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Dynamic Observation of Bainite Transformation in a Fe-C-Mn-Si Superbainite Steel

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Abstract: The dynamic observations of bainitic transformation in a Fe-C-Mn-Si superbainite steel were conducted on a high temperature laser scanning confocal microscope. It is indicated that the mutual intersection of bainite sheaves often occurs during growth of bainite ferrite, resulting in an interlocked bainite microstructure. Moreover, bainite transformation is promoted by higher austenization temperature and the longer and finer bainite platelets are obtained. Further, The average growth rate of bainite after austenization at 1 100 ℃ is calculated as 5.8 $\mu m \cdot s^{-1}$. In situ observation investigation makes it possible to identify bainite transformation in real time during isothermal holding.

Key words: bainite transformation; dynamic observation; microstructure; growth rate

1 Introduction

Investigation on bainite transformation can analyze the influence of various factors on transformation to obtain expected microstructure and properties by controlling the transformation process. So far a lot of research works on bainitic transformation have been reported[1-4], most of which were conducted by conventional metallographic investigation. Only few researches on bainite transformation were carried out with in situ observation method[5-8]. Zhang *et al*[5] studied bainitic transformation of a 0.15%C steel on high temperature laser scanning confocal microscope (LSCM). Kolmskog *et al*[6] directly observed bainite formation below martensite starting temperature (Ms) on LSCM. Additionally, Kang *et al*[7] investigated the nucleation and growth of bainite using in situ transmission electron microscope observation. Yada *et al*[8] studied the lengthening of bainitic plates in iron-nickel-carbon alloys using a hot-stage microscope. The conventional metallographic investigation can only watch the bainite morphology after transformation for a certain time. The study of continuous nucleation and growth process of bainite cannot be realized by this method. In contrary, real-time observation of bainitic transformation can be conducted continuously, which has more advantages over conventional method.

Further, although much information on transformation feature of other bainitic steels is available, no scientific data on transformation behavior of superbainite steel, a promising high strength steel, had been reported. In situ observations of transformation of a superbainite steel were conducted on LSCM. The phase transformation and the morphological development of tested steel were analyzed.

2 Experimental

The steel was a superbainite steel with the chemical composition of 0.40 C, 2.81 Mn, 2.02 Si and balance Fe (wt%). The material was refined in a vacuum induction furnace and cast into a small ingot followed by rolling to the flat of 10 mm thick.

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Samples for LSCM were machined to a cylinder of 8 mm diameter and 10 mm height. The top and bottom surfaces of samples were polished conventionally to keep the measurement face level. The investigations were performed on a VL2000DX LSCM according to the test procedures as shown in Fig.1. The specimen chamber was initially evacuated to 6×10^{-3} Pa before heating and argon was used to protect the specimens from surface oxidation. The bainite start and finish temperatures and M_s were 423 ℃, 305 ℃, and 256 ℃, respectively, calculated by MUCG83 software developed by Bhadeshia at Cambridge University. Therefore, the isothermal temperature for bainitic transformation was chosen as 330 ℃.

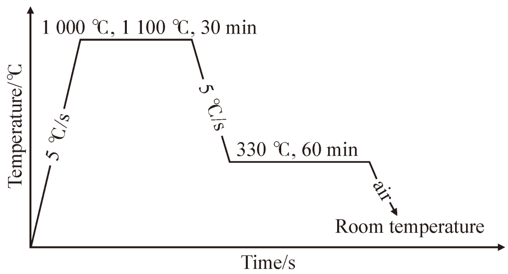

Fig.1 Test procedure of in situ observation

The specimens were heated at a rate of 5 $℃\cdot s^{-1}$ to two austenization temperatures (*i e,* 1 000 ℃ and 1 100 ℃) and held for 30 min. Austenite grains would become larger with increasing austenization temperature[9]. The purpose of using two heating temperatures was to analyze the effect of austenite grain sizes on bainitic transformation. Then the specimens were cooled to 330 ℃ at a rate of 5 $℃\cdot s^{-1}$ and isothermally treated for 60 min for transformation followed by final air cooling to room temperature. The LSCM images were recorded continuously with 15 frames at 100× magnification per second during isothermal treatment. A video showing the bainite transition process was simultaneously obtained. The principle for in situ observation of bainite nucleation and growth is the relief phenomenon of new phase occurring during phase transition due to volume change resulted from lattice change.

3 Results and discussion

3.1 Bainite transformation

It is normally believed that nucleation of bainite ferrite initiates on grain boundary, inclusion and dislocation because of carbon diffusion in parent austenite grain. During the incubation period of bainite transformation, carbon-enriched and carbon-depleted regions form in the parent phases due to the diffusion and segregation of carbon atoms[7,10]. In cooling process once the isothermal holding temperature is lower than the Bs temperature of the carbon-depleted regions, bainite embryo nucleates within the carbon-depleted regions in parent austenite grain.

After nucleation, the growth of bainite lath can be directly watched using in situ observation on LSCM. Fig.2 presents the in situ observed micrographs showing the morphology of bainite ferrite at 330 ℃ following autenizing at 1 100 ℃ for 30 min. The parent austenite grain and transformed bainite morphologies are given in Fig.2(a) and Fig.2(b), respectively. It is shown that some virgin bainite platelets traverse parent austenite grain as shown by arrow A in Fig.2(b), while later formed bainite laths, such as that pointed by arrow B in Fig.2(b), are impinged on pre-formed platelets during their growing. The impingement of the bainitic ferrite is directly shown in Fig.2(b), where the bainitic plates causing impingement grow in different directions with the primary bainite platelets. Meanwhile, with the process of transformation, the mutual intersection of bainite plates often occurs, resulting in an interlocked bainite packet microstructure as indicated in circle area in Fig.2(b). Further, some bainite platelets pass through vanished original austenite grain boundary (as pointed by C in Fig.2(b)), whereas others are trapped in original austenite grain (as pointed by D in Fig.2(b)).

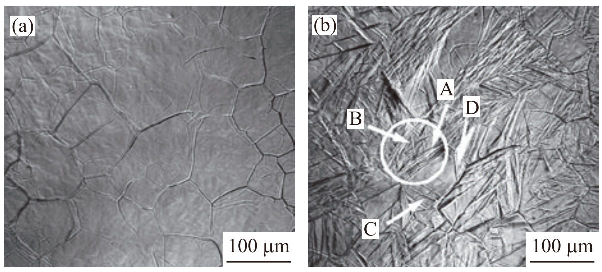

Fig.2 In situ observed micrographs showing bainite growth: (a) original austenite grain after austenizing for 30 min at 1 100 ℃; (b) bainite morphology transformed at 330 ℃ for 140 seconds

There are two conflicting hypotheses regarding the growth mechanism of bainite ferrite[6]. One hypothesis assumes that bainite transformation is governed by the displacing mechanism caused by the coordinated movement of atoms. Although the hypothesized high growth velocity of bainite has not been observed experimentally, this viewpoint has been accepted by many proponents including Bhadeshia[11] because of the surface relief during bainitic transformation similar to that of martensite. Another hypothesis supposes that the growth rate of bainitic ferrite is controlled by the rate of carbon diffusion in the parent austenite. More researchers support the diffusion mechanism due to an increasing number of reports of slow growth of bainite units. The lengthening rate of bainite sheaves can be calculated with in situ micrographs. Fig.3 shows the lengthening process of a bainite sheaf marked by arrows at different time. The lengths of sheaf in Figs.3(a)-3(c) are 23.1, 34.0, and 48.6 μm, respectively. Thus, the lengthening rate of the bainite sheaf in Fig.3 can be obtained as 5.1 $\mu m \cdot s^{-1}$. Based on the above method the average growth rate of bainite sheaves is calculated as 5.8 $\mu m \cdot s^{-1}$, which is much slower compared with the growth rate of martensite. Therefore, the bainite transformation in tested steel is consistent with the diffusion mechanism from the viewpoint of growth rate.

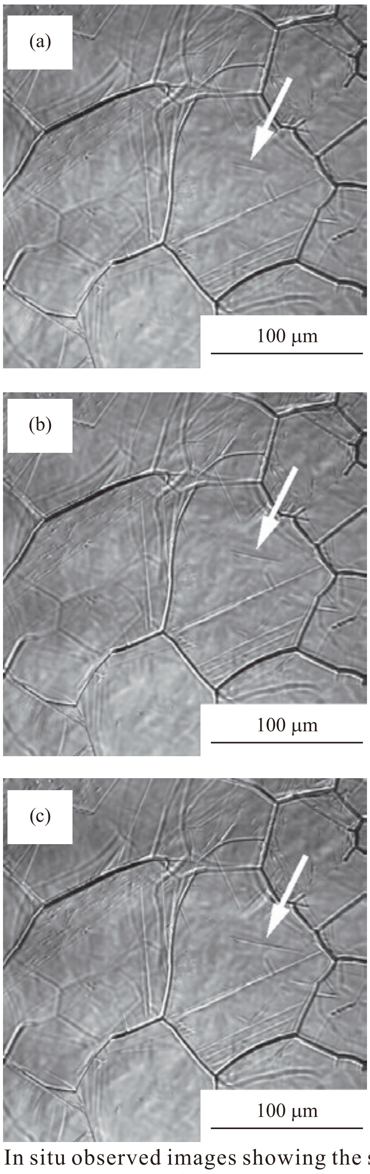

Fig.3 In situ observed images showing the same bainite sheave at different time: (a) 2 159 s; (b) 2 161 s; (c) 2 164 s

3.2 Effect of austenization temperature on bainite transformation

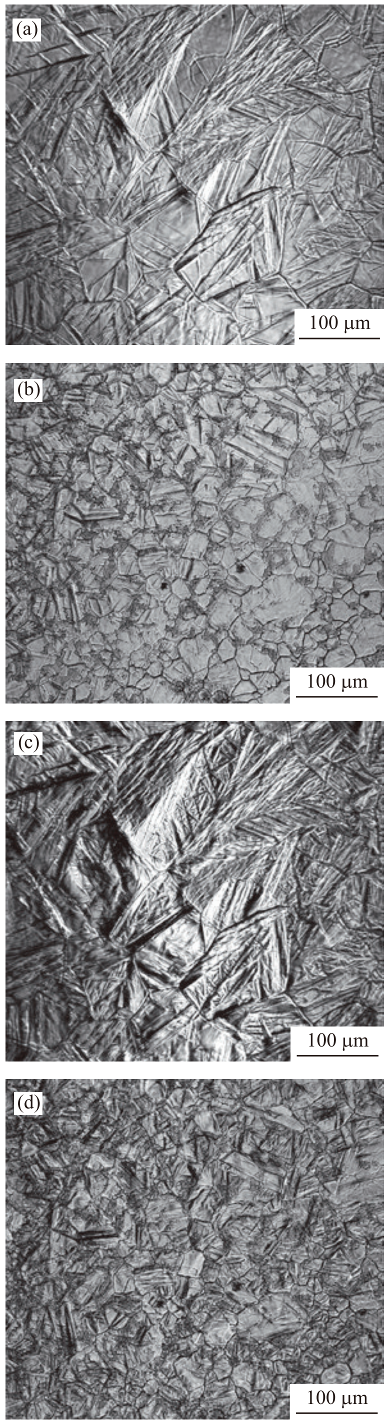

Fig.4 Comparison of bainitic transformation: (a) bainite distribution after isothermal holding for 150 s in the sample austenized at 1 100 ℃; (b) bainite distribution after isothermal holding for 150 s in the sample austenized at 1 000 ℃; (c) bainite morphology after transformation finishes in 1155 s for the sample austenized at 1 100 ℃; (d) bainite morphology after transformation finishes in 1 340 s for the sample austenized at 1 000 ℃

In order to investigate the effect of austenization temperature on bainitic transformation and resultant bainite morphology, samples were austenized at 1100 °C and 1000 °C, respectively, followed by cooling to 330 °C for bainitic transition for 60 min. The in situ observation micrographs indicating the bainite transformation after austenization at 1 100 ℃ and 1 000 ℃ are presented in Fig.4. A comparison of Figs.4(a) and 4(b) reveals that more bainite plates are transformed from parent austenite for the sample austenized at 1 100 ℃ than the one austenized at 1 000 ℃, and bainite of the former sample distributes more uniformly than the later, confirming the effect of austenization temperature on bainite transformation kinetics to a certain extent. Figs.4(c) and 4(d) demonstrate that bainite phase transition finishes in 1 155 s and 1 340 s for the sample austenized at 1 100 ℃ and 1 000 ℃, respectively, revealing more rapid phase transformation for the former sample than the later. On one hand, higher heating temperature results in larger austenite grain size, leading to longer bainite sheaves. On the other hand, driving forces for phase transformation are the same with two processing routes except for austenization temperature because of the same undercooling, so that bainite sheaves in the large grain material grow more quickly under the same driving force due to fewer nuclei. This study aims to investigate the effect of austenite temperature on bainitic transformation, so two high temperatures were used. However, heating temperature should be properly lower in order to obtain smaller grains in steels in industrial production.

3.3 Effect of austenization temperature on bainite morphology

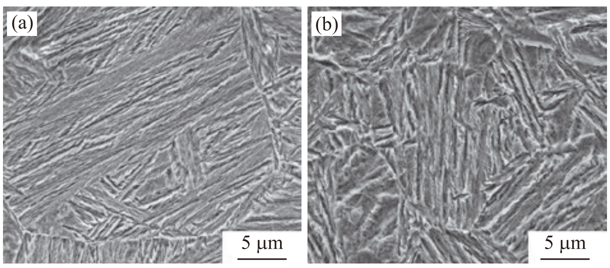

Fig.5 SEM images after bainitic transformation at 330 ℃ for 60 min: (a) austenization at 1 100 ℃; (b) austenization at 1 000 ℃

The SEM images after bainite transformation at 330 ℃ for 60 min are shown in Fig.5, which demonstrates that the bainite sheaves in the sample austenized at 1 100 ℃ are longer and finer compared with the sample austenized at 1 000 ℃. Bainite sheaves are normally restricted in the austenite grains and larger austenite grains result in longer bainite sheaves. The growth of bainite sheaves is three-dimensional with the maximum rate in the longitudinal direction. The bainite sheaves are shorter in the smaller austenite grains resulted from lower austenization temperature. However, for samples austenized at 1 100 ℃, the bainite lath can continuously extends with less limitation caused by grain boundaries due to the larger austenite grain. In this case, the bainite growth in the width direction is easier, leading to longer and finer bainite platelets. The strength of bainitic microstructure mainly depends on the lath space between the baibite sheaves, thus the longer and finer bainite platelets could result in a better property for the sample austenized at 1 100 ℃.

4 Conclusions

a) The bainite growth was dynamically observed using in situ observation on LSCM, which can not be realized by conventional metallographic investigation. Bainite growth has the features of interlocking and impingement of bainitic platelets.

b) Bianite transformation is promoted by higher austenization temperature. The average growth rate of bainite after austenization at 1100 ℃ is calculated as 5.8 μm·s^{-1}, which is consistent with the diffusion mechanism of bainite transformation from the viewpoint of growth rate.

c) Higher austenization temperature results in longer and finer bainite platelets.

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