Solute-drag, kinetics & and the mechanism of the bainite reaction in steels

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A variety of models for the growth of bainite in steels are compared with experimental results and it is suggested that neither the local equilibrium nor the paraequilibrium mechanisms of transformation are appropriate for bainite growth. It also is demonstrated that segregation-induced solute drag cannot be claimed to influence the growth of bainite. The growth rate of an individual bainite sub-unit is found to be many orders of magnitude greater than that expected under conditions of carbon diffusion control.

Introduction

The purpose of this work is to critically examine the ways in which bainite might grow and to compare these growth models with information obtained from high-resolution experiments. Attention is focussed primarily on the kinetic aspects, but the results should be considered in the context of other recent work [1] on the mechanism of the bainite reaction in steels.

Before discussing the details, it is noteworthy that the long range redistribution of substitutional (X) alloying elements does not occur during bainite growth; the X/Fe atom ratio is the same in the parent and product lattices. This is expected since the transformation is accompanied by a surface relief effect which has the characteristics of an invariant-plane strain with a significant shear component. On the other hand, short range X atom concentration fluctuations have sometimes been suggested to exist in the vicinity of the transformation interface although this would seem inconsistent with the observed surface relief effects. Any short-range X atom concentration fluctuations at the transformation interface may reduce the mobility of the interface by means of various solute-drag effects.

Theory, Results and Discussion

Local Equilibrium

In the local equilibrium model [2], both the X atoms and C atoms partition between the α and γ lattices during transformation, such that each element has the same partial molar free energy in the α and γ lattices at the interface; local equilibrium therefore exists at the interface. At low super saturations, where equilibrium partitioning is a thermodynamic necessity, it is the long range diffusion of X atoms that is meant to control interface motion. The parent and product lattices then differ substantially in X element concentration.

At high supersaturations, bigger departures from equilibrium can be tolerated and the transformation is supposed to occur in such a way that although local equilibrium is maintained at the interface, only a very narrow X atom spike is allowed to exist in the γ immediately adjacent to the interface. The growth of α is then controlled by the diffusion of carbon in the γ and the parent and product lattices have a negligible difference in X/Fe atom ratio.

From the point of view of bainite, we are concerned with the high super saturation case. Hence, in addition to implying a carbon diffusion controlled growth rate, the local equilibrium model also requires the existence of a narrow X atom spike in the γ at the interface, such that the concentration of X at the interface amounts to the equilibrium concentration.

Fig. 1 illustrates an imaging-atom-probe study of the austenite/bainitic-ferrite interface. The bainite was formed by isothermally transforming a Fe-0.43C-2.02Si-3.0Mn wt% alloy at 350°C; the details are given in [1]. The imaging atom probe has both spatial and compositional resolution on an atomic scale and the micrographs illustrate a uniform distribution of substitutional alloying elements despite the presence of the interface. The required composition spike of the local equilibrium model does not exist.

Solute Drag

The theory of solute segregation-induced drag at transformation interfaces is not well established [3] and the experimental evidence in this area is all the more difficult to interpret. There have been a number of suggestions implying the existence of significant interactions between substitutional alloying elements and austenite-ferrite interfaces, but there is no clear evidence for such effects as far as the bainite reaction is concerned.

All of the recent solute drag models rely entirely on the segregation of solute elements to the austenite-ferrite interface. Fig. 1 provides direct evidence (on an atomic scale) that there is no solute segregation at the bainitic-ferrite/austenite interface. Solute drag cannot therefore be claimed to affect the growth of bainite.

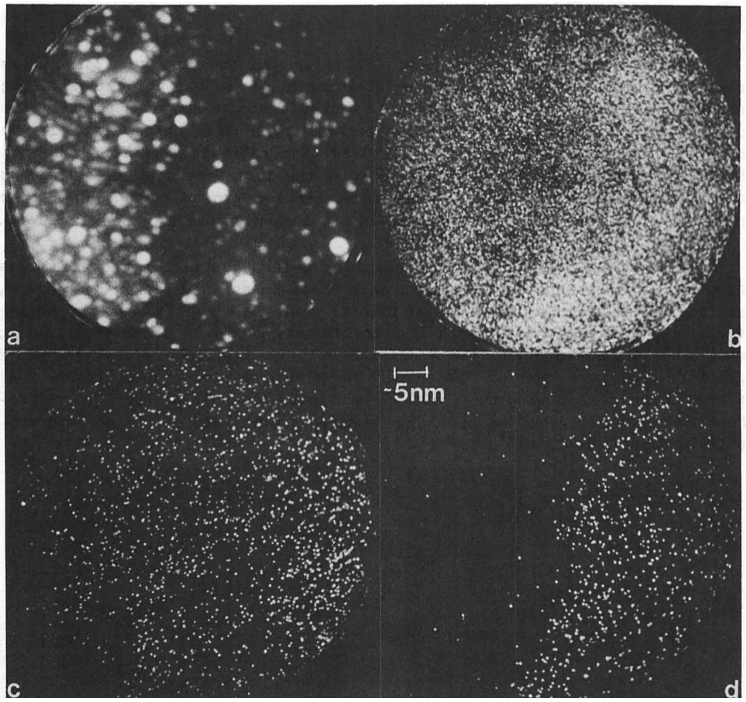

Figure 1: Imaging atom probe pictures, taken across an austenite-bainitic ferrite interface. (a) Field ion image, the α_b/γ interface is vertical. (b) Corresponding iron map. (c) Corresponding silicon map. (d) Corresponding carbon map. After [1].

Paraequilibrium Transformation

Paraequilibrium transformation [1] refers to the formation of α from alloyed austenite without any redistribution of substitutional alloying elements, even on the finest conceivable scale. Carbon is supposed to partition during transformation, such that its partial molar free energy is equal in both the phases at the interface. The X/Fe atom ratio is therefore constant throughout the transforming sample, even at the interface so that X elements are not in equilibrium at the interface. Ferrite growth occurs at a rate controlled by the diffusion of carbon in the austenite ahead of the interface.

The possibility of bainite growing by a paraequilibrium mechanism was examined with hot-stage experiments in a photo-emission electron microscope, so that the individual sub-units of bainite could be directly resolved during transformation. The present work is a preliminary report on these experiments; many more experiments and other details will be published elsewhere. Fig. 2 illustrates a sequence of photo-emission electron micrographs, taken at 1 second intervals, showing the growth of a bainite sub-unit at 380°C in the Fe-Mn-Si-C alloy described earlier. The measured growth rate of the arrowed sub-unit is about $7.5 \times 10^{-5}\ \mathrm{m\,s^{-1}}$.

These results were compared with the theoretically expected carbon diffusion controlled paraequilibrium growth rate using the theory due to Trivedi [4]. This theory has been presented in detail

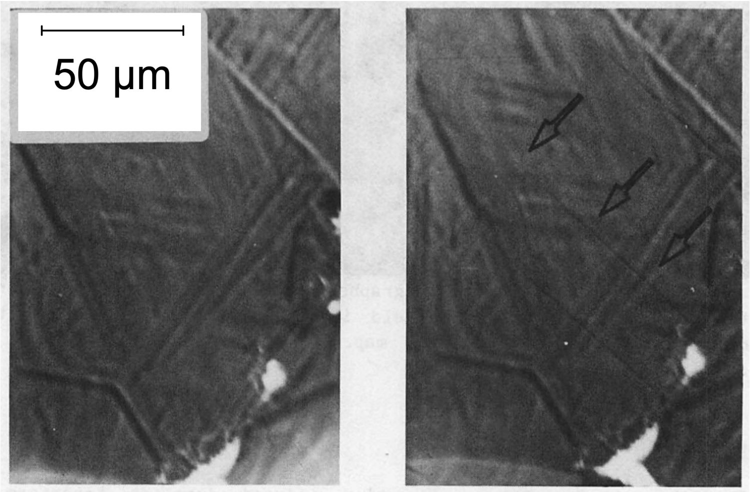

Figure 2: Photoemission electron micrographs showing the growth of an individual bainite sub-unit, as discussed in the text.

elsewhere [4], but the following crucial points should be noted:

(a) The paraequilibrium phase diagram was calculated as in [5], giving the paraequilibrium carbon concentration in the austenite at 380°C as 0.1164 mole fraction.

(b) The calculations assume that the plate tip radius adjusts itself to a value consistent with the occurrence of a maximum growth velocity. Hence, the equilibrium concentration of carbon in the austenite at the plate tip is 0.096869 mol. frac. when the α/γ interface energy is taken to be 0.2 $\mathrm{J\,m^{-2}}$.

(c) Strain energy effects are ignored; these can only reduce the calculated growth velocity.

(d) The calculations are based on a carbon diffusion coefficient evaluated as a weighted average of the composition range in the matrix, as discussed by Trivedi and Pound [4]. The relevant composition range which delimits the carbon concentration profile ahead of the growing edge is thus 0.0196-0.096869, giving the effective diffusivity as $0.1205\times10^{-15}\ \mathrm{m^2s^{-1}}$. The diffusivity was expressed as a function of carbon content using the method of Bhadeshia [5].

All the above conditions should give an accurate estimate of the maximum possible growth rate under carbon diffusion control, and this was calculated to be $8.34\times10^{-8}\ \mathrm{m\ s^{-1}}$. This is clearly many orders of magnitude lower than that observed experimentally, despite the fact that the calculations allow the maximum possible growth rate to be evaluated. The growth of bainite clearly occurs at a rate much faster than expected from carbon diffusion control. Recent work [1] has indicated that this is only to be expected since the experimental evidence [1] implies that bainite grows by a shear mechanism with a supersaturation of carbon in the bainitic ferrite.

Conclusions

It has been demonstrated that bainite does not grow under conditions of local- or para-equilibrium; the growth rate as measured experimentally is many orders of magnitude higher than that expected from C diffusion control. Atom-probe experiments also indicate that the segregation necessary for solute drag does not exist.

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