The mechanism of bainite formation; a current assessment

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Outline:

Aspects of bainite formation

- •Perspective(s) on bainite, and a personal view.
- Microstructure
- •Kinetics (nucleation and growth)
- Chemistry (including thermodynamics)
- •Interface properties (equilibrium and dynamic)
- Surface relief

Questions still to be addressed Conclusions



Perspectives on bainite formation:

These have been discussed at length, recently and notably in a viewpoint set edited by Mats Hillert (Scripta Mat. **47**,2002, 137).

The main differences concern the role of carbon diffusion: before or after the initial growth of bainitic ferrite? Other debates concern the structure and migration mode of the ferrite/austenite interface, the role(s) of alloying elements and of carbide precipitation, The formation of subunits, and (even) the definition of bainite.

(I belong to the diffusional camp.)



Schools:

Diffusionless growth: Zener, Ko&Cottrell, Oblak&Hehemann, Bhadeshia&Edmonds, others.

Diffusional growth: Stockholm school (Hultgren, Hillert, Agren); Aaronson and colleagues (Enomoto, Spanos, Reynolds Jr., Muddle, Nie), Quidort&Brechet, others.

Both agree that nucleation is probably thermally activated.



Microstructure:

Many observations have been made of the microstructures of bainite and Widmanstatten ferrite, mainly via optical microscopy.

These give an overall view of the product, although the two-dimensional nature of the technique and the presence of quenching artifacts can sometimes be misleading.

A few examples:





Fig. 2. (a) Grain boundary initiated plates of Widmanstätten ferrite formed in 0.5 s at 630° C. Etched in picral. Magnification × 1200. (b) Same area etched in nital. The Widmanstätten plates happened to have such a crystalline orientation that the nital attack is slow. The micrograph indicates that much of the adjoining martensite, formed on quenching has the same orientation. From Ref. [3].

Hillert (1960):

Widmanstätten ferrite and martensite have similar orientation and habit plane. (internal report, Swedish Instutite for Metal Research)





Fig. 1. Formation of bainite during 10 s at 445° C and its continued growth as Widmanstätten ferrite during 20 s and 693°C in a 0.6% C steel. Magnification ×1800. From Ref. [7].

Hilert's demonstration that bainite will continue to grow as Widmanstätten Ferrite. (Värmländ Bergsmann Ann. p.1, 1958)





Fig. 2. (a) Typical micrographs of the grain boundary ferrite formed after the first isothermal step at 600° C in the alloy A; (b) and (c) micrographs of the bainite growth during the second holding (at 400° C in this case) after 12 and 50 s, respectively.

Quidort and Brechet: Bainite grows from previously formed grain boundary ferrite allotriomorphs. This allowed the isolation of growth kinetics, and the evaluation of nucleation kinetics from overall kinetics.

Acta Materialia 2001, **49**, 4161 Scripta Materialia 2002, **47**, 151





Fig. 8. Optical micrograph of alloy D partially transformed into bainite at 400°C then quenched. A narrow white layer is clearly visible around each laths of bainitic ferrite (dark gray). The matrix in light gray is martensite.

Quidort and Brechet (2001)

Note: there are no breaks in growth kinetics or in microstructure from Widmanstätten ferrite through bainite, unless attributable to carbide formation.





Fe 1,5%Mn 0,4%C Decarburized With a mixture of CO and CO_2 (%C on the surface = 0.11 t = 30min, T = 1075°C Oil quenching



Fe 1,5%Mn 0,4%C Decarburized With a mixture of CO and CO₂ (%C on the surface = 0.11 t = 30min, T = 1075°C (Chihab, 2008)





Carbides:

These are thought to be formed from the austenite adjacent to the ferrite; there is often only one variant present, suggesting that they nucleate at facets on the ferrite-austenite interface (three phase junctions).

Carbides also act as sinks for carbon, and are expected to influence the kinetics of ferrite growth.



Autocatalytic formation of stacks of tetragonal θ' in Al-Cu; for combined shear and dilation, similar results are predicted by modeling of elastic interactions.



Concerning subunits:

The three-dimensional morphology is little understood; it would be useful to have a better idea of the geometrical/crystallographic relations among the different subunits in a sheave.

One possibility is that the units are sympathetically nucleated, and are in at some point in contact with one another.

Another is that they are autocatalytically nucleated, as in the documented case of θ' in Al-Cu;

A third is that they stem from an initial ferrite plate via a morphological instability.



Autocatalysis:

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Perovic, Purdy, Brown:
Scripta Met., 1981, 15, 217
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"inclined stacks of subunits will form when the dilatational component ε_{33} dominates the shear component ε_{13} , and when the potential for nucleation is such that a small elastic component is sufficient to select the location, orientation, and crystallographic variant of the daughter phase. The interactions possess a minimum for low inclination angles (<20°) of the stacks to the habit plane."

Alloying element effects:

Possible effects:

- Thermodynamic; effects on supersaturation, phase equilibria (stable and metastable, PE or LE).
- Suppression of carbide precipitation (e.g. Si),
- Change of carbide type, chemistry,
- Kinetic effects; (e.g. stasis due to Mo, Cr),
- Morphological effects; e.g. degeneracy,
- Interface specific effects (segregation, solute drag).
- stabilization of parent austenite (e.g. Mn, Ni).

See a review by Prof. Enomoto (Scripta Mat., 2002, 47, 145)



Interfaces:

Widmanstatten ferrite, martensite and bainite/austenite interfaces are typically faceted, lying on defined habit planes. Their structure has been investigated (usually in alloy steels) by a number of researchers, including Rigsbee and Aaronson, Sandvik and Wayman, Moritani, Miyajima, Furuhara and Maki, with rather different conclusions. In the latter case, comparisons were made between bainite/austenite and lath martensite/austenite interfaces.



Crystallography of interfaces:

It has been shown several times that the phenomenological theory of martensite crystallography works well for bainite laths, *as well as for a number of purely diffusional transformations in substitutional solid solutions.*

The newly developed theory of "disconnections", due to Pond and Hirth (e.g. Acta, 2003, **52**, 5385), gives more detailed insights into the mechanism of plate/lath formation: disconnections are structural elements whose lateral motion is responsible for the advance of the interface as well as the accompanying structural change; their dislocation character is also responsible for surface relief.







Disconnection geometry





Crystallography of interfaces (2):

Following Hirth and Pond, lath martensite/austenite interfaces are glissile, containing mobile structural disconnections. This places severe geometrical restrictions upon them; they will not generally be of lowest energy for given OR and habit plane.

This strongly suggests that many bainite/austenite interfaces are relaxed to a lower energy configuration, and are therefore not necessarily glissile. (They may however, have originally been glissile, thus reconciling the different observations.)



It is considered that:

Widmanstatten ferrite lengthens by diffusion of carbon; the plate tips are close to a local equilibrium.
Upper bainite is *structurally and kinetically* continuous

with Widmanstatten ferrite.

•The presence of a transformation shear is not sufficient evidence for a martensitic mechanism, nor is it evidence for a fast transformation.



Questions to be addressed (suggestions for further research):

What is the origin and the role of sub-unit structures? [strain energy/autocatalytic nucleation/morphological instability?]

Since martensite/austenite interfaces are considered to propagate by the synchronous motion of disconnections, do they differ significantly from bainite/austenite interfaces?

[i.e.Are bainitic interfaces relaxed to a lower energy state?]

How important is solute drag in the formation of bainites in alloy steels?

What are the true (3-dimensional) morphologies?

What is the role of carbide precipitation in the formation of bainites?

[This includes quantitative kinetics of lengthening and thickening.]

