Low-temperature Bainite in a Low Alloy Steel

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***Abstract*- This paper designed a nanostructured, low-temperature bainite in a novel bainitic steel with low alloy content of 2.83 wt% in total. Relationships of microstructural characteristic between adjacent bainite sheaves in a prior austenite grain are multiform. Most of the bainite sheaves are randomly distributed in matrix phase, and some specific sheaves are interestingly observed. Butterfly bainite sheaves with angle of 30° are found, and perpendicular sheaves are also obtained.**

***Keywords*- Microstructural Characterization; Bainite; Austempering; Phase Transformations; Nanostructure**

I. INTRODUCTION

It has been demonstrated that nanostructured bainite generated at low temperature consists of slender plates of bainitic ferrite and carbon-enriched films of retained austenite, and has an optimization of mechanical properties [1-10]. The typical bainitic steels by Bhadeshia contain high carbon at a level of 0.8–1.0 wt% and mass alloy elements, such as the manganese and chromium for hardenability, and the silicon to prevent cementite formation during the growth of bainite, or the cobalt and aluminum to accelerate the transformation [11]. This structure can also be produced in some lower carbon steels [12-15]. Normally, the reported microstructures [1-18] of low temperature bainite appear only in the forms of parallel ferrite sheave or individual acicular dispersed in the matrix under metallographic observations. In this paper, we aimed to produce low temperature bainite in a low alloy steel, and to achieve the microstructural characteristic between adjacent bainite sheaves.

II. EXPERIMENTAL PROCEDURE

The designed low alloy steel was prepared through electro-slag refining process, and represented as Fe-0.88C-1.35Si-1.12Cr-0.37Mn wt%. The martensite-start temperature (M_S) was measured using a Formastor-Digit 2 full automatic dilatometer, and M_S=210 ℃. The forged sample was homogenized at 1200 ℃ for 24 h in a quartz capsule containing pure argon. The homogenized specimens of 10 mm in diameter and 12 mm in length were austenitized at 980 ℃ for 1200 s, isothermally transformed at low temperatures in the range 240-280 ℃ for 200-1800 s, and then quenched into water.

X-ray experiments were carried out using a D/Max-2500 V X-ray diffractometer (XRD) with CuKα radiation at a voltage of 40 kV and a current of 100 mA. The samples for optical microstructure were mechanically polished using 1200 grit silicon carbide paper, etched by 5 vol. % nital solution, and observed by a Zeiss Axio Scope A1 optical microscopy (OM). Specimens of 3 mm diameter discs for transmission electron microscopy (TEM) were ground down to 50 μm thickness, and then electropolished at 50 V using a DJ200 twin-jet unit with an electrolyte consisting of 5% perchloric acid and 95% methanol. The fine microstructure was investigated using a JEM-2100 transmission electronic microscopy. Hardness testing was conducted using an HX-1000TM Vickers and the values presented were averaged over 5 tests.

III. RESULTS AND DISCUSSION

X-ray diffraction patterns of samples isothermally transformed at different temperatures are shown in Fig. 1. It reveals that all the resulting microstructures are composed of austenite and bainitic ferrite, with absence of carbides. The carbon content of the bainitic ferrite was calculated using equation determined by Dyson and Holmes [19]. The results demonstrate the existence of carbon supersaturation in bainitic ferrite plates. The average carbon concentration of bainite is about 0.56-1.08 at%, as a function of transformation temperature. It could reach the maximum value when transformed at 250 ℃. In case, volume fraction of retained austenite obtains the minimum value.

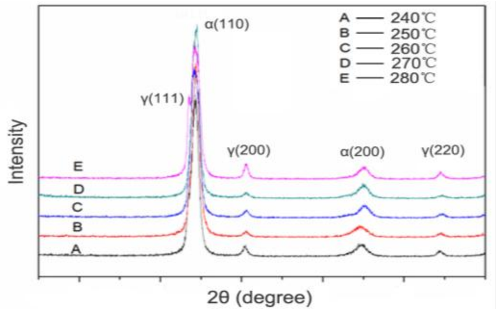

Fig. 1 X-ray diffraction patterns of samples isothermally transformed at 240-280 ℃

From Fig. 2, it can be seen that most of the bainite sheaves are randomly distributed in matrix phase, in a similar way as the references mentioned above. At the early stage of transformation, bainite forms as acicular ferrite in parent phase. With increasing transformation time, bainite gradually forms as sheaves, and the quantity can also become large. Meanwhile, each bainite plate in a sheave grows simultaneously in a certain direction.

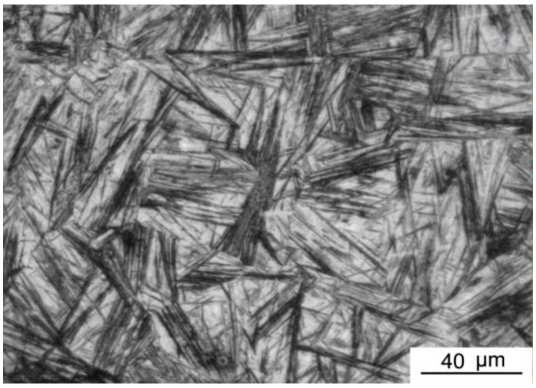

Fig. 2 Morphology of bainite isothermally transformed at 250 ℃ for 250 s

Bainite sheaves with microstructural characteristic different from that of the aforementioned reports are unexpectedly found under metallographic observations with greater regard, as shown in Fig. 3. In the local region marked A, bainite sheaves mostly look like butterfly wings, appearance of which is graceful. In the local region marked B, many sheaves grow in probably perpendicular directions. Though adjacent bainite sheaves border on each other, V-type morphology can be found, rather than X-type. It might imply in a certain degree that sheaves of butterfly wing probably nucleated on defects or grain boundaries and could grow in only two directions.

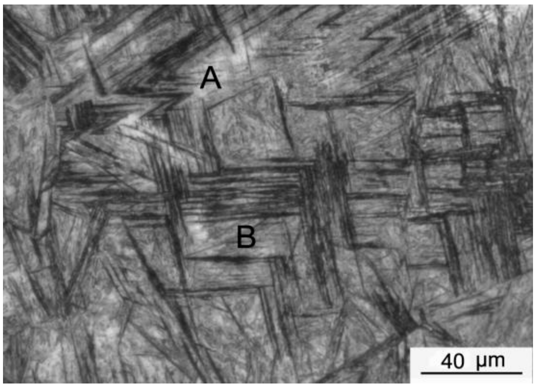

Fig. 3 Morphology of bainite isothermally transformed at 260 ℃ for 250 s

These butterflies cannot be regarded as an occasional existence, due to the fact that they were found in many samples isothermally transformed at 250, 260 and 270 ℃, as shown in Fig. 4. Nevertheless, the volume fraction of the butterfly bainite is undoubtedly small. The angles of 30° between two wings of butterfly are indeed observed. Each wing consists of parallel bainitic ferrite plates about 20-50 μm in length with an approximately same growth direction.

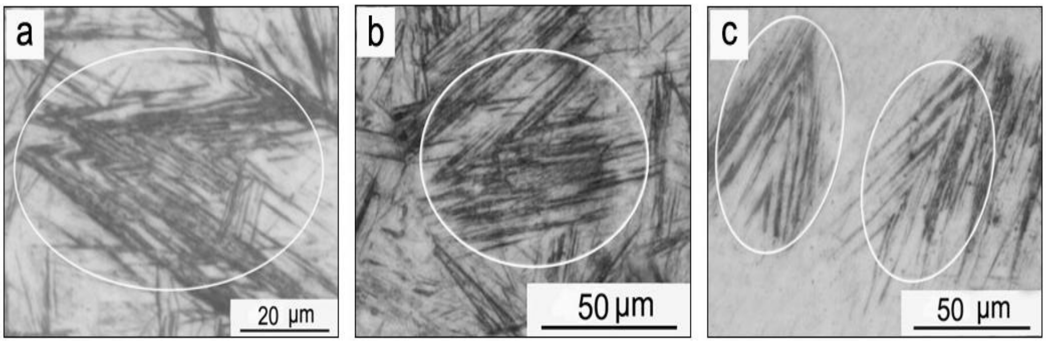

Fig. 4 Morphology of butterfly bainite isothermally transformed at (a) 270 ℃ for 250 s, (b) 250 ℃ for 250 s, and (c) 260 ℃ for 200 s

Some other kinds of microstructural characteristic between adjacent sheaves in prior austenite grains are shown in Fig. 5. They reflect the feasible microstructures of low-temperature bainite with a volume fraction of about 80%. The bainitic transformation has nearly been accomplished with an incomplete-reaction phenomenon. Fig. 5a proclaims that it is one great bainite sheave that saturates a prior austenite grain, while Fig. 5b exhibits several perpendicular bainite sheaves in a prior austenite grain. The bainitic ferrite in each sheave grows in the same direction inside the grains, and stops at the grain boundaries. No evidence is found that bainite traverses the austenite grain boundaries.

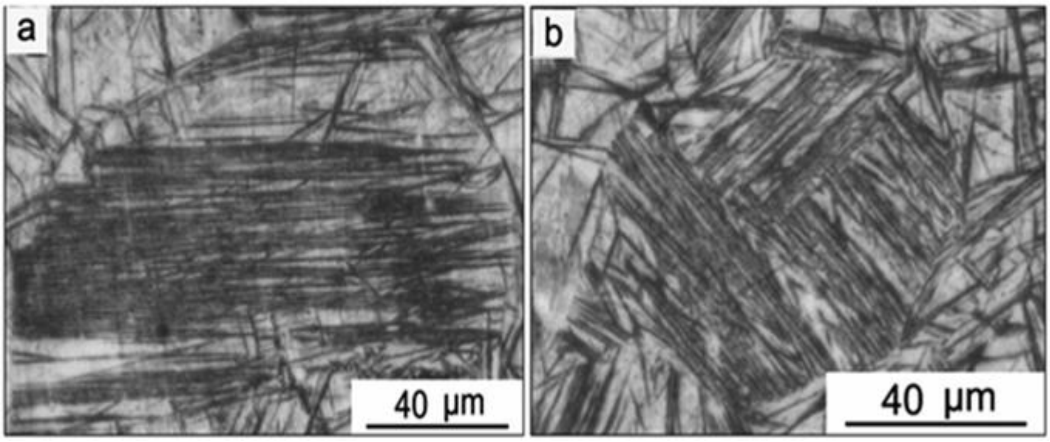

Fig. 5 Microstructural characteristic between adjacent sheaves of the completely transformed bainite

Fig. 6 illustrates TEM morphology and diffraction spectrum of the bainite obtained at 260 ℃ for 300 s. Diffraction spots indicating existence of carbides are not found, in accordance with the results of XRD. The microstructures of bainite sheaves reveal a most elegant fine scale of an intimate mixture of austenite films and slender ferrite plates with a width of just 30-50 nm, according with description of nanobainite [8-10, 20-22]. It also confirms the existence of sub-plate, and the sub-plate grows into a limited side of about 300 nm in length. It indicates that sub-units of phase transformation exist during stages of bainitic formation. The morphology features of bainite sheaves reflect that lengthening contributes the most to bainite growth, and the lengthening can be regarded as a consequence of new platelets nucleation and growth at leading tip of the already formed platelets [4]. Due to the yield strength of austenite at low temperature, thickening and lengthening of platelets have limited sides [23]. From Fig. 6 it can be seen that these bainite/austenite interfaces are lattice-distorted, indicating the characteristics of a displacive transformation. Diffusionless growth of this kind can only occur with a proper carbon concentration of the parent austenite less than that given by the T'_0 curve [4], one consequence of which is that a substantial quantity of carbon is trapped at dislocations with a high density in the vicinity of the ferrite-austenite interface [7, 17]. All these results make an important contribution in enhancing the strength and hardness of this designed bainitic steel, which are about 1860 MPa and 720 HV, respectively.

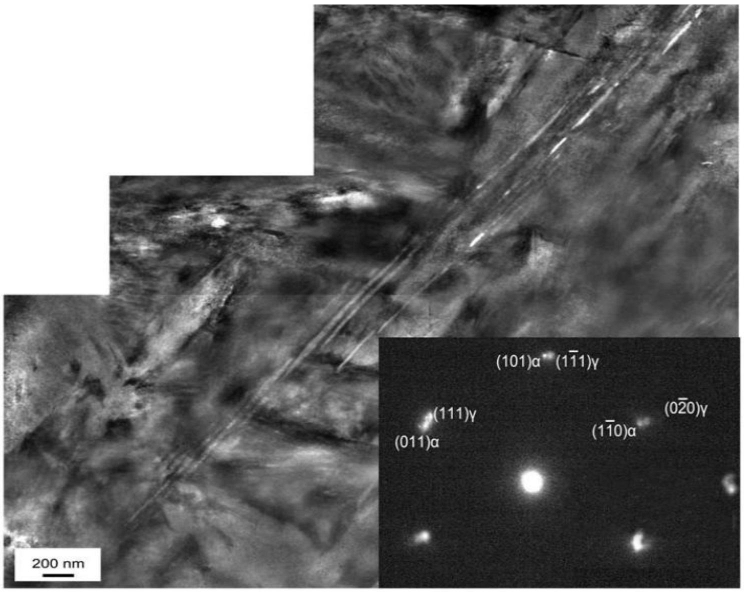

Fig. 6 TEM morphology and diffraction spectrum of the low-temperature bainite

IV. CONCLUSIONS

Low temperature bainite is obtained in a low alloy steel by isothermal transformation, and microstructural characteristic between adjacent bainite sheaves in prior austenite grains is characterized. Evidence of butterfly bainite is found under metallographic observations. However, micrograph only is not enough. Formation mechanism of butterfly bainite needs more accurate evidences and more detailed fine microstructural information to be considered as right.

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