs about 350 °C, and this is also independent of the bulk carbon content.

Excepting the transition temperature of bainite morphology, these results are in good agreement with that reported in 2Si-1Mn-0.34C and 2Si-1Mn-0.59C steels[5].

4. DISCUSSION

According to the displacive model[3], the carbon poor zones in the parent austenite are formed as a results of statistical fluctuation of carbon concentration. When the Ms temperature in these zones rises up to the isothermal transformation temperature, the bainite nucleates martensitically. This model predicts that the Bs temperature of an Fe-2Si-C ternary alloy corresponds to the Ms temperature of the Fe-2Si binary alloy, and is independent of the bulk carbon content. Ms temperatures in Fig. 5 were determined metallographically. The upper and lower error bars represent the lowest temperature at which martensite was not observed and the highest temperature at which martensite was observed, respectively. The Ms temperature extrapolated linearly to the zero carbon content is 400 °C, and does not correspond to the microstructural–Bs temperature. However, the Ms temperature rises as shown by a dashed line in Fig. 5 because it rises rapidly in ultra-low carbon steels[6]. Thus, it is explained that the Bs temperature is a constant of 550 °C by the displacive mechanism[3].

It can also be explained the transition temperature of bainite morphology by the displacive model as follows. Figs. 6(a) and (b) show the three-dimensional shapes of upper and lower bainites, respectively. A plane-1 and plane-2 are perpendicular to each other. The edge of the two planes is represented by W-E. The two planes were observed by a scanning electron microscope

Fig.1 Scanning electron micrographs of isothermal transformation products in an Fe-2Si-0.6C steel. (a) 600 °C 10s, (b) 500 °C 10s, (c) 400 °C 15s, (d) 300 °C 30s.

Fig.2 Scanning electron micrographs of isothermal transformation products in an Fe-2Si-0.8C steel. (a) 600 °C 10s, (b) 500 °C 20s, (c) 400 °C 45s, (d) 300 °C 255s.

Fig.3 Scanning electron micrographs of isothermal transformation products in an Fe-2Si-1.1C steel. (a) 600 °C 10s, (b) 500 °C 45s, (c) 400 °C 120s, (d) 300 °C 600s.

Fig.4 Scanning electron micrographs of isothermal transformation products in an Fe-2Si-1.4C steel. (a) 600 °C 20s, (b) 500 °C 90s, (c) 400 °C 1200s, (d) 300 °C 1080s.

Fig. 5 Morphology map of isothermal transformation products in Fe-2Si-C steels. Marks ◆, ◇, ○ and △ represent the pearlite, pearlite + proeutectoid ferrite, upper bainite and lower bainite, respectively.

Fig. 6 Two surface SEM micrographs showing three dimensional shape of bainites formed in an Fe-2Si-0.8C steel. (a) lath shaped upper bainite, 400 °C, 165s, (b) plate shaped lower bainite, 300 °C, 190s.

with long focal distance. It can be seen that the three-dimensional shapes of the upper and lower bainites are the lath and plate, respectively. The morphology of bainites varies with their formation temperature.

The morphology of martensite, however, depends on the bulk carbon contents, and is a lath in plain low carbon steels and a plate in plain high carbon steels[7]. The morphology of martensites in the present steels with 2% silicon is plate. Figs. 7(a) and (b) show the examples in the Fe-2Si-0.3C and Fe-2Si-0.6C steels. Therefore, the lath martensite will be formed below 0.3% carbon in 2% silicon alloyed steels. The critical carbon content at which the martensite morphology varies from plate to lath will be about 0.2%C as shown in Fig. 5.

From the morphological similarity between the bainite and martensite, we propose a new mechanism on the transition between the upper and lower bainites. "If the carbon concentration at the nucleation site of bainite is as low as that forms the lath martensite, the lath shaped bainite, i.e., the upper bainite is formed. If it is as high as that forms plate martensite, the plate shaped bainite, i.e., the lower bainite, is formed." Based on the above proposal, we can explain that the transition temperature of bainite morphology is 350 °C because the critical carbon content at which martensite morphology varies from plate to lath is about 0.2%C, and the M_s temperature is independent of the bulk carbon content since the statistical fluctuation of carbon concentration in austenite is assumed.

The proeutectoid ferrite and pearlite are observed in a temperature range higher than that of bainites. However, the proeutectoid ferrite was not observed at 700 °C in the Fe-2Si-1.1C steel and above 650 °C in the Fe-2Si-1.4C steel as shown in Fig. 5. The A_1 , A_3 and A_{cm} lines in

Fig. 7 Optical micrographs showing the morphology of martensite formed just below the M_s temperature is plate. (a) Fe-2Si-0.3C steel, (b) Fe-2Si-0.6C steel.

Fig. 5 were determined by dilatometric measurements. The microstructural-PFs temperature is the highest temperature at which the proeutectoid ferrite is observed. The microstructural-PFs line and the A_3 line are connected smoothly. This means that the microstructural-PFs line corresponds to the metastable extrapolated A_3 line. The facts that the proeutectoid ferrite forms in the metastable ($\alpha + \gamma$) two-phase field, and the highest temperature at which the proeutectoid ferrite is observed corresponds to the extrapolated A_3 line can be explained by the diffusional model[2] as described in the introduction.

5. SUMMARY

A metallographic study of isothermal transformation products was made in 2% silicon alloyed high-carbon steels ($C\% = 0.6, 0.8, 1.1$ and 1.4) in the temperature range between 700 and 200°C . It was shown that the proeutectoid ferrite transforms diffusively, but the bainite nucleates displacively. From the morphological similarity between the bainite and martensite, we proposed a new mechanism on the transition between the upper and lower bainites as follows. "If the carbon concentration at the nucleation site of bainite is as low as that forms the lath martensite, the lath-shaped bainite, *i.e.*, the upper bainite, is formed. If it is as high as that forms plate martensite, the plate-shaped bainite, *i.e.*, the lower bainite, is formed."

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