Bimodal Size-distribution of Bainite Plates

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Abstract

There are two well-known phenomena associated with the bainite reaction, which have been exploited in the present work to enhance the mechanical behaviour of steel. Firstly, the bainite plate size decreases as the transformation temperature is reduced. Secondly, it is bad to have large regions of untransformed austenite in the microstructure; this is because they can transform, under the influence of external stress, into corresponding large regions of untempered, brittle martensite.

By adopting a two stage heat treatment in which coarse bainite is produced by isothermal transformation at a high temperature, followed by isothermal transformation at a lower temperature, it has been possible to eliminate blocks of austenite. This leads to a microstructure containing an organized dispersion of fine plates of bainitic ferrite in the regions between the coarse plates. The mechanical properties of this mixture are shown to be better than those of bainite obtained by transformation at any single temperature.

The experiments have been conducted in the context of very strong steels, where the strength and hardness can exceed 2.5GPa and 650 HV respectively.

Keywords: Strong bainite, bimodal size distribution

1. Introduction

Bainite reaction is expected below T_0' temperature when:

$$\Delta G^{\gamma\rightarrow\alpha} < -G_{SB} \quad \text{and} \quad \Delta G_m < G_N \qquad (1)$$

where G_{SB} ($\cong$ 400J/mol) is the stored energy of bainite (α) [1] ; $\Delta G^{\gamma\rightarrow\alpha}$ is the free energy change accompanying the transformation of austenite (γ) without any change in chemical composition.; ΔG_m is the maximum molar Gibbs free energy change accompanying the nucleation of bainite [2]. The first condition describes the limits to growth. The second condition refers to nucleation. Recently, a new high strength bainitic steel containing sufficient silicon to suppress the precipitation of cementite has been developed based on this theory. This steel consists of two phases, bainitic ferrite and austenite. The bainite plate size, which is determined by the transformation temperature, strongly affects the hardness [3]. Large regions of untransformed austenite in the microstructure also affect the ductility of the steel by transforming to the brittle untempered martensite under the influence of external stress. According to the incomplete-reaction phenomenon [4], the bainite transformation can restart when the transformation temperature decreased after being kept at the same temperature until the transformation stop. By using a two stage isothermal treatment, it is possible to reduce the amount of blocky retained austenite because fine bainite plates can transform in this region at the second stage.

The purpose of the work present here was to clarify the kinetics, microstructural features, and mechanical properties of the bain[1]itic steel with bimodal size-distribution of bainite plate comparing to the single stepped ones.

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[1] This work was done at the University of Cambridge when the author stayed there between 2002~2004.

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2. Experimental procedure

The chemical composition of the steel used is listed in Table 1. The high-carbon steel used has a very simple microstructure following transformation, consisting only of two phases, bainitic ferrite and retained austenite. Cylindrical specimens, 8 mm diameter and 12 mm length were machined for experiment, which were carried out in an adapted thermomechanical simulator, Thermecmaster Z. The heat schedule utilized are illustrated in Fig. 1. The same heat treatment is done for the specimen for mechanical testing by using electric furnaces in Ar atmosphere. Quantitative X-ray analysis was used to determine the volume percent of bainite and retained austenite [5], [6]. Tensile specimen with a section of 5 mm diameter and a gauge length of 25 mm was tested at room temperature with a crosshead speed of 0.1 mm/min. Plane strain fracture toughness (K_{1c}) test was done at the room temperature with tensile specimens of B = 13 mm and W = 26 mm.

Table 1 Chemical composition of steel examined (mass%)

C	Si	Mn	P	S	Al	Mo	Cr	Co
0.79	1.56	1.98	0.002	0.002	1.01	0.24	1.01	1.51

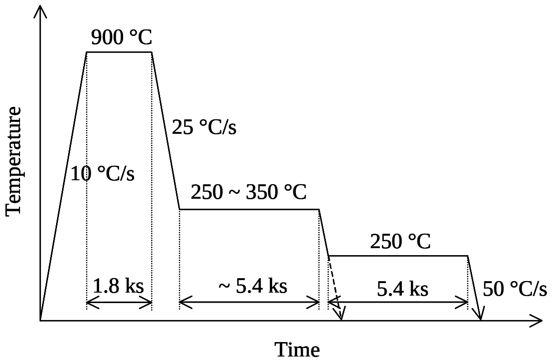

Fig. 1 The form of the heat treatment

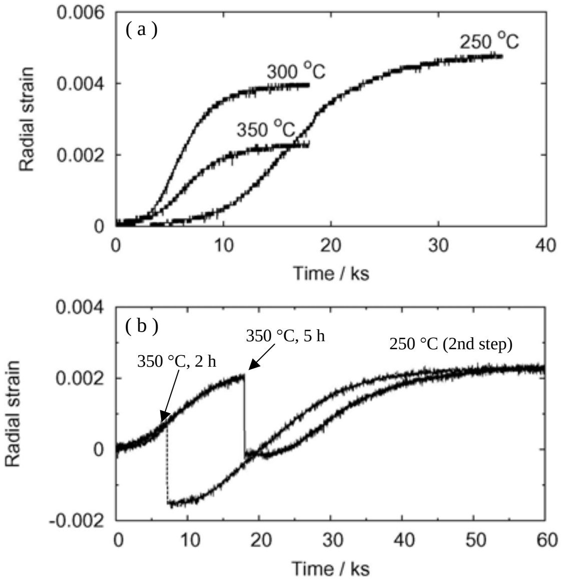

Fig. 2 Change in radial strain associated with the bainite transformation by (a) single stage and (b) two stage isothermal treatments.

3. Result and discussion

3.1 Kinetics

Fig. 2 shows a change in radial strain associated with the bainite transformation during the isothermal treatment. The treatments were carried on until the bainite reaction at each temperature stopped. Fig. 2a shows that the maximum extent of transformation in the single stepped treatment increases with increasing undercooling below Bs. Fig. 2b shows the radial strain recorded during the course of 2-stage isothermal treatment. Once the bainite transformation stopped after holding for 5 h at 350 °C, then the transformation restarted when the isothermal temperature decreased to 250 °C, as expected from the incomplete reaction phenomenon [4].

3.2 Transformed microstructure

Fig. 3 shows the scanning electron micrographs of the sample transformed by single and a two stage isothermal treatments. In the single stepped samples, the bainite plate size becomes thinner as the transformation temperature decreased [d]. Both of the size and the amount of blocky retained austenite decreased with decreasing the isothermal temperature. On the other hand, the bimodal size-distribution of bainite plates are observed in the 2-stage samples. The size of the thick plates and thin plates are very similar to the bainite plate transformed at 350 °C and 250 °C, respectively. The volume fraction of these thick plates increased with increasing the holding time at 350 °C. It is obvious that these thick bainite plates are formed at the first stage and the thin plates are formed at the second stage. The

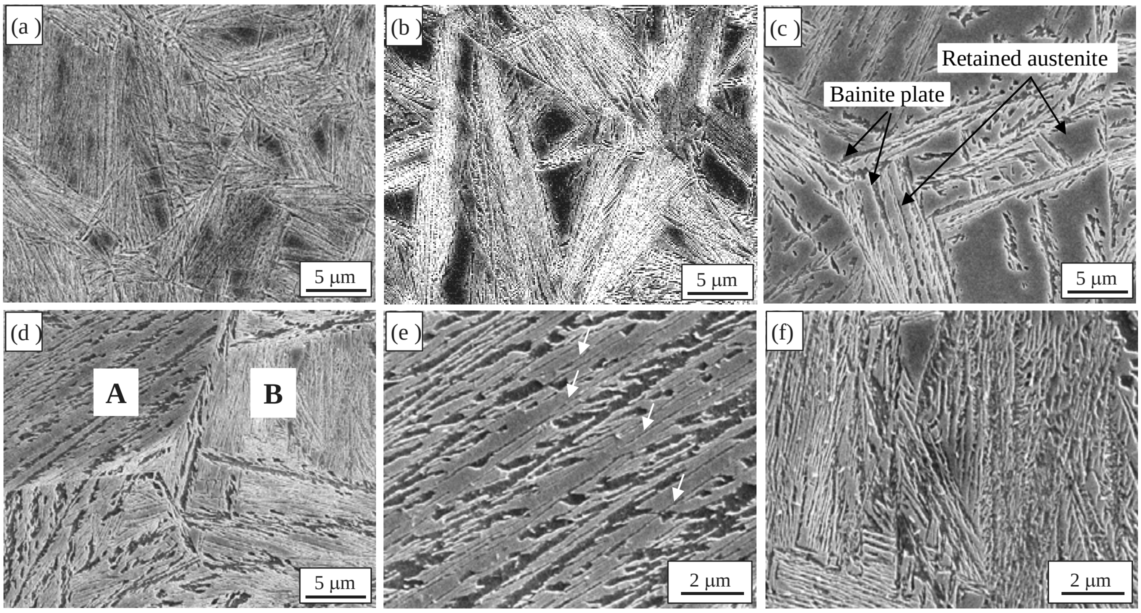

Fig. 3 Typical scanning electron micrographs of bainite transformed at (a) 250 ºC, 15hr, (b) 300 ºC, 5hr, (c) 350 ºC, 5hr with a single stage isothermal treatment and (d) 350 ºC, 5 h followed by 250 ºC, 15 h with a two stage isothermal treatment. (e) is enlarged in area A and (f) is enlarged in area B in (d).

blocks of austenite left untransformed seem less and smaller in a two stage sample, which may be beneficial to the ductility and toughness of the steel. The higher magnification micrographs of the area with mark A and B in Fig. 3d are shown in Fig. 3e and Fig. 3f, respectively. A is the area with thick bainite plates transformed at 350 °C and B is the one without thick bainite plates. Although the very fine bainite plates are observed in both of the micrographs, their features are very different from each other. In Fig. 3e, very thin bainite plates are observed in film-like retained austenite, which formed at 350 °C. The density of these fine bainite plates is very low. On the other hand, the large numbers of fine bainite plates are observed in Fig. 3b. From the point of carbon partitioning during the bainite transformation, carbon content of the film-like retained austenite might be much higher than the blocky austenite because it is located between bainite plates and diffusion distance of carbon is much shorter than blocky austenite. This might affect both of the sizes and the densities of bainite plates transformed at the second stage.

3.3 Mechanical properties

Fig. 4 shows the stress-strain curves of single and two stage samples tested at room temperature. In the case of single stage samples, UTS increases with decreasing the transformation temperature.

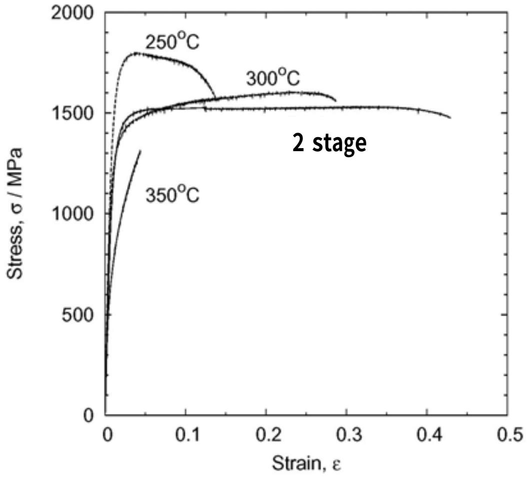

Fig. 4 Stress-strain curve of the specimens transformed by single and dual step isothermal treatment.

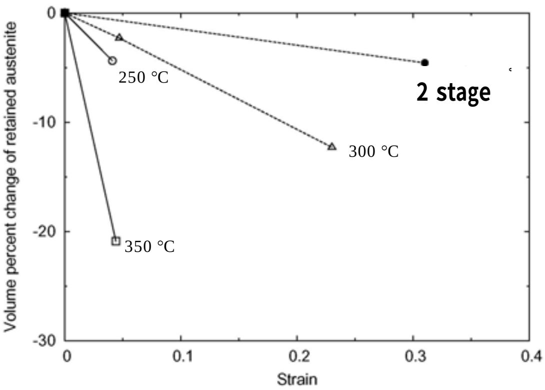

Fig. 5 Change in volume percent of retained austenite as a function of strain applied by tensile test.

This behaviour is related to the microstructural features of the different transformation temperatures. It is noticeable that the two stage sample, which has less blocky austenite shows the very good ductility than the single stepped samples. It is well known that the stability of retained austenite against straining affects the uniform elongation [7], so the amount of retained austenite in each specimen was measured by quantitative X-ray analysis. Fig. 5 shows the volume change in retained austenite under the influence of uniform tensile strain. It is obvious that the stability of retained austenite has a good relation to the elongation. In other word, the stabilized sample shows the better elongation. Fig.6 shows the result of K1C test as a function of tensile strength. It is obvious that the two stage sample, which has stabilized retained austenite, shows the good balance of strength and fracture toughness.

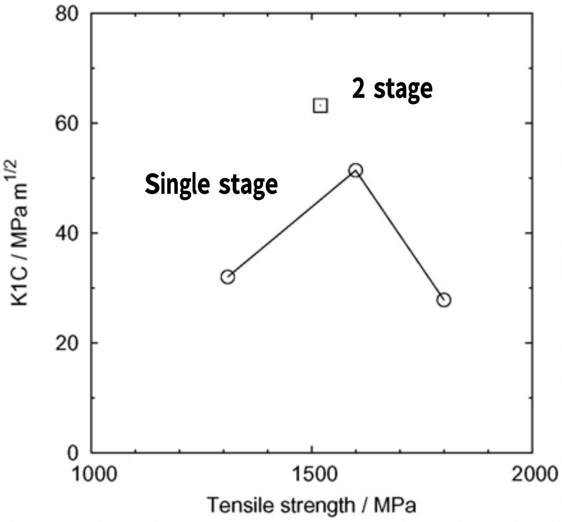

Fig. 6 Fracture toughness (K1C) as a function of tensile strength.

4. Conclusion

Transformation behaviour and mechanical properties of two stage isothermal treatment are invstigated with comparing single stepped treatment.

Once the bainite transformation incompletely stopped after holding at 350 °C for 5 h, then the bainite transformation restarted after quenched to 250 °C as expected from the incomplete reaction phenomenon.

The dual stepped sample has the bimodal distribution of thick and fine bainite plates, which are formed at the first and the second stage, respectively. Although the very fine bainite plate are formed from both of film-like and blocky retained austenite, which were formed at 350 °C, finer bainite plates transformed from blocky retained austenite. This result suggests that the carbon content of film-like austenite is higher than the blocky austenite. This affects the amount of bainite plates transformed at the second step. The two stage sample indicates the good ductility, more than 40 % of total elongation and 63 MPa/m1/2 even though the UTS is 1.5GPa. It is because the amount of blocky austenite of dual stepped sample, which is more unstable than the film-like austenite, is much lower than the single stage samples.

References

[1] H. K. D. H. Bhadeshia, Acta Metall. 29 (1981) 1117-1130
[2] H. K. D. H. Bhadeshia, Bainite in Steels, 2nd ed. Institute of Materials, London, 2001
[3] C. Garcia-Mateo, F. G. Caballero, and H. K. D. H. Bhadeshia: ISIJ Int. 43 (2003) 8 1238-1243
[4] H. K. D. H. Bhadeshia and D. V. Edmonds: Metall Trans. 10A (1979) 895-907
[5] M. J. J. Dickson: J. Appl. Crystallogr. 2 (1969) 176-180
[6] D. B. Wiles and R. A. Young: J. Appl. Crystallogr. 14 (1981) 149
[7] K. Sugimoto, N. Usui, M. Kobayashi, and S. Hashimoto, ISIJ Int., 32 (1992) 1311