Effect of austenite grain size and bainite morphology on overall kinetics of bainite transformation in steels

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An attempt is made to rationalise some contradictory observations on the effect of austenite grain size on the overall kinetics of the bainite transformation in steels. Experiments have been carried out on two steels which show opposite effects of austenite grain size on the reaction rate. General equations describing the reaction rate are derived by taking into account the morphology of the bainite in each steel. The equations derived can explain the contradictory effects of the austenite grain size on the overall reaction rate. The results are also found to be in good agreement with the published data. MST/4135

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Introduction

The effect of austenite grain size on the evolution of the bainite transformation in steels is not yet certain in spite of many investigations.[1–7] Barford and Owen[1] reported that the reaction rate was accelerated by decreasing the grain size, because of an increase in the number density of grain boundary nucleation sites. Umemoto *et al.*[2] reported similar results and proposed an equation that described the grain size dependence of overall kinetics. Davenport[3] argued that the grain size had no appreciable effect upon the transformation kinetics. By contrast, Graham and Axon[4] suggested that because the growth of a bainite plate is resisted by the matrix, a smaller austenite grain size must retard growth. These apparently contradictory studies have yet to be rationalised.

It has been demonstrated recently[8,9] that different steels can show opposite effects of the austenite grain size on the bainite reaction rate and that the difference in kinetic behaviour is accompanied by obvious distinctions between the bainite microstructures. The purpose of the present work was to derive a general equation describing the reaction rate, taking into account the bainite morphology experimentally observed, with the aim of rationalising the austenite grain size effect.

Experimental procedure

The chemical compositions of the two types of steel investigated are given in Table 1. Specimens were prepared by machining into 3 and 8 mm diameter cylinders with lengths of 10 and 12 mm from alloys A and B respectively. Specimens were then homogenised at 1200°C to eliminate the possible effects of solution and precipitation behaviour on the bainite transformation. Figure 1 shows the heat treatment used. The austenite grain size was varied by changing the maximum heating temperature. To avoid any intrinsic effect of the austenitisation temperature itself, specimens were then cooled rapidly to a constant secondary temperature of 800°C within the austenite phase field, followed by cooling to the isothermal transformation temperature. This permits the effect of austenite grain size to be investigated in isolation. The strain was measured during the formation of bainite.[10] Optical metallography was carried out on specimens etched using 2% nital.

Table 1 Chemical composition of steels, wt-%

Steel	C	Si	Mn	Cr	Fe
A	0·12	2·03	2·96	...	Bal.
B	0·96	0·21	0·38	1·26	Bal.

Experimental results

Figure 2 shows the effect of the maximum heating temperature on the austenite grain size. The austenite grain size increases monotonically with the maximum heating temperature. Figure 3 shows the effect of maximum heating temperature on the overall kinetics of the bainite transformation. The reaction rate increases with increasing austenite grain size in steel A, but decreases in steel B. It is therefore demonstrated experimentally that these two steels exhibit contradictory behaviour with respect to the relationship between the austenite grain size and the rate of the bainite reaction.

The sheaf morphology of bainite at the early stages of transformation is illustrated in Fig. 4, together with schematic interpretations of the characteristic features. A bainite sheaf is an aggregate of fine plates, identified as a black microstructure in the schematic diagrams. Bainite sheaves nucleate mainly at the austenite grain boundaries and grow into the grains. It is evident that the characteristics of the evolution of bainite sheaves in steels A and B are markedly different. For steel A, the growth rate of the bainite sheaves is relatively high compared with the rate of nucleation at the austenite grain surfaces. Once the nucleation is completed the sheaf penetrates the grain rapidly until impingement occurs. By contrast, in steel B the growth rate is not as high compared with the nucleation rate at the austenite grain boundaries, so that the boundaries become almost completely decorated well before impingement occurs.

Discussion

An attempt is made here to represent quantitatively the contrasting behaviour of steels A and B, taking into account the differences in microstructure.

KINETIC EQUATIONS

The overall reaction rate of a nucleation and growth transformation can be expressed using the Kolmogorov[11]–

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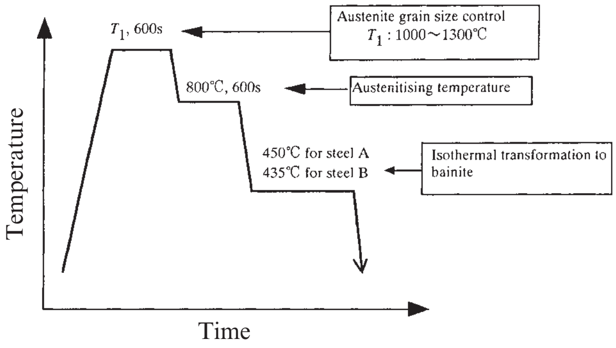


1 Heat treatment of experimental steels

Johnson–Mehl[12]–Avrami[13] type equation

$$X(t) = 1 - \exp\left[- \int_0^t \dot{J}(\tau) V(t, \tau) \, d\tau \right] \quad . \; . \; . \; . \; . \quad (1)$$

where t is isothermal transformation time, $X(t)$ is the fraction of bainite at time t, $\dot{J}(\tau)$ is the nucleation rate per unit volume at time τ, and $V(t, \tau)$ is the volume, at time t, of the bainite nucleated in the time interval between τ and $\tau + d\tau$.

Although the essential unit of nucleation and growth of bainite transformation is a plate, the bainite sheaf, which is an aggregate of plates, also has a characteristic growth rate. The bainite sheaf, therefore, can reasonably be considered as a unit transformation in its own right.

The number density of sheaf nucleation sites per unit volume $J(\tau)$ can be given by

$$J(\tau) = S_V N(\tau) \quad . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \quad (2)$$

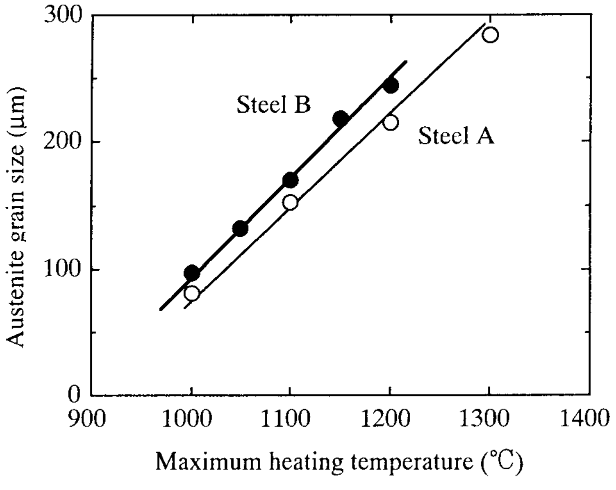
where S_V is the grain boundary area per unit volume, and $N(\tau)$ is the number density of nucleation sites per unit area of grain boundary. Since the grain boundary area per unit volume is reciprocally related to the grain size R, equation (2) can be expressed as

$$J(\tau) = C_1 \frac{N(\tau)}{R} \quad . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \quad (3)$$

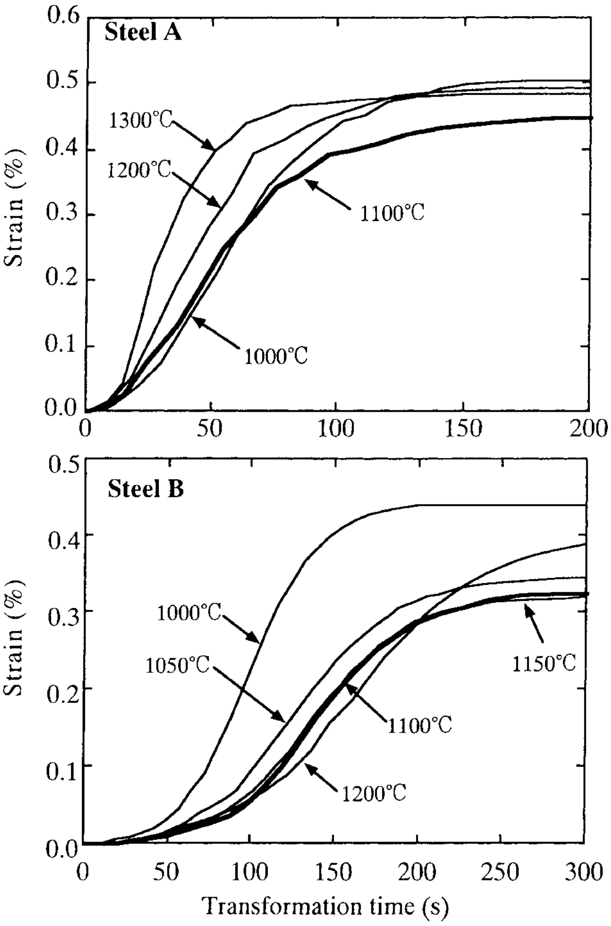
where C_1 is a constant. The number of nucleation sites consumed in a small time interval $d\tau$ is given by

$$dJ(\tau) = -J(\tau) \nu \, d\tau \quad . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \quad (4)$$

where the frequency ν represents the rate at which an individual site becomes a nucleus.



2 Effect of maximum heating temperature on austenite grain size



3 Effect of maximum heating temperature on development of strain during isothermal formation of bainite

The number density $J(\tau)$ and its time derivative $\dot{J}(\tau)$ can, therefore, be described by[14]

$$J(\tau) = \frac{C_1 N_0}{R} \exp(-\nu\tau) \quad . \; . \; . \; . \; . \; . \; . \; . \; . \; . \quad (5)$$

$$\dot{J}(\tau) = -\frac{dJ(\tau)}{d\tau} = \frac{C_1 N_0 \nu}{R} \exp(-\nu\tau) \quad . \; . \; . \; . \; . \; . \quad (6)$$

where N_0 is the initial number density of nucleation sites per unit grain boundary area.

The formulation of $V(t, \tau)$ depends on the characteristics of the development of bainite sheaves as follows. For steel A, in which growth is relatively rapid, it is justified to assume that each nucleus is associated with a fixed volume of transformation since the sheaf dimension is related directly to R

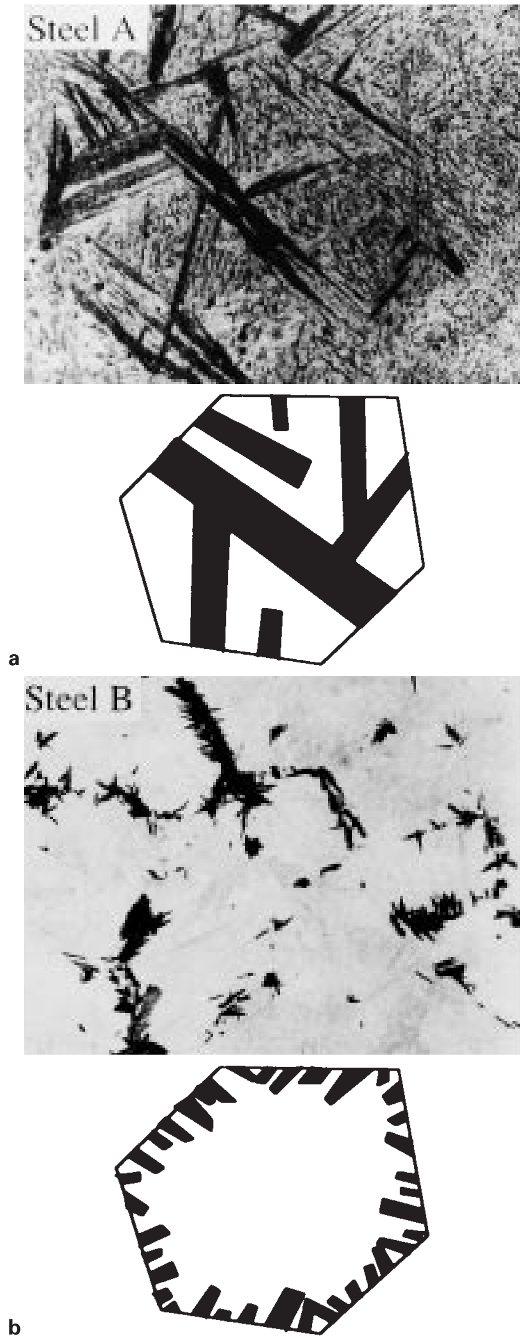
$$V(t, \tau) = C_2 R^3 \quad . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \quad (7)$$

where C_2 is a constant. The growth rate therefore does not feature explicitly in the kinetic equations. Consequently, the Avrami equation for steel A can be described by substituting equations (6) and (7) into equation (1) to give

$$X(t) = 1 - \exp\{-C_1 C_2 N_0 R^2 [1 - \exp(-\nu t)]\} \qquad (8)$$

There is no doubt that growth is a limiting factor for steel B and the kinetics can be approximated by considering the growth of rapidly nucleated particles with an initial number density of sites proportional to R^{-1}, and the volume for a sheaf can be described in terms of a constant growth rate according to

$$V(t, \tau) = C_3 (t - \tau)^3 \quad . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \quad (9)$$

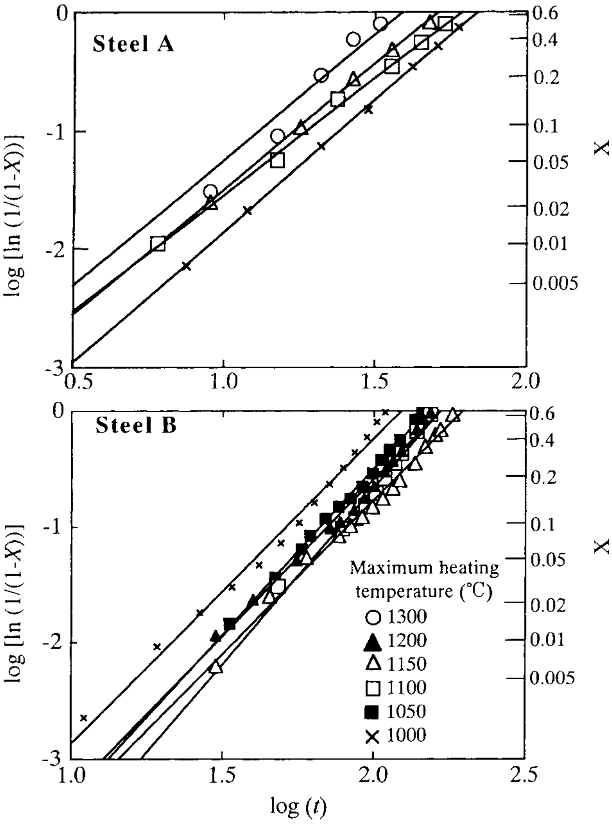


4 Observed (optical, ×100) and schematic morphology of bainite sheaves at early stages of isothermal transformation in *a* steel A with maximum heating temperature $T_1 = 975°C$ and *b* steel B with $T_1 = 1000°C$

where C_3 is a constant. Consequently, the equation for the bainite transformation in steel B can be obtained by substituting equations (6) and (9) into equation (1) to give[14]

$$X(t) = 1 - \exp\left\{ -C_1 C_3 N_0 6 v^{-3} R^{-1} \times \left[\exp(-vt) - 1 + vt - \frac{v^2 t^2}{2} + \frac{v^3 t^3}{6} \right] \right\} \qquad (10)$$

The important feature in equations (8) and (10) is that the indices of grain size R are different, and are consistent with the experimental data. It is evident from these equations that the reaction rate increases in steel A and decreases in steel B with increasing grain size. It is therefore safe to conclude that the effect of austenite grain size on the reaction rate can be different depending on the limiting cases described in this subsection.



5 Avrami plot with tangent equal to *n* value in equation (16)

COMPARISON OF GRAIN SIZE EFFECT BETWEEN EXPERIMENTS AND THEORY

The experimental data were analysed on the basis of equations (8) and (10). Assuming that the values of vt are small for both steels, limiting forms of equations (8) and (10), obtained by expanding $\exp(-v\tau)$, are identical with equations (11) and (12) respectively. Small values of vt imply that the nucleation rate is effectively constant.[14] A reasonable assumption for both steels at the relatively early stages of transformation is, therefore

$$X(t) = 1 - \exp(-C_1 C_2 N_0 v R^2 t) \quad . \; . \; . \; . \; . \; . \; . \; (11)$$

$$X(t) = 1 - \exp\left(-\frac{C_1 C_3 N_0}{4} v R^{-1} t^4 \right) \quad . \; . \; . \; . \; . \; (12)$$

where equations (11) and (12) originate from equations (8) and (10) and describe steels A and B respectively. Equations (11) and (12) can be described in a general form as

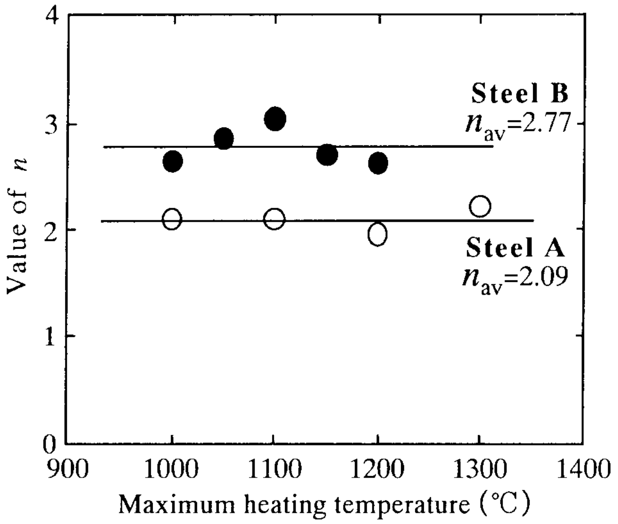
$$X(t) = 1 - \exp(-C_4 R^m t^n) \quad . \; . \; . \; . \; . \; . \; . \; . \; . \; (13)$$

where C_4, m, and n are constants. The exponent of grain size m can be derived by analysing the experimental data on the basis of equation (13) as follows.

The maximum volume fraction of bainite varies according to the chemical composition and transformation temperature.[15] Consequently, the volume fraction of bainite $X(t)$ is expressed in a normalised form

$$X(t) = \frac{V(t)}{V_{\max}} \quad . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; (14)$$

where $V(t)$ is the actual volume fraction of bainite at transformation time t and $V_{\max}$ is the maximum volume fraction of bainite that can be achieved in a particular steel



6 Value of index *n* as function of maximum heating temperature

at a given temperature. Takahashi and Bhadeshia[10] have demonstrated that the linear relation between the volume fraction of bainite and the corresponding relative length change is preserved up to a volume fraction of at least 0·7. Since the maximum volume fraction of bainite in the present work was 0·6 it can be assumed that

$$X(t)=\frac{\varepsilon(t)}{\varepsilon_{\max}} \quad . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \quad (15)$$

where $\varepsilon(t)$ is the relative length change at transformation time t, and $\varepsilon_{\max}$ is the maximum length change.

Equation (13) can be written as

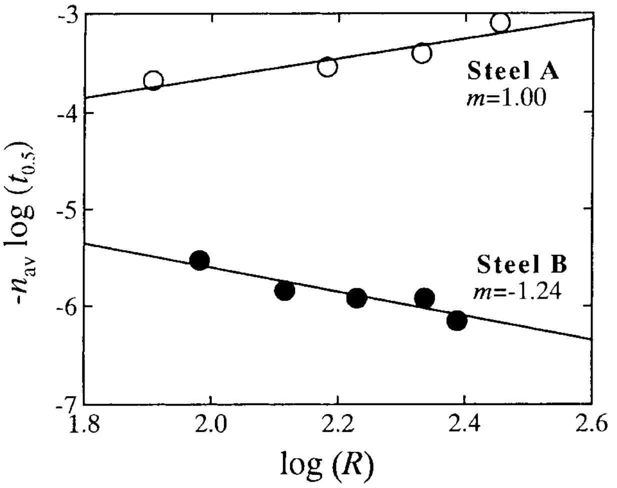
$$\log\left[\ln\left(\frac{1}{1-X(t)}\right)\right]=n\log t+m\log R+\log C_4 \qquad (16)$$

Therefore the value of n is given by the slope of each line in Fig. 5. In this analysis, the data were limited to those having a value of $\log\{\ln[1/(1-X)]\}$ less than zero, that is $X<0{\cdot}6$, where linearity between $\log\{\ln[1/(1-X)]\}$ and $\log(t)$ is well preserved. The values of n that were evaluated from Fig. 5 were plotted in Fig. 6 as a function of the austenitising temperature. Since the change in the value of n with the maximum heating temperature, i.e. grain size, is not very significant, n is considered to be independent of the grain size. The average values of n, denoted by n_{av}, are 2·09 and 2·77 for steels A and B respectively. Consequently the value of m can be derived from the equation

$$-n_{av}\log t_{0\cdot5}=m\log R-\log\left[\ln\left(\frac{1}{1-0\cdot5}\right)\right]+\log C_4 \quad . \; . \; . \; . \; . \; . \; . \; . \; . \; . \quad (17)$$

where $t_{0\cdot5}$ is the time required to attain a bainite volume fraction of 0·5. Figure 7 shows the relation between $-n_{av}\log(t_{0\cdot5})$ and $\log(R)$, the gradient of which gives the value of m. The values of m were thus found to be 1·00 and −1·24 for steels A and B respectively. These values are in good qualitative agreement with the indices in the kinetic equations (11) and (12). This further supports the conclusion that the effect of austenite grain size on the reaction rate of bainite transformation depends on the nature of the microstructure.

This result explains many of the discrepancies in previous work,[1–7] where different effects were observed when the austenite grain size was changed. It is necessary to distinguish between the effects of maximum heating temperature and austenite grain size. The maximum heating temperature changes not only the austenite grain size but also the precipitation and solution behaviour. Some studies[5–7] do not take this into account whereas others[1,2] are compatible with the procedure used in the present work, with a secondary austenitisation temperature that is independent of the austenite grain size.



7 Relationship between $-n_{av}\log(t_{0\cdot5})$ and $\log(R)$, with tangent equal to value of grain size exponent *m*

The microstructural characteristics of the bainite sheaves reported by Barford and Owen[1] and Umemoto *et al.*[2] are similar to those of steel B. They claimed that bainite formation was accelerated as the grain size decreased, which is in accordance with steel B in the present study. A fine grain size thus accelerates the kinetics by increasing the number density of nucleation sites.

Conclusions

The effect of austenite grain size on the overall kinetics of isothermal bainite transformation in steels has been studied. It is found that a refinement of the austenite grain structure leads to an acceleration of the rate of transformation when the overall reaction is limited by a slow growth rate. Conversely, for rapid growth from a limited number of nucleation sites, a reduction in the austenite grain size reduces the total volume transformed per nucleus and hence retards the overall reaction rate.

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