Case Study: Design of Bainitic Steels

Bainite Summarised

Bainite is a non–lamellar aggregate of carbides and plate–shaped ferrite (Fig. 1). Each ferrite plate is about 10μm long and about 0.2×10^{-6} m thick, making an individual plate invisible in the optical microscope. The fine scale of the microstructure is beneficial to both the strength and toughness. Within the broad classification of bainite, there are two particular forms.

Upper bainite consists of clusters of platelets of ferrite which are in identical crystallographic orientation and intimately connected to the austenite in which they grow. Elongated cementite particles decorate the boundaries of these platelets, the amount and continuity of the cementite layers depending on the carbon concentration of the steel.

As the transformation temperature is reduced, some of the carbon is encouraged to precipitate inside the ferrite plates, leading to the lower bainite microstructure (Fig. 1).

Alloy Design

High–strength bainitic steels have not in practice been as successful as quenched and tempered martensitic steels, because the coarse cementite particles in bainite are detrimental for toughness. The precipitation of cementite during the bainite transformation can be suppressed by alloying with about 1.5 wt.% of silicon, which has a very low solubility in cementite and greatly retards its growth.

An interesting microstructure results when this silicon–alloyed steel is transformed into upper bainite. The carbon that is rejected into the residual austenite, instead of precipitating as cementite, remains in the austenite and stabilises it down to ambient temperature. The resulting microstructure consists of fine plates of bainitic ferrite separated by carbon–enriched regions of austenite (Fig. 2).

The potential advantages of the mixed microstructure of bainitic ferrite and austenite can be listed as follows:

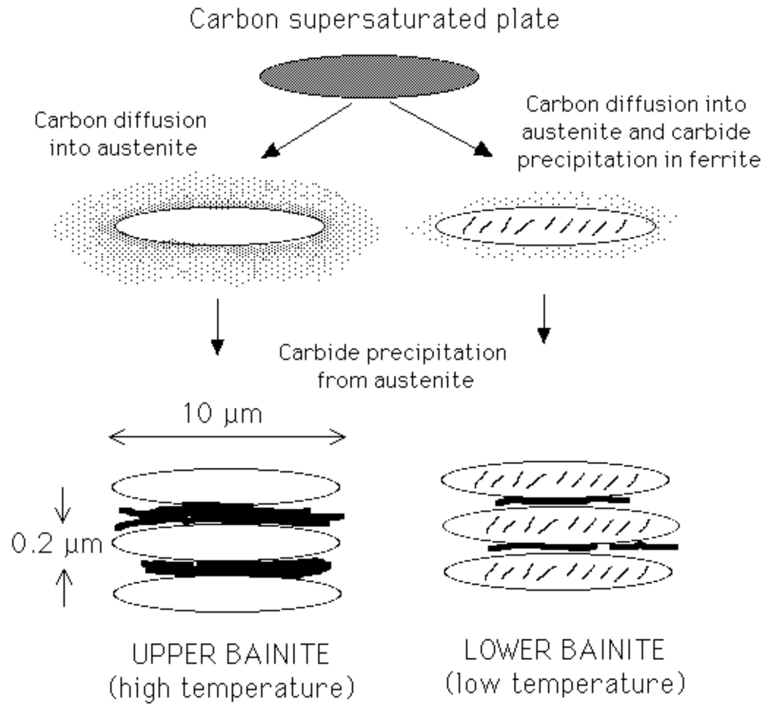

Fig. 1: Summary of the mechanism and microstructure of bainite in steels. A plate of bainite forms without diffusion, but any trapped carbon then partitions into the residual austenite where it eventually precipitates as cementite. If the transformation temperature is sufficiently small, some cementite may also precipitated within the supersaturated bainitic ferrite, giving rise to the lower bainitic microstructure.

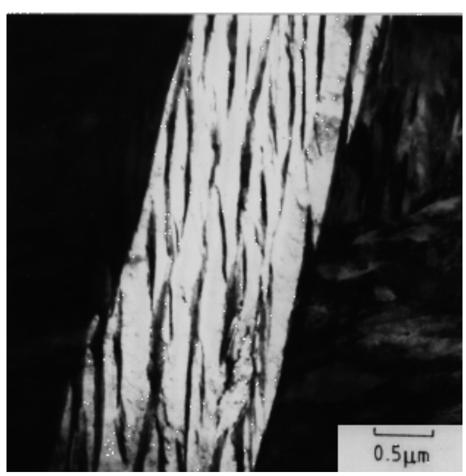

Fig. 2: Transmission electron micrograph of a sheaf of bainite, consisting of fine ferrite platelets separated by films of carbon–enriched retained austenite.

(a) Brittle cementite is eliminated, making the steel more resistant to cleavage fracture and void formation.

(b) The bainitic ferrite is depleted in carbon; dissolved carbon is known to embrittle ferrite.

(c) The microstructure, which is generated by a simple heat treatment, derives its strength from ultrafine ferrite plates, which are much less than one millionth of a meter in thickness. This cannot be achieved by any other commercially viable process. Furthermore, refinement is the only mechanism for simultaneously improving the strength and toughness of steels.

(d) The ductile films of austenite which are intimately dispersed between the plates of ferrite have a crack blunting effect.

(e) The diffusion of hydrogen in austenite is slower than in ferrite. Austenite can therefore lead to an improved stress–corrosion resistance.

(f) Steels with this microstructure are cheap. All that is required is that the silicon concentration should be large enough to suppress cementite.

In spite of these appealing features, the bainitic ferrite/austenite microstructure does not always give the expected good combination of strength and toughness. Although the films of austenite enhance toughness, there remain relatively large "blocky" regions of austenite between the sheaves of bainite (Fig. 3). These blocks are less stable and transform into high–carbon martensite under the influence of a small applied stress. This untempered, hard martensite embrittles the steel. The blocks can in principle be eliminated by allowing more transformation, but as shown in the next section, there is a thermodynamic limit to the amount of bainite that can form in the absence of carbide precipitation. It is ironic that the prevention of cementite precipitation (in order to eliminate a brittle phase) leads to the retention of large blocks of unstable austenite which then embrittle the steel. To solve the problem, it is necessary to manipulate the thermodynamic limit to permit more bainitic ferrite to form and consume the large blocks of austenite whilst still retaining the films of stable austenite.

Model

An apparently ideal microstructure consisting of bainitic ferrite and ductile austenite in a Fe–3Mn–2.02Si–0.43C wt% exhibits poor toughness because of the presence of blocky, unstable austenite. It is necessary to increase the amount of bainitic ferrite in the microstructure and

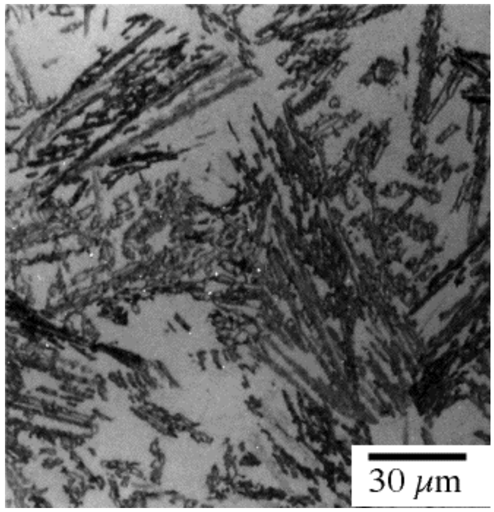

Fig. 3: Optical micrograph of upper bainite in an Fe–0.43C–3Mn–2.02Si wt.% showing the blocks of retained austenite between sheaves of bainite.

to increase the stability of the austenite. Both of these aims can be achieved by changing the substitutional solute concentration such that the T_0' curve is shifted to higher carbon concentrations (*i.e.* T_0' is raised at any given carbon concentration).

The remarkable improvement in toughness achieved by doing this, without any sacrifice of strength, is illustrated in Fig. 4, along with the T_0' curves.

Commercial Applications

We demonstrated above, that a knowledge of the mechanism of bainite formation can be exploited towards the design of new steels. These concepts have now been used both in the development of novel ultra–high strength steels with strength and toughness combinations which match or exceed more expensive alloys Fig. 5.

A recent major application has been in the development of rail steels which are tough and at the same time extremely resistant to wear. Producers of steel for railway tracks have had the long standing difficulty that the harder they make the rail, the longer it lasts but can increase the wear can be suffered by the rolling stock wheels. The microstructure of conventional rails is based on a mixture of cementite and ferrite in the form of pearlite. The cementite is hard and therefore provides wear resistance, but is at the same time brittle. The new bainitic rail steel is completely free of carbides; it has a much higher toughness while at the same time being harder due to the fine grain size and the presence of some martensite and retained austenite.

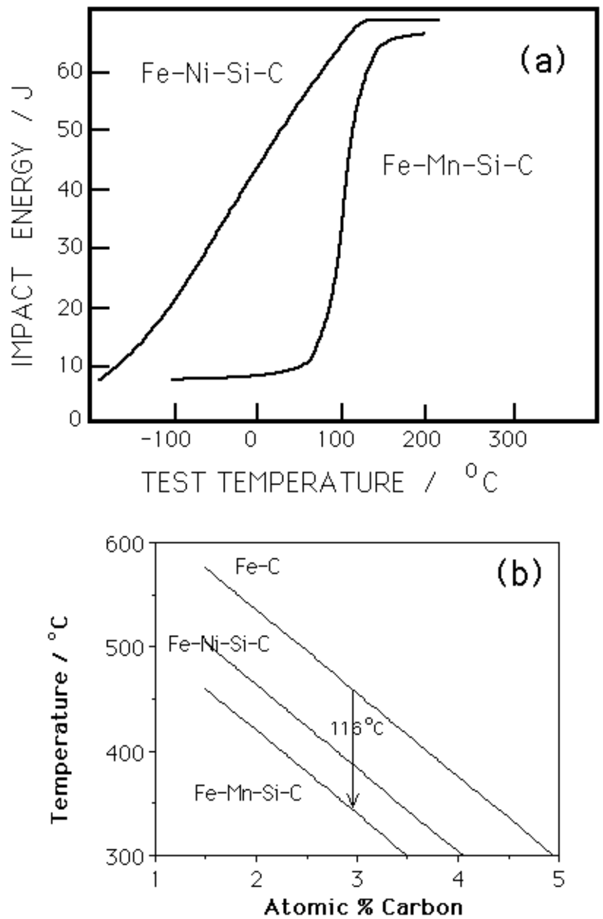

Fig. 4: (a) Experimentally determined impact transition curves showing how the toughness improves as the amount of blocky austenite is reduced. (b) Calculated T_0' curves for the Fe–C, Fe–Mn–Si–C and Fe–Ni–Si–C steels.

Tests show that it has remarkable wear resistance, reduces wear on the wheels, is tough and weldable (Fig. 6). The steel is now commercialised.

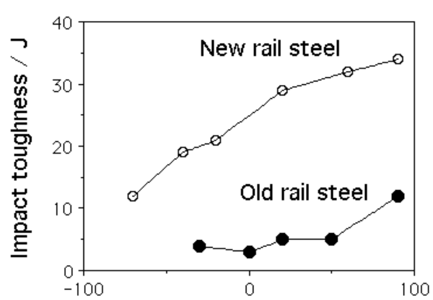

Fig. 6: Toughness of new rail steel against conventional rail steels

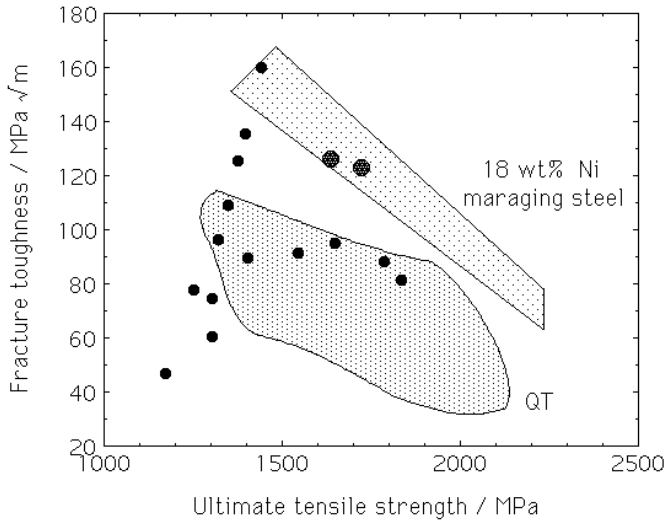

Fig. 5: Some of the new cheap bainitic steels match the properties of expensive alloys.