Bainite Transformation at Atomic Scale

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Research at the Oak Ridge National Laboratory ShaRE User Facility was sponsored by the Scientific User Facilities Division, Office of Basic Energy Sciences, U.S. Department of Energy.
Bainite Transformation Mechanisms
Displacive vs. Reconstructive. 70 Years of Controversy

**Displacive Theory:** bainitic ferrite forms by shear and the individual atom movements are less than one inter-atomic spacing.

**Reconstructive Theory:** bainitic ferrite forms by thermally activated atom movements and grows by the migration of growth ledges on the broad faces of the interface.
Bainite Transformation Mechanisms
Diffusionless vs. Diffusional. Today Controversy

Today it is accepted that bainite grows with a displacive mechanism i.e. as plate-shaped (or lath-shaped) transformation product exhibiting an invariant plane strain surface relief effect. But there is still much discussion on the diffusion or diffusionless nature of bainite.

When it is stated that ferrite grows with a displacive mechanism, it does not imply that it is also diffusionless. For instance, Widmanstätten ferrite forms with a displacive but diffusional growth mechanism.

**Diffusionless Theory:** bainitic ferrite grows without any diffusion of carbon, and carbon supersaturation is subsequently relieved by partitioning to austenite, or through carbide precipitation.

**Diffusional Theory:** bainitic ferrite growth is controlled by carbon diffusion, and not distinctly different in character from Widmanstätten ferrite with carbide precipitation at the austenite/ferrite boundaries.
The criterion for distinguishing between these rival theories of bainite transformation is whether the newly formed bainitic ferrite has the para-equilibrium carbon content (~0.12 at.%) or if it is supersaturated with carbon.

In most alloys, it is impossible to experimentally estimate the initial carbon content of bainitic ferrite because the time taken for any carbon to diffuse into austenite can be extremely short. Carbon can be very mobile at low temperatures.
The carbon level in newly formed bainitic ferrite may be determined indirectly by analyzing the carbon concentration in the austenite at the end of the bainite reaction.

Carbon concentrations of the residual austenite confirming the incomplete reaction phenomenon i.e. the $T_0$ curve, indicate that bainite initially forms having a full supersaturation of carbon.

Bainite reaction is expected to cease as soon as the austenite carbon content reaches the value at which diffusionless growth becomes thermodynamically impossible.
Slow Bainite Transformation Kinetics

Fe-4.3C-2.8Si-1.2Mn-1.3Cr (at.%) Steel
- 200°C

Slow reaction rates can be advantageous for determining the carbon content of the bainitic ferrite during growth. The rate at which bainite forms will slow down dramatically as the transformation temperature is reduced.
XRD provides an average estimate of the carbon in the ferrite matrix and all carbon-enriched regions, such as dislocations and boundaries. Therefore, it is not always appropriate to monitor the progressive decarburization of the super-saturated ferrite plates, as bainite transformation progresses.
Fe-4.3C-2.8Si-1.2Mn-1.3Cr (at.%) steel transformed at 200 °C for 10 days

APT results on carbon content of the ferrite are lower than those measured by XRD, but still slightly higher than that expected from paraequilibrium with austenite at 200 °C (0.12 at.%).
APT is able to measure the true carbon content of the ferrite and effectively monitor the decarburization of supersaturated bainitic ferrite as the transformation progresses. Bainitic ferrite grows supersaturated with carbon consistently with a diffusionless growth mechanism. However, it seems natural to believe that trapping of carbon in the growing ferrite require faster kinetics than those observed experimentally.
The carbon supersaturation of bainitic ferrite was investigated by APT in three steels with different carbon and silicon contents to elucidate the effect of the reaction velocity on the mechanisms controlling bainite formation with and without the interference of cementite precipitation.
No sharp change of the carbon content in bainitic ferrite that could indicate a difference in bainite growth mechanism between high and low temperatures.

No essential difference in the observed results between steels that transform to bainite with and without the interference of cementite precipitation.

This fact lends strong support for the opinion that, the bainitic ferrite grows supersaturated with carbon independently of the transformation temperature and the overall reaction rate.

As the transformation temperature is increased, carbon diffusion is enhanced providing an opportunity for the decarburization of the supersaturated ferrite soon after the growth event.
Partitioning of Carbon into the Residual Austenite

Fe-4.3C-2.8Si-1.2Mn-1.3Cr (at.\%) steel heat treated at 200 °C for 10 days.

Austenite films entrapped between neighboring subunits of bainitic ferrite

Blocks of residual austenite located between the sheaves of bainite
Dislocations in Nanocrystalline Bainitic Steels

Fe-4.3C-2.8Si-1.2Mn-1.3Cr (at.%) steel heat treated at 200 °C for 2 days.

Dislocations are created when the shape deformation accompanying bainite growth is accommodated by plastic relaxation of the surrounding austenite.
Carbon Trapped at Dislocations

Fe-4.3C-2.8Si-1.2Mn-1.3Cr (at.%) steel heat treated at 200 °C for 10 days.

Complementary APT results reveal carbon trapping at dislocations in the vicinity of a ferrite–austenite interface.

CENIM-CSIC, ORNL and Tohoku University Collaboration
Accommodation Twinning in Austenite

Fe-3.5C-3.8Si-1.4Mn-1.3Cr (at.%) steel heat treated at 200 °C for 10 days.

Plastic relaxation of the shape change occurring in the adjacent austenite can also take the form of accommodation twinning.

CENIM-CSIC, ORNL and National Taiwan University Collaboration
Carbon Trapped at Nanoscale Twins in Austenite

Fe-4.3C-2.8Si-1.2Mn-1.3Cr (at.%) steel heat treated at 200 °C for 2 days.

CENIM-CSIC, ORNL and National Taiwan University Collaboration
Carbide Precipitation in Ferrite

High Carbon High Silicon Steel heat treated at 200 °C

Bainitic carbides nucleates and grows within supersaturated ferrite in a process identical to the tempering of martensite.
Conclusions

- In this work, the carbon supersaturation of bainitic ferrite was determined by means of atom-probe tomography to elucidate the effect of transformation temperature and the reaction velocity on the mechanisms controlling bainite formation with and without the interference of cementite precipitation.

- The results indicated that there was no difference in the growth mechanism over the entire range of temperatures studied. The original bainitic ferrite seemed to retain much of the carbon content of the parent austenite, but secondary processes such as the partitioning of carbon into the residual austenite, carbon trapping at dislocations and carbide precipitation are activated soon after the growth event.

- Atom-probe tomography results provided strong evidence that bainite transformation is essentially martensitic in nature.