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# Bimodal Size-distribution of Bainite Plates

K. Hase* [a], C. Garcia-Mateo [b], and H. K. D. H. Bhadeshia [c]

a) JFE Steel Corporation, Steel Research Lab., Kawasakidori 1-chome, Mizushima, Kurashiki 712-8511, Japan

b) CENIM, CSIC, Avda. Gregorio del Amo, 8, 28040 Madrid, Spain

c) University of Cambridge, Materials Science and Metallurgy, Pembroke street, Cambridge CB2 3QZ, U. K.

## Abstract

There are two well-known phenomena associated with the bainite reaction, both of which have been exploited here 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 induces 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 is expected to form below the $T_0$' temperature when:

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

where $G_{SB}$ ($\cong$ 400 J mol$^{-1}$) is the stored energy of bainite ($\alpha_b$) [1]; $\Delta G^{\gamma\rightarrow\alpha}$ is the free energy change accompanying the transformation of austenite ($\gamma$) without any change in chemical composition; $\Delta G_m$ is the maximum molar Gibbs free energy change accompanying the nucleation of bainite [2]. The first condition describes the limits to growth; the second refers to nucleation. Recently, a new high strength, carbide-free bainitic steel has been developed using this theory [3-5]. This silicon-rich steel contains only bainitic ferrite and carbon-enriched retained austenite. The bainite plate size, which is determined by the transformation temperature, strongly affects the hardness [2]. Large regions of untransformed austenite in the microstructure can be detrimental to toughness because they are prone to transform into brittle, untempered martensite under the influence of an external stress [6,7]. The reason for the existence of these large regions of untransformed austenite is the $T_0$' curve, which limits the amount of bainite that can be obtained at any temperature, even though equilibrium is not reached. According to this incomplete-reaction phenomenon [2], when isothermal transformation stops, it can be induced to continue if the temperature is reduced. Therefore, it should be possible using a heat-treatment in which two isothermal transformation temperatures are used, to reduce the blocky austenite and obtain better toughness. Two-stage heat treatments like this have been previously reported [8]. The purpose here was to study the consequences on mechanical properties.

## 2. Materials and experimental procedure

The chemical composition of the steel used is listed in Table 1. The alloy has a simple final

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* Tel: +81-86-447-3897, Fax: +81-86-447-3939, E-mail: k-hase@jfe-steel.co.jp

microstructure consisting only of bainitic ferrite and retained austenite. Cylindrical specimens, 8 mm diameter and 12 mm length were prepared for a thermomechanical simulator, *Thermecmaster Z* for the heat-treatment illustrated in Fig. 1. For larger specimens suitable for ambient temperature mechanical testing, the same heat treatment was implemented using electric furnaces with the samples protected in an Ar atmosphere. X-ray analysis was used to determine the phase fractions [9,10]. Cylindrical tensile specimens 5 mm diameter with a gauge length of 25 mm were tested with a crosshead speed of 0.1 mm min$^{-1}$. Plane strain fracture toughness ($K_{IC}$) tests were done on standard samples with $B$ = 13 mm and $W$ = 26 mm [11].

## 3. Results and Discussion

### 3.1 Kinetics

Fig. 2 shows the change in radial strain as bainite forms during the isothermal treatment. The transformation at each temperature was allowed to terminate before changing the temperature. The maximum extent of isothermal transformation in a single-stage treatment clearly increases with the undercooling below the bainite-start temperature $B_S$ (Fig. 2a). The two-stage treatment involved reaction at 350 °C followed by further isothermal transformation at 250 °C (Fig. 2b).

### 3.2 Transformed microstructure

Fig. 3 shows the scanning electron micrographs following the two kinds of heat treatment. The microstructure becomes more refined as the transformation temperature is reduced when dealing with a single-stage heat treatment [11]. Both the size and the amount of blocky austenite decreased as the isothermal temperature was reduced. On the other hand, a bimodal size-distribution of bainite plates is observed in the 2-stage samples, as previously reported [12]. The size of the thick plates and thin plates correspond to those obtained in the 350 °C and 250 °C single-stage treatments, respectively. The major observation is that the two-stage treatment reduced the amount of blocky austenite when compared with the single-stage treatment. In figures 3d-f, the region marked (A) contains the thick plates generated at 350 °C and (B) is the region without thick bainite plates. In Fig. 3e, a low number-density of thin plates (arrowed) is observed within the film-like retained austenite left untransformed at 350 °C. On the other hand, large numbers of fine bainite plates are observed in Fig. 3f, in regions which represented blocks of austenite following the 350 °C treatment. This is because the thin regions of austenite are known to contain more carbon than the blocks [13-16]; a higher carbon content in the austenite would lead to a smaller fraction of finer bainite during the 250 °C treatment, as is observed. The non-uniform distribution of carbon results from the trapping of some regions of austenite [2].

### 3.3 Mechanical properties

Fig. 4 shows the stress-strain curves of the heat-treated samples. For the single-stage samples, the ultimate tensile strength (UTS) increases with decreasing the transformation temperature, as expected from the microstructural refinement and larger fraction of bainitic ferrite associated with lower reaction temperatures. More interesting is the fact that a greater ductility is observed in the two-stage treated sample, which contain less blocky austenite.

It is well known that the mechanical stability of retained austenite influences uniform elongation [16]. Austenite which transforms at a late stage in the deformation process is better able to compensate for the critical damage which occurs at large strains. In the present context, a sample with more stable austenite should show better ductility and toughness. Fig. 5 shows the change in retained austenite as a function of tensile strain during the uniform stage of deformation. Fig.6 shows the $K_{IC}$ test data as a function of tensile strength. It is evident that the two-stage sample exhibits the best combination of strength and fracture toughness. Finally, it seems that the two-stage treatment results in more stable austenite because the larger regions of austenite left untransformed at 350 °C are partitioned (geometrically divided) by the formation of many *different* crystallographic variants of bainite during the 250 °C treatment; simply lowering the transformation temperature to eliminate blocky austenite does not promote the formation of different variants of bainite, leaving a less divided austenite. In other words, it is important in subdividing the blocky austenite to do this using many orientations of bainite.

Notice that although the total austenite content is greater in the 2-stage treatment when compared with the single 250 °C case, it is the refinement of the *blocky* austenite in the former case that leads to the optimum combination of properties. There remain some fine blocks of austenite in the 2-stage heat treatment - further work needs to be done to discover ways of further reducing their quantitiy.

## 4. Conclusions

The use of a two-stage isothermal heat treatment to generate a microstructure consisting of bainitic ferrite and retained austenite has been found beneficial to the mechanical properties of a particularly strong steel. An incredible ductility of 40 % of total elongation and a toughness of 63 MPa $m^{-1/2}$ at an ultimate tensile strength of 1.5 GPa have been achieved, more than was possible with microstructure generated using a single isothermal heat treatment. The double isothermal treatment leads to a bimodal distribution of bainite plate size and a geometrical division of residual austenite in such a manner that the mechanical stability of the austenite is improved, thereby enabling it to compensate for critical damage expected during the late stages of deformation in a tensile test.

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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 |

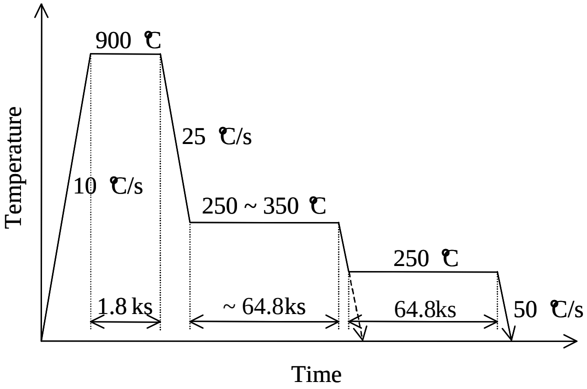

Fig. 1 The form of the heat treatment

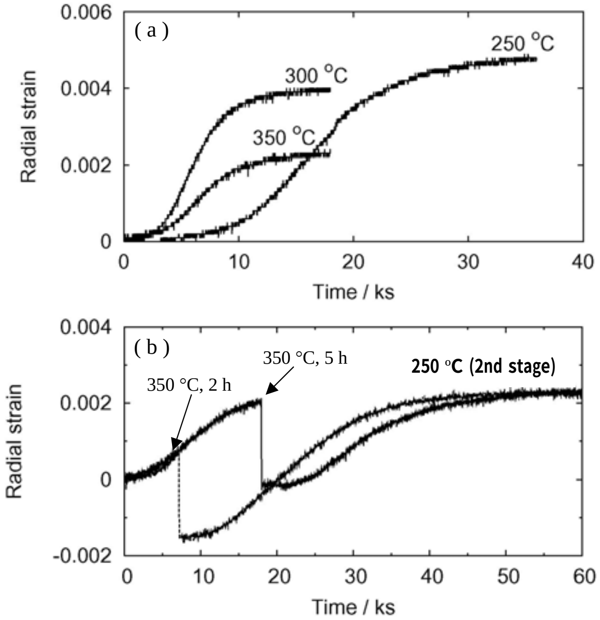

Fig. 2 Change in radial strain associated with the bainite transformation by (a) single stage and (b) two stage isothermal treatments.

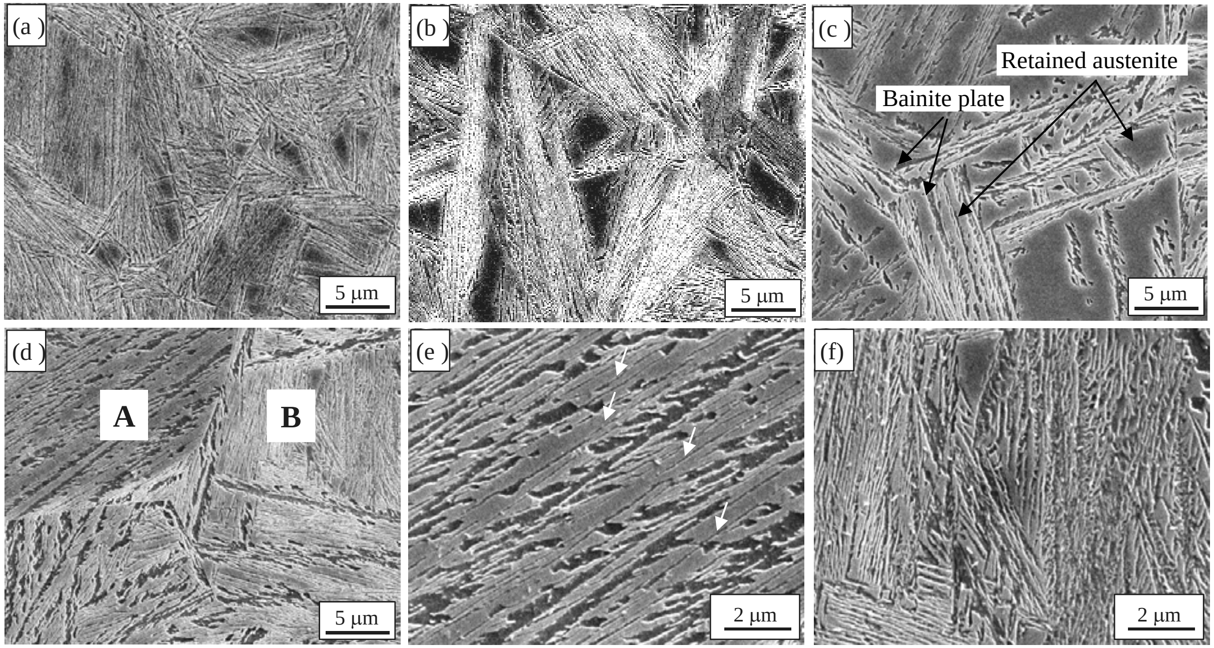

Fig. 3 Scanning electron micrographs of bainite transformed at (a) 250 ºC, 15 h, (b) 300 ºC, 5 h, (c) 350 ºC, 5 h in a single-stage isothermal treatment. (d) 350 ºC, 5 h followed by 250 ºC, 15 h using a two-stage isothermal treatment. (e) and (f) are magnified views of the regions marked A and B in (d).

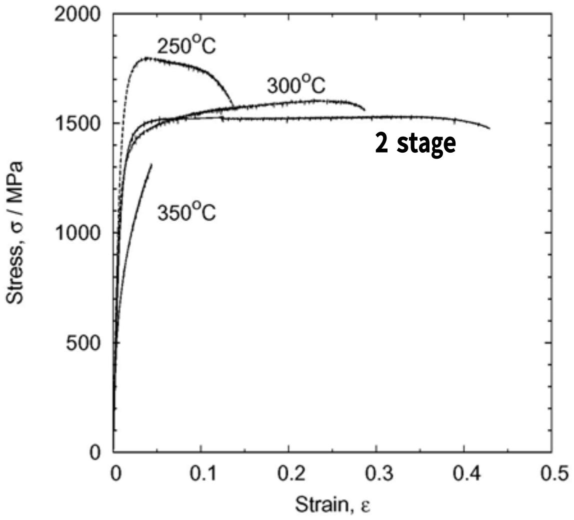

Fig. 4  Stress-strain curves of the single and two-stage transformed samples.

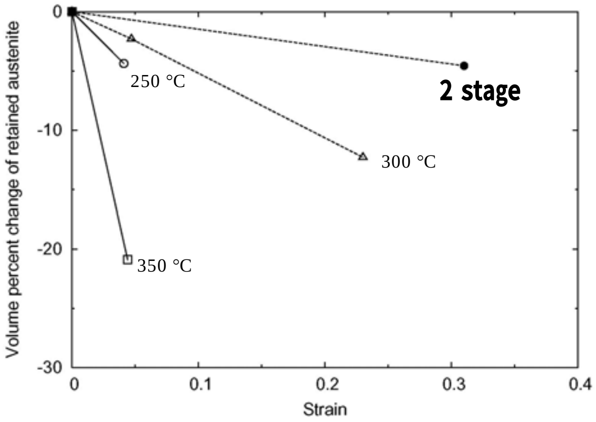

Fig. 5  Change in volume percent of retained austenite as a function of strain in a tensile test.

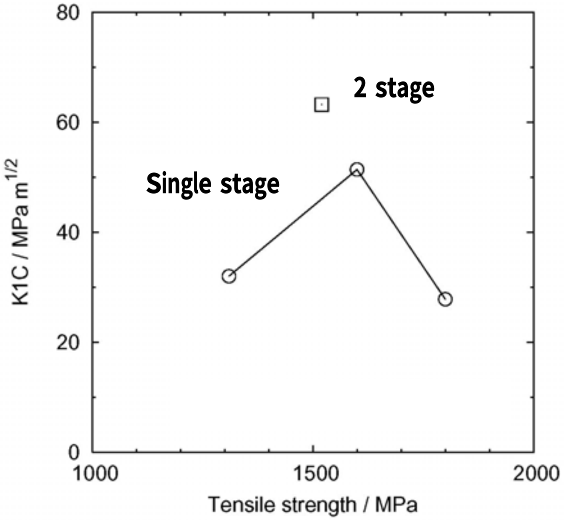

Fig. 6 Fracture toughness ($K_{1C}$) as a function of tensile strength.