11 *Other Morphologies of Bainite*

Upper and lower bainite are established terms describing microstructures which can easily be distinguished using routine microscopy, and whose mechanisms of formation are well understood. There are, however, a number of other descriptions of steel microstructures which include the word 'bainite'. These additional descriptions can be useful in communicating the form of the microstructure. But this must be done with care, avoiding the natural tendency to imagine a particular mechanism of transformation, simply because someone has chosen to coin the terminology.

11.1 Granular Bainite

Of all the unusual descriptions of bainitic microstructures, granular bainite is probably the most useful and frequently used nomenclature. During the early 1950s, continuously cooled low-carbon steels were found to reveal microstructures which consisted of 'coarse plates and those with an almost entirely granular aspect', together with islands of retained austenite and martensite, Fig. 11.1 (Habraken, 1956, 1957, 1965; Ridal and McCann, 1965; Habraken and Economopolus, 1967). Habraken and coworkers called this granular bainite and the terminology became popular because many industrial heat-treatments involve continuous cooling rather than isothermal transformation. The energy generation industry in particular uses enormous quantities of bainitic microstructures generated by allowing large steel components to cool naturally (Chapter 12). Granular bainite is supposed to occur only in steels which have been cooled continuously; it cannot be produced by isothermal transformation.

The coarse ferrite plates referred to earlier, do not really exist. They are in fact, sheaves of bainitic ferrite with very thin regions of austenite between the sub-units because of the low carbon concentration of the steels involved (Leont'yev and Kovalevskaya, 1974; Josefsson and Andren, 1989). Hence, on an optical scale, they give the appearance of coarse plates (Fig. 11.1a). Many of the original conclusions were reached from microstructural observations which were not of sufficient resolution to establish the fine structure within the sheaves of bainite. Indeed, evidence of this interpretation of so-called coarse plates appeared in the literature as early as 1967 when thin foil TEM

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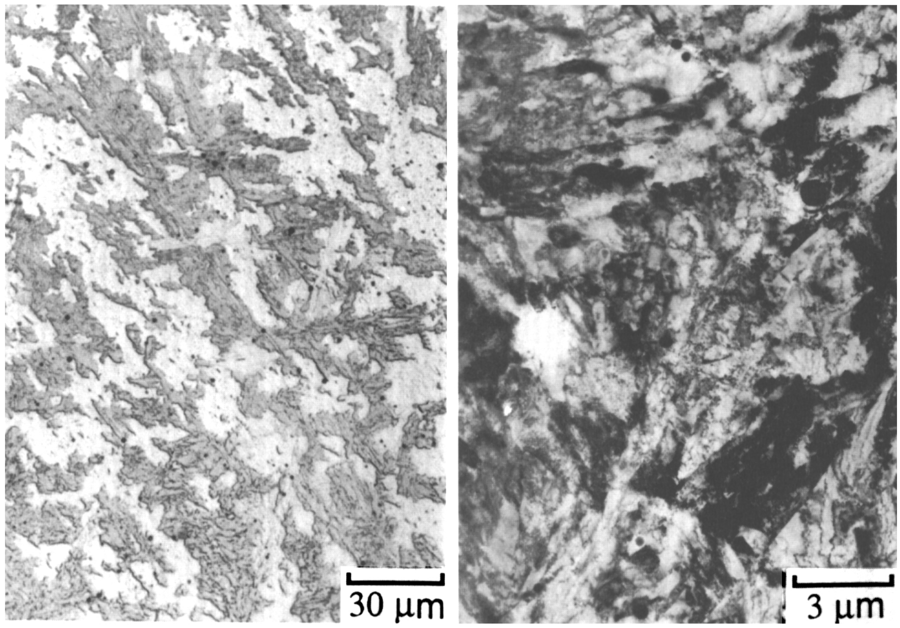

Fig. 11.1 Granular bainite in a Fe–0.15C–2.25Cr–0.5Mo wt.% steel: (a) light micrograph; (b) corresponding transmission electron micrograph (after Joseffson, 1989).

observations were made by Habraken and Economopolus, revealing the fine bainitic ferrite platelets within the sheaves.

A characteristic (though not unique) feature of granular bainite is the lack of carbides in the microstructure. The carbon that is partitioned from the bainitic ferrite stabilises the residual austenite, so that the final microstructure contains both retained austenite and some high-carbon martensite. Consistent with observations on conventional bainite, there is no redistribution of substitutional solutes during the formation of granular bainite (Tenuta-Azevedo and Galvao-da-Silva, 1978).

The extent of transformation to granular bainite is found to depend on the undercooling below the bainite-start temperature (Habraken and Economopolus, 1967). This is a reflection of the fact that the microstructure, like conventional bainite, exhibits an incomplete reaction phenomenon.

The evidence therefore indicates that granular bainite is not different from ordinary bainite in its mechanism of transformation. The peculiar morphology is a consequence of two factors: continuous cooling transformation and a low carbon concentration. The former permits extensive transformation to bainite during gradual cooling to ambient temperature. The low carbon concentration ensures that any films of austenite or regions of carbide that might exist between sub-units of bainite are minimal, making the identification of individual platelets within the sheaves rather difficult using light microscopy.

Finally, it is interesting that in an attempt to deduce a mechanism for the formation of granular bainite, Habraken (1965) proposed that the austenite prior to transformation divides into regions which are rich in carbon, and those which are relatively depleted. These depleted regions are then supposed to transform into granular bainite. The idea is the same as that of Klier and Lyman (1944) and has been shown to be thermodynamically impossible in steels (Aaronson *et al*., 1966a).

11.2 Inverse Bainite

Ferrite is the dominant phase in conventional bainite; carbide precipitation when it occurs is a secondary event. In the so-called 'inverse bainite' which is found in hypereutectoid steels, it is the cementite which is the first phase to form (Hillert, 1957). A central plate-like spine of cementite grows directly from austenite (Hehemann, 1970) and then becomes surrounded by a layer of ferrite (Fig. 11.2). The term 'inverse' reflects the fact that, unlike conventional bainite, cementite is the first phase to precipitate from austenite.

The mechanism of the transformation is virtually unknown; there is no evidence that the growth of the ferrite occurs by a coordinated movement of atoms, and no crystallographic or chemical composition data. Judging from the shape alone, the ferrite probably forms by a reconstructive transformation mechanism. It is premature to classify the transformation as bainite.

11.3 Columnar Bainite

'Columnar bainite' is a description of a non-lamellar aggregate of cementite and ferrite, the overall shape of which is like an irregular and slightly elongated colony (Fig. 11.3). The distribution of cementite particles within the colony is rather peculiar, the majority of needle-shaped particles being aligned to the longer dimension of the colony. This latter region is surrounded by a layer of a different microstructure, in which the coarse cementite particles meet the austenite/ferrite interface edge on (Nilan, 1967). The structure is normally observed in hypereutectoid steels (Greninger and Troiano, 1940; Vilella, 1940; Jellinghaus, 1957; Speich and Cohen, 1960) but has been found in lower carbon steels transformed at high pressures (Nilan, 1967). It may be relevant to point out that the eutectoid composition is shifted to lower carbon concentrations by hydrostatic pressure.

The microstructure can be obtained at transformation temperatures comparable with those associated with conventional bainite, but there is no invariant-plane strain surface relief accompanying the growth of 'columnar bainite'. It is

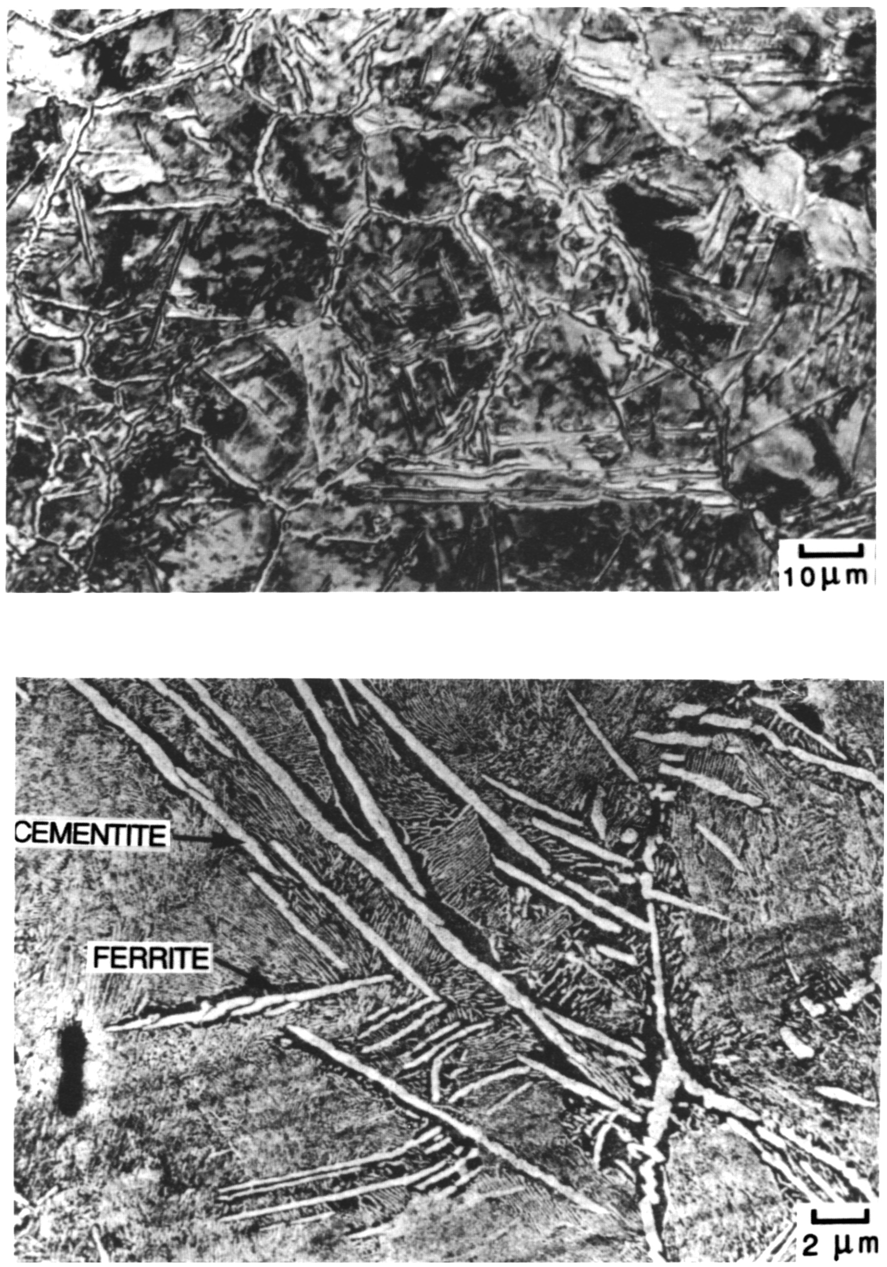

Fig. 11.2 Inverse bainite in a hypereutectoid steel: (a) light micrograph; (b) transmission electron micrograph (after Farooque and Edmonds).

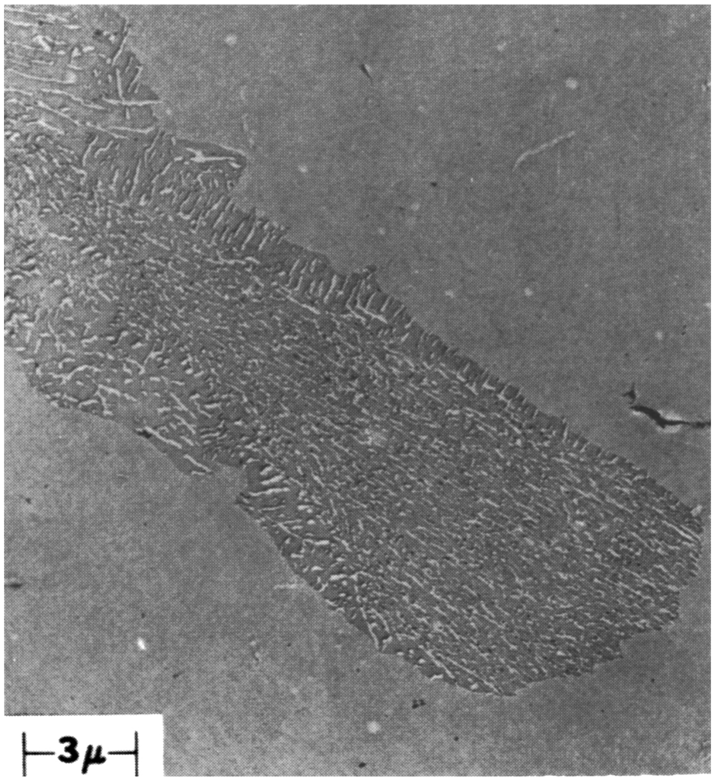

Fig. 11.3 Electron micrograph, obtained using a replica technique, showing a colony of 'Columnar Bainite' in an Fe–0.82C wt.% following isothermal transformation at 288 °C and at a pressure of 30 kbar (after Nilan, 1967).

probable that columnar bainite is more akin to pearlite than bainite, but further investigations are needed to make any sensible decisions about the mechanism of growth.

11.4 Pearlitic Bainite

In steels containing strong carbide-forming elements, it is possible to obtain pearlite, in which the carbide phase is an alloy carbide (such as M_7C_3) instead of cementite. The alloy pearlite can form at temperatures above B_S, or somewhat below that temperature but only after holding at the transformation temperature for very long time periods (usually many days). On the scale of light microscopy, the pearlite etches as dark nodules (Fig. 11.4), but the colonies tend to have crystallographic facets rather than the nicely rounded

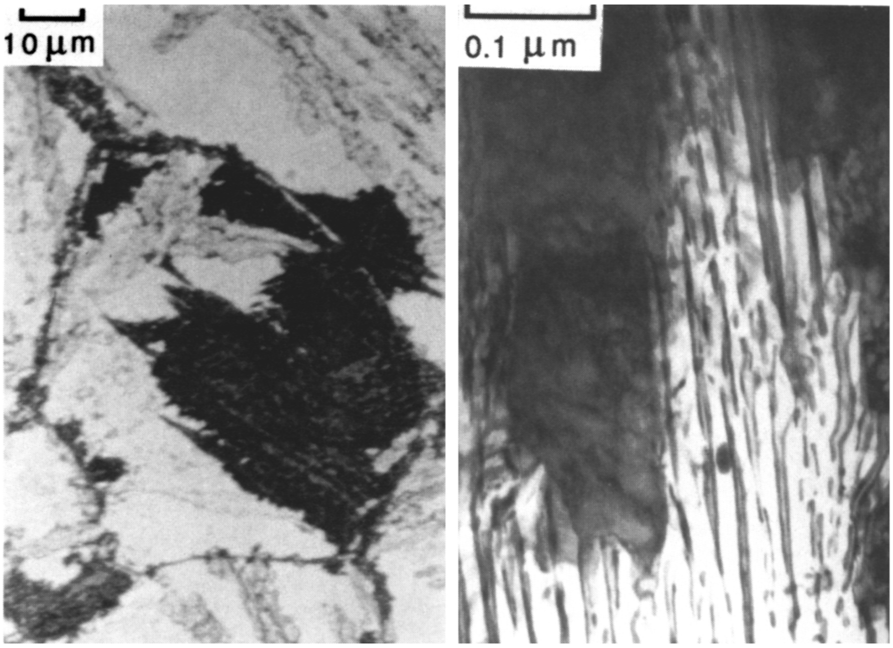

Fig. 11.4 Microstructure of the so-called 'pearlitic bainite', which is really just a pearlite with alloy carbide (in this case M_7C_3) instead of cementite: (a) light micrograph; (b) transmission electron micrograph.

colonies of normal pearlite. This is probably a reflection of the orientation dependence of the interfacial energy of the alloy carbide.

Because of this faceting, transmission electron microscopy observations can be misleading. The crystallographically faceted nodules of pearlite at a high resolution give the appearance of parallel ferrite plates with intervening carbides, a microstructure on that scale similar to upper bainite. The terminology 'pearlitic bainite' given to this transformation product is misleading. There is gross partitioning of substitutional solutes during the transformation, there is no surface relief effect, the carbide and ferrite phases grow cooperatively, and there is no reason to associate this microstructure with bainite.

11.5 Grain Boundary Lower Bainite

Bainite nucleation in most steels occurs heterogeneously at the austenite grain boundaries. The nucleation rate of lower bainite can be large at temperatures close to M_S; the austenite grain surfaces then become covered by lower bainite sub-units (Fig. 11.5). The rate at which carbon partitions from supersaturated

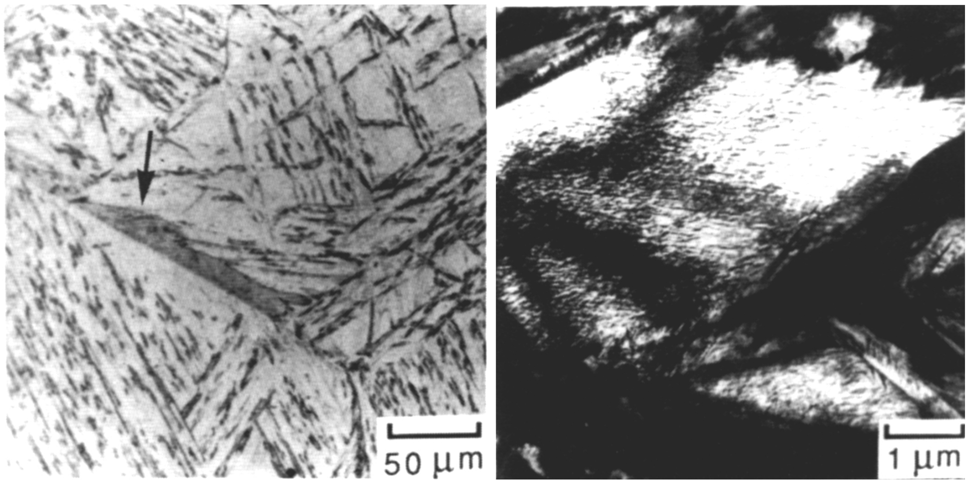

Fig. 11.5 The microstructure of grain boundary lower bainite: (a) light micrograph; (b) transmission electron micrograph.

ferrite is slow when transformation is at such low temperatures. Therefore, the sub-units are able to form in arrays without any intervening austenite (Bhadeshia and Edmonds, 1979a). These layers of sub-units have the overall form of allotriomorphs, but there is no doubt that they form individually.

The microstructure has caused some concern in the context of 300M, which is an ultrahigh-strength steel used in the quenched and tempered condition (Padmanabhan and Wood, 1984). The alloy has a very high hardenability – 10 cm diameter sections can be made martensitic by air cooling from the austenitisation temperature. However, optical microscopy revealed the surprising presence of allotriomorphs, which on detailed examination turned out to be the grain boundary lower bainite described above.

11.6 Summary

Granular bainite is basically ordinary bainite generated by continuous cooling transformation of low-carbon steels. The mechanism of inverse bainite is unclear, but it involves the formation of cementite as the primary phase. It is not clear whether the ferrite, when it eventually forms and engulfs the cementite, forms by a reconstructive or displacive mechanism.

Whilst there is some doubt about the mechanism of inverse bainite, the terms columnar and pearlitic bainite are undoubtedly misnomers and are best avoided. Columnar bainite is simply an aggregate of cementite and ferrite which grows by a reconstructive transformation mechanism. Pearlitic bainite is simply a crystallographically faceted alloy pearlite.

At high supersaturations, arrays of lower bainite sub-units can rapidly decorate the austenite grain surfaces, giving the appearance of allotriomorphs. This 'grain boundary lower bainite' is much harder than allotriomorphic ferrite, and hence is easily distinguished.

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