

# Widmanstätten ferrite and bainite

## *Introduction*

In order to interpret the effect of alloying elements on the formation of Widmanstätten ferrite and bainite it is necessary to have an understanding of the mechanisms governing their formation in the binary Fe-C system. However, there are conflicting ideas about those mechanisms and it is thus necessary to start by discussing those ideas. The first question concerns the mechanism by which the fcc lattice of austenite transforms into the bcc lattice of ferrite when these structures form. How closely related is it to the mechanism of martensite formation, which gives a surface relief? The second question concerns the behaviour of carbon during the transformation of the ferrite. Does it partition between ferrite and austenite at the moving interface or is it sufficiently immobile to remain in its positions between the neighbouring Fe atoms?

Important information on both questions was obtained by Ko and Cottrell (1) who observed that bainite gives rise to a surface relief similar to martensite. They also reported that the lengthening of the acicular bainite units were slow enough to allow carbon to escape into the matrix austenite. In a second paper Ko (2) showed that Widmanstätten ferrite also gives rise to a surface relief although he confused the issue by calling it bainite. Hillert (3) accepted both results and developed a model describing the gradual transition from diffusion control of acicular ferrite to rapid diffusionless growth of martensite as the carbon content was decreased. Oblak and Hehemann (4) argued for rapid diffusionless growth of bainitic ferrite and explained the low, experimental growth rate by a series of rapidly growing subunits of ferrite but slow nucleation of each subsequent subunit. Aaronson (5) argued that the acicular units of bainitic ferrite thicken by a ledge mechanism and both thickening and lengthening are governed by the rate of carbon diffusion. In more recent years, the nature of the moving interface between austenite and acicular ferrite was discussed intensively and it no longer seems justified to make a sharp distinction between martensitic and non-martensitic interfaces (6). This is supported by recent reports that the transformation to Widmanstätten ferrite, bainitic ferrite and lath martensite all result in the 24 variants of ferrite orientations relative to the parent austenite (7,8). There is still a conflict regarding the role of carbon diffusion during growth of bainitic ferrite but there seems to be essential agreement that Widmanstätten ferrite grows under carbon diffusion.

## *Effect of alloying elements*

Hultgren (9) first realized that alloying elements may be too sluggish to partition between the two phases during the transformation from austenite to ferrite. He hypothesized a restricted local equilibrium between the two phases characterized by equilibrium for carbon but no movements of the atoms of alloying elements and iron relative to each other. He called it paraequilibrium. Hillert (10) pointed out that ferrite could inherit the content of alloying elements from austenite even if it partitions at the interface. This is possible by a very local pile-up in front of the moving interface. He called this false paraequilibrium and later quasiparaequilibrium (11). Today it is usually called NPLE (No

Partition Local Equilibrium) (12). Whether a phase interface moves under paraconditions or quasiparaconditions may have a strong effect on the carbon activity at the interface and thus affect the rate of transformations occurring under long-range diffusion of carbon. Kirkaldy (13) reached the same conclusion by an ambitious treatment of the problem of diffusion in a ternary system where one alloying element is much more mobile than the other.

Ferrite nucleates most easily at austenite grain boundaries and at high temperatures it usually grows into one of the austenite grains and obtains bulky shapes, so-called grain boundary allotriomorphs. Sluggish elements cannot escape from such ferrite and the transformation will be partitionless. By using the diffusion coefficient one can estimate the expected width of the pile-up and by comparing with the atomic distances one may decide if the pile-up should be well developed, in which case there should be quasiparaconditions, i.e., full local equilibrium between the phases at the interface, or should not at all exist, in which case there should be paraconditions, i.e. full local equilibrium for carbon but movements of alloy elements relative to iron. Experimental growth rates indicate that full local equilibrium at the austenite/ferrite interface is rarely possible.

The lengthening rate of Widmanstätten ferrite with its acicular shape is considerably faster, if controlled by carbon diffusion, and it is common to assume that it grows under paraconditions. This is even more certain for the acicular bainitic ferrite, whether its growth is controlled by carbon diffusion or is diffusionless.

The critical temperature where bainite starts to form has attracted much attention. According to the hypothesis of diffusionless growth it should be closely related to the so-called  $T_0$  temperature which is the thermodynamic boundary below which there is a driving force for the diffusionless transformation. That has been emphasized by Bhadeshia (14) who proposed that a driving force of 400 J/mol is required due to transformation stresses. For Widmanstätten ferrite he proposes a much lower driving force, 50 J/mol. With this hypothesis it is straight-forward to predict the effect of alloying elements on both acicular kinds of ferrite through the effect on the thermodynamic properties of austenite and ferrite. On the other hand, it does not predict the effect of alloying elements on the growth rate of bainite because that is supposed to depend on the length of each subunit and how much time it takes until the next subunit nucleates. Such information is not available.

When comparing predicted growth rates of both types of acicular ferrite with experimental results with the diffusional approach, already Hillert (3) had found it necessary to accept that a considerable driving force is necessary before acicular ferrite can start growing. He obtained an energy barrier that varies considerably with temperature and is considerably larger than 400 J/mol at the lower temperatures. Hillert et al. (15) revised the estimate of that energy and applied the approach to alloyed steels. They also accounted for the effect of the alloying elements thermodynamically. However, they evaluated the effect of the energy barrier and of the alloying elements through their effects on the equilibrium carbon activity of austenite in paraequilibrium with ferrite.

For Cr and Mo they found it necessary to accept that there is a further factor slowing down the formation of bainitic ferrite and they regarded it as a kind of solute drag. Using the magnitude of that effect, evaluated for Mo, they could give an explanation of the bay in TTT diagrams of steels alloyed with Mo (16). This may open a possibility of rationalizing the effect of alloying elements on the bay phenomenon in the TTT diagrams.

The effects of alloying elements on the formation of the carbide constituent of bainite should be interpreted differently depending on what picture of the transformation mechanism is accepted, i.e., whether the carbide particles form by precipitation inside a highly supersaturated ferrite or by growth together with ferrite into the parent austenite. It seems that this effect has not yet been analyzed in any detail. On the other hand, the well-known effect of Al and Si to inhibit the formation of cementite has been put into commercial use by the production of steels with so-called carbide-free bainite. Of course, that carbide-free bainite should simply be fine Widmanstätten ferrite in view of the hypothesis of diffusion-controlled transformation to bainite. There does not seem to be any detailed study yet of the relation between the amount of Al and Cr and the conditions for inhibition of cementite formation, nor of other carbides.

It is well known and even self-evident that austenite stabilizers depress the formation of all kinds of ferrite to lower temperatures. This is an important effect in practice and Mn and Ni are usually used for this purpose. This effect is usually studied through the effect on the TTT diagram but more detailed studies should be most welcome. More fundamental information is mainly obtained for the pearlite transformation.

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