

1 Introduction

We begin with a historical survey of the exciting early days of metallurgical research during which bainite was discovered, covering the period up to about 1960, with occasional excursions into more modern literature. The early research was usually well conceived and was carried out with enthusiasm. Many of the original concepts survive to this day and others have been confirmed using the advanced experimental techniques now available. The thirty years or so prior to the discovery of bainite were in many respects formative as far as the whole subject of metallurgy is concerned. The details of that period are documented in the several textbooks and articles covering the history of metallurgy,[†] but a few facts deserve special mention, if only as an indication of the state-of-the-art for the period between 1920–1930.

The idea that martensite was an intermediate stage in the formation of pearlite was no longer accepted, although it continued to be taught until well after 1920. The β -iron controversy, in which the property changes caused by the paramagnetic to ferromagnetic transition in ferrite were attributed to the existence of another allotropic modification (β) of iron, was also in its dying days. The first evidence that a solid solution is an intimate mixture of solvent and solute atoms in a single phase was beginning to emerge (Bain, 1921) and it soon became clear that martensite consists of carbon dispersed atomically as an interstitial solid solution in a tetragonal ferrite crystal. Austenite was established to have a face-centred cubic crystal structure, which could sometimes be retained to ambient temperature by quenching. Bain had already proposed the homogeneous deformation which could relate the face-centred cubic and body-centred cubic or body-centred tetragonal lattices during martensitic transformation. It had been established using X-ray crystallography that the tempering of martensite led to the precipitation of cementite, or to alloy carbides if the tempering temperature was high enough. Although the surface relief associated with martensitic transformation had been observed, its impor-

[†]Notable historical works include: *The Sorby Centennial Symposium on the History of Metallurgy*, published by the A.I.M.E. in 1965 (includes an article by Bain himself), the commentary by H. W. Paxton, *Metallurgical Transactions* **1** (1970) 3479–3500, and by H. W. Paxton and J. B. Austin, *Metallurgical Transactions* **3** (1972) 1035–1042. Paxton's 1970 article is published along with a reproduction of the classic 1930 paper on the discovery of bainite by Davenport and Bain, and is based on first hand historical knowledge obtained directly from Davenport and Bain.

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tance to the mechanism of transformation was not fully appreciated. Widmanstätten ferrite had been identified and was believed to precipitate on the octahedral planes of the parent austenite; some notions of the orientation relationship between the ferrite and austenite were also being discussed.

It was an era of major discoveries and great enterprise in the metallurgy of steels. The time was therefore ripe for the discovery of bainite. The term 'discovery' implies something new. In fact, microstructures containing bainite must have been encountered prior to the now acknowledged discovery date, but the phase was never clearly identified because of the confused microstructures that followed from the continuous cooling heat treatment procedures common in those days. A number of coincidental circumstances inspired Bain and others to attempt isothermal transformation experiments. That austenite could be retained to ambient temperature was clear from studies of Hadfield's steel which had been used by Bain to show that austenite has a face-centred cubic structure. It was accepted that increasing the cooling rate could lead to a greater amount of austenite being retained. Indeed, it had been demonstrated using magnetic techniques that austenite in low-alloy steels could exist at low temperatures for minutes prior to completing transformation. The concept of isothermal transformation was already exploited in industry for the manufacture of patented steel wire, and Bain was aware of this through his contacts at the American Steel and Wire Company. He began to wonder 'whether exceedingly small heated specimens rendered wholly austenitic might successfully be brought unchanged to any intermediate temperature at which, then their transformation could be followed' and he 'enticed' E. C. Davenport to join him in putting this idea into action.

1.1 The Discovery of Bainite

During the late 1920s, in the course of these pioneering studies on the *isothermal* transformation of austenite at temperatures above that at which martensite first forms, but below that at which fine pearlite is found, Davenport and Bain (1930) discovered a new microstructure consisting of an 'acicular, dark etching aggregate' which was quite unlike the pearlite or martensite observed in the same steel (Fig. 1.1). They originally called this microstructure 'martensite-troostite' since they believed that it 'forms much in the manner of martensite but is subsequently more and less tempered and succeeds in precipitating carbon'.

The structure was found to etch more rapidly than martensite but less so than troostite (fine pearlite). The appearance of 'low-range' martensite-troostite (formed at temperatures just above the martensite-start temperature M_s) was found to be somewhat different from the 'high-range' martensite-troostite formed at higher temperatures. The microstructure exhibited unusual

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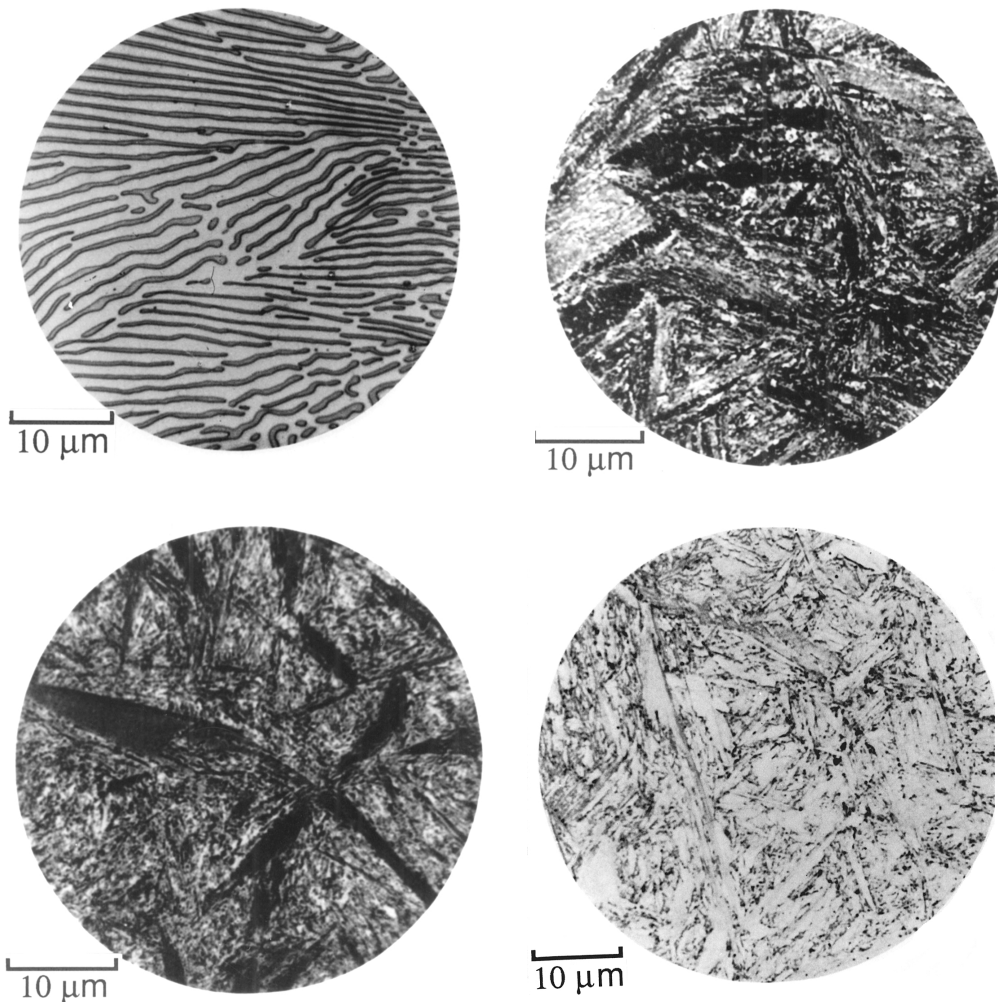


Fig. 1.1 Microstructures in a eutectoid steel: (a) Pearlite formed at 720°C; (b) bainite obtained by isothermal transformation at 290°C; (c) bainite obtained by isothermal transformation at 180°C; (d) martensite. The micrographs were taken by Vilella and were published in the book *The Alloying Elements in Steel* (Bain, 1939). Notice how the bainite etches much darker than martensite, because its microstructure contains many fine carbides.

and promising properties; it was found to be 'tougher for the same hardness than tempered martensite' (Bain, 1939), and was the cause of much excitement at the newly established United States Steel Corporation Laboratory in New Jersey. It is relevant to note here the contributions of Lewis (1929) and Robertson (1929), who were the first to publish the results of isothermal

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transformation experiments on eutectoid steel wires, probably because of their relevance to patented steel. But the Davenport and Bain experiments were unique in showing the progressive nature of the isothermal transformation of austenite, using both metallography and dilatometry. Their experiments were successful because they utilised very thin samples. Their method of representing the kinetic data in the form of time-temperature-transformation curves turned out to be so simple and elegant, that it would be inconceivable to find any contemporary materials scientist who has not been trained in the use or construction of 'TTT' diagrams.

In 1934, the research staff of the laboratory named the microstructure 'Bainite' in honour of their colleague E. C. Bain who had inspired the studies, and presented him with the first ever photomicrograph of bainite, taken at a magnification of $\times 1000$ (Smith, 1960; Bain, 1963).

The name 'bainite' did not immediately catch on. It was used rather modestly even by Bain and his co-workers. In a paper on the nomenclature of transformation products in steels, Vilella, Guellich and Bain (1936) mentioned an 'unnamed, dark etching, acicular aggregate somewhat similar to martensite' when referring to bainite. Hoyt, in his discussion to this paper appealed to the authors to name the structure, since it had first been produced and observed in their laboratory. Davenport (1939) ambiguously referred to the structure, sometimes calling it 'a rapid etching acicular structure', at other times calling it bainite. In 1940, Greninger and Troiano used the term 'Austempering Structures' instead of bainite. The 1942 edition of the book *The Structure of Steel* (and its reprinted version of 1947) by Gregory and Simmons contains no mention of bainite.

The high-range and low-range variants of bainite were later called 'upper bainite' and 'lower bainite' respectively (Mehl, 1939) and this terminology remains useful to this day. Smith and Mehl (1942) coined the term 'feathery bainite' for upper bainite which forms largely, if not exclusively, at the austenite grain boundaries in the form of bundles of plates, and only at high reaction temperatures, but this description has not found frequent use. Both upper and lower bainite were found to consist of aggregates of parallel plates, aggregates which were later designated sheaves of bainite (Aaronson and Wells, 1956).

1.2 The Early Research

Early work into the nature of bainite continued to emphasise its similarity with martensite. Bainite was believed to form with a supersaturation of carbon (Wever, 1932; Wever and Jellinghaus, 1932; Portevin and Jolivet, 1937, 1938; Portevin and Chevenard, 1937). It had been postulated that the transformation involves the abrupt formation of flat plates of supersaturated ferrite along

certain crystallographic planes of the austenite grain (Vilella *et al.*, 1936). The ferrite was then supposed to decarburise by rejecting carbon at a rate depending on temperature, leading to the formation of carbide particles which were quite unlike the lamellar cementite phase associated with pearlite. The transformation was believed to be in essence martensitic, 'even though the temperature be such as to limit the actual life of the quasi-martensite to millionths of a second'. Bain (1939) reiterated this view in his book *The Alloying Elements in Steel*. Isothermal transformation studies were by then becoming very popular and led to a steady accumulation of data on the bainite reaction, still variously referred to as the 'intermediate transformation', 'dark etching acicular constituent', 'acicular ferrite', etc.

In many respects, isothermal transformation experiments led to the clarification of microstructures, since individual phases could be studied in isolation. There was, however, room for difficulties even after the technique became well established. For alloys of appropriate composition, the upper ranges of bainite formation were found to overlap with those of pearlite, preceded in some cases by the growth of proeutectoid ferrite. The nomenclature thus became confused since the ferrite which formed first was variously described as massive ferrite, grain boundary ferrite, acicular ferrite, Widmanstätten ferrite, etc. On a later view, some of these microconstituents are formed by a 'displacive' or 'military' transfer of the iron and substitutional solute atoms from austenite to ferrite, and are thus similar to carbon-free bainitic ferrite, whereas others form by a 'reconstructive' or 'civilian' transformation which is a quite different kinetic process (Buerger, 1951; Christian, 1965a).

1.2.1 Crystallography

By measuring the crystallographic orientation of austenite using twin vestiges and light microscopy, Greninger and Troiano (1940) were able to show that the habit plane of martensite in steels is irrational. These results were consistent with earlier work on non-ferrous martensites and put paid to the contemporary view that martensite in steels forms on the octahedral planes of austenite. They also found that with one exception, the habit plane of bainite is irrational, and different from that of martensite in the same steel (Fig. 1.2). The habit plane indices varied with the transformation temperature and the average carbon concentration of the steel. The results implied a fundamental difference between bainite and martensite. Because the habit plane of bainite approached that of Widmanstätten ferrite at high temperatures, but the proeutectoid cementite habit at low temperatures, and because it always differed from that of martensite, Greninger and Troiano proposed that bainite from the very beginning grows as an aggregate of ferrite and cementite. A competition between the ferrite and cementite was supposed to cause the changes in the

Fe-0.92C-0.22Mn-0.03Si wt.%

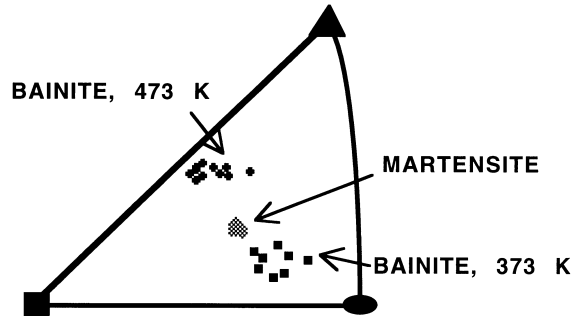


Fig. 1.2 An example of the results obtained by Greninger and Troiano (1940), showing the irrational habit of bainite, which changed as a function of the transformation temperature. Notice also that the habit plane of bainite is different from that of martensite in the same steel.

bainite habit, the ferrite controlling at high temperatures and the cementite at low temperatures. The competition between the ferrite and cementite was thus proposed to explain the observed variation of bainite habit plane. The crystallographic results were later confirmed using an indirect and less accurate method (Smith and Mehl, 1942). These authors also showed that the orientation relationship between bainitic ferrite and austenite does not change very rapidly with transformation temperature and carbon content and is within a few degrees of the orientations found for martensite and Widmanstätten ferrite, but differs considerably from that of pearlitic ferrite/austenite. Since the orientation relationship of bainite with austenite was not found to change, Smith and Mehl considered Greninger and Troianos' explanation for habit plane variation to be inadequate, implying that the habit plane cannot vary independently of the orientation relationship.

1.2.2 The Incomplete Reaction Phenomenon

It was known as long ago as 1939 that in certain alloy steels 'in which the pearlite change is very slow', the extent of transformation to bainite decreases, ultimately to zero, as the transformation temperature is increased (Allen *et al.*, 1939). For example, the bainite transformation in a Fe-2.98Cr-0.2Mn-0.38C wt% alloy was found to begin rapidly but cease shortly afterwards, with the maximum volume fraction of bainite obtained increasing with decreasing transformation temperature (Klier and Lyman, 1944). At no temperature investigated did the complete transformation of austenite occur solely by decomposition to

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bainite. The residual austenite remaining untransformed after the cessation of the bainite reaction, reacted by another mechanism (pearlite) only after a further long delay. Cottrell (1945) in his experiments on a low-alloy steel, found that the amount of bainite that formed at 525 °C ($\ll A_{e3}$) was negligible, and although the degree of transformation increased as the isothermal reaction temperature was decreased, the formation of bainite appeared to stop before reaching completion. Other experiments on chromium-containing steels revealed that the dilatometric expansion due to bainite became larger as the transformation temperature was reduced (Fig. 1.3, Lyman and Troiano, 1946). Oddly enough, the bainite transformation did not seem to reach completion on isothermal heat treatment, even though all of the austenite could readily transform to pearlite at a *higher* transformation temperature (Klier and Lyman, 1944). Often, the transformation of austenite at lower temperatures occurred in two stages, beginning with the bainite reaction which stopped prematurely, to be followed by the formation of pearlite at a slower rate. It is significant that the two reac-

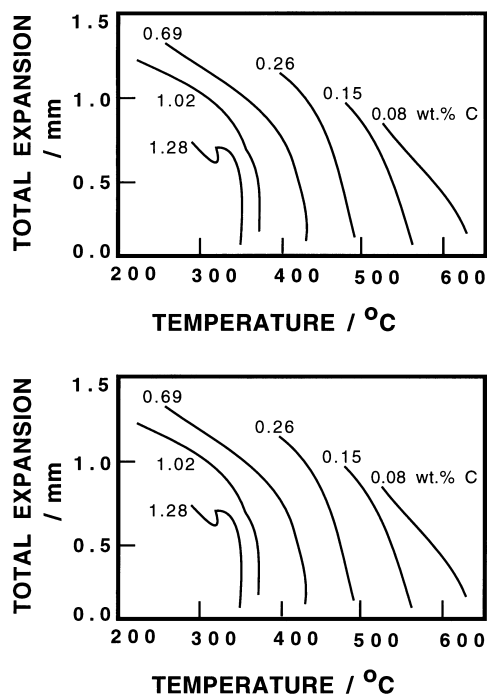


Fig. 1.3 Temperature dependence of the total dilatometric expansion due to the formation of bainite (Lyman and Troiano, 1946). Transformation to bainite does not begin until a critical temperature B_S , which is well below the equilibrium A_{e3} temperature. The amount of bainite that can form at any temperature increases with the undercooling below B_S .

tions may only be separated by a long delay in well-alloyed steels; in plain carbon steels 'the second reaction sets in within a few seconds after the beginning of the bainite reaction' (Klier and Lyman, 1944).

1.2.3 Carbon Redistribution

X-ray and other experiments indicated that the formation of bainite enriches the residual austenite in carbon. Klier and Lyman (1944) took this to mean that the austenite, prior to its transformation to bainite, becomes compositionally unstable and separates into carbon-rich and carbon-depleted volumes; in modern terminology, this would require uphill diffusion. The low carbon regions were then supposed to transform into supersaturated bainite of the same composition, by a 'martensite-like' lattice rearrangement, to be followed soon after by the precipitation of iron carbides. A similar suggestion had been made earlier by Kurdjumov (1933) in the context of Widmanstätten ferrite: 'regions of low carbon concentration in the γ crystal result from diffusion within the γ phase, and these regions can at this time transform into the α phase ...' Entin (1962) seemed to rediscover this idea, leading Aaronson (1966a) to prove using thermodynamics that an austenitic Fe-C solid solution cannot spontaneously undergo separation into carbon-rich and carbon-poor regions. There is no tendency for the austenitic solid solution to undergo spinodal decomposition. The concept nonetheless seems to crop up with notorious regularity even in modern literature (e.g. Prado, 1986; Prado *et al.*, 1990).

The proof by Aaronson *et al.* does not of course rule out random fluctuations of composition, of the type associated with any solid solution in dynamic equilibrium. It has therefore been argued that the nucleation of bainite is favoured in regions of austenite where the carbon concentration is relatively low as a consequence of fluctuations (Degang *et al.*, 1989). Indeed, carbon-free regions of several thousand iron atoms can exist at all temperatures in austenite of eutectoid composition (Russell, 1971). The difficulty arises when it is claimed that these carbon-depleted regions lead to an enhancement of the nucleation rate. For every such region there must also exist a carbon-enriched region where the probability of ferrite nucleation is presumably reduced, thereby balancing the effects of the depleted regions. Consequently, there is no advantage in adopting this microscopic approach. The usual macroscopic thermodynamic model in which the driving forces are calculated for uniform composition should suffice.

1.2.4 Thermodynamics

In a far-reaching paper, Zener (1946) attempted to give a rational thermodynamic description of the phase transformations that occur in steels. He

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assumed that bainite growth is diffusionless, any carbon supersaturation in bainitic ferrite being relieved subsequent to growth, by partitioning into the residual austenite. The atomic mechanism of bainite growth was not discussed in detail, but he believed that unlike martensite, there is no strain energy associated with the growth of bainite. Thus bainite should form at a temperature just below T_0 , where the austenite and ferrite of the same composition have identical free energies (Fig. 1.4).

However, T_0 is frequently used in martensite theory for the temperature at which austenite and martensite (i.e. supersaturated tetragonal 'ferrite') have the same free energy; for clarity, we follow Christian and Edmonds (1984) and call this temperature T_{om} . The Bain strain applied to a random interstitial solution of carbon in austenite automatically produces the ordered tetragonal form of ferrite if the carbon atoms are trapped in their original sites, but Zener

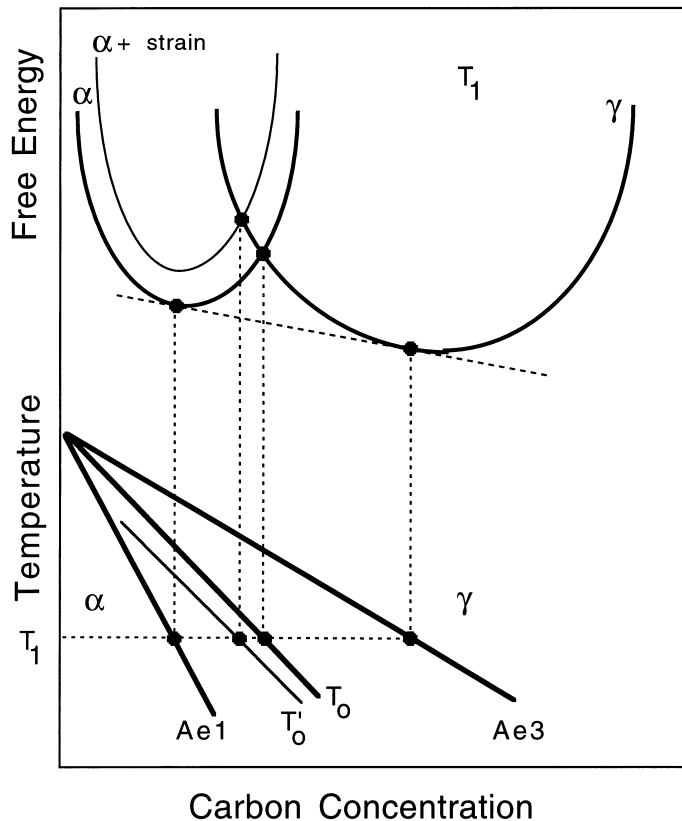


Fig. 1.4 Schematic illustration of the origin of the T_0 curve on the phase diagram. The T'_0 curve incorporates a strain energy term for the ferrite, illustrated on the diagram by raising the free energy curve for ferrite by an appropriate quantity.

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also supposed that the tetragonal form may be regarded as a result of an ordering of the interstitial atoms into one set of sites of the cubic structure. He derived an equation for the critical temperature T_c at which the cubic and tetragonal forms of ferrite have the same free energy. T_c rises with interstitial solute content, and thus intersects the M_S temperature and also has a joint intersection with the T_0 and T_{om} temperatures. Clearly T_{om} lies below T_0 at low carbon contents and above T_0 at high carbon contents. According to one interpretation (Owen, Wilson and Bell, 1964), martensite formed above room temperature is cubic at carbon contents below the intersection of M_S and T_c (above 2.5 at% carbon in plain iron-carbon alloys) and tetragonal above it. As Zener pointed out, martensite cannot form until the driving force obtained by supercooling below the T_0 or T_{om} temperature is large enough to provide the necessary strain energy.

It is usually assumed that bainite forming first as fully supersaturated ferrite nevertheless has a cubic structure, but it would seem more logical to assume a tetragonal structure unless the temperature of formation is above T_c .

The Zener model failed to provide an explanation of why the strain energy should exist for martensite and not for bainite. On the other hand, it explained the data showing that the degree of transformation to bainite increases with supercooling from zero at an upper limit, which is generally known as the bainite-start or B_S temperature. The carbon that partitions into the austenite *after* the formation of bainite changes its composition, until it eventually becomes thermodynamically impossible for the austenite to transform and the reaction stops. For a given alloy, a larger undercooling below T_0 would allow more bainite to form before diffusionless growth becomes impossible. Consistent with experimental data, the model also requires the bainite C curve of the TTT diagram to tend asymptotically to infinite time (Fig. 1.5) at a temperature corresponding to the T_0 or T_{om} temperature whichever is higher, since the transformation of austenite without a composition change cannot occur above this limit.

The initial plates of bainite, unlike those of many martensites, often grow to a limited size less than that of the parent austenite grain. Zener suggested that a layer of cementite around the plate stifles its subsequent growth.

1.2.5 Paraequilibrium

By 1947, it was evident that the cementite associated with bainite is different from that found in pearlite. The latter was always found to have a different substitutional solute concentration when compared with the average value, whereas the cementite in bainite had about the same substitutional content as the matrix from which it grew. Hultgren (1947), has cited several references

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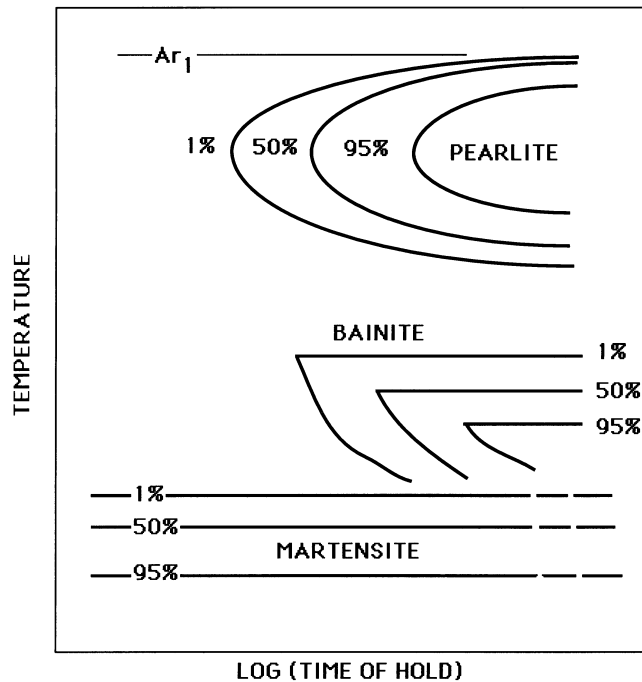


Fig. 1.5 Schematic TTT diagram illustrating the flat tops on the bainite C-curves (after Zener, 1946).

which report magnetic, chemical and X-ray data on extracted carbides which confirm this difference between the two kinds of cementite.

Hultgren was at the time proposing a model for the role of substitutional alloying elements in steels; at high temperatures where diffusion rates are reasonable, these elements can redistribute during transformation in a way consistent with equilibrium. The transformation was then said to occur under 'ortho-equilibrium' conditions. This contrasts with 'para-equilibrium' in which the substitutional alloying elements are unable to partition, although carbon, which is a fast diffusing interstitial element, redistributes between the phases until its chemical potential is uniform throughout.

The mechanism of pearlite growth was not clear in those days, but the transformation was believed to be initiated by the nucleation of cementite. This led to the contrasting suggestion that bainite is initiated by the nucleation of ferrite (Mehl, 1939; Smith and Mehl, 1942; Mehl, 1948). Hultgren put these ideas together and proposed that upper bainite begins with the nucleation and growth of ferrite with a para-equilibrium carbon concentration, causing the residual austenite to become enriched in carbon. This bainitic ferrite, unlike the ferrite associated with pearlite, was believed to have a rational Kurdjumov-

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Sachs or Nishiyama–Wasserman orientation relationship with the parent austenite in which it grows. This was considered to explain the observed difference in ferrite morphologies in bainite and pearlite. Bainitic ferrite was always found to consist of individual plates or sheaves whereas the ferrite in pearlite apparently formed alternating plates of a regularly spaced two-phase lamellar aggregate. The enrichment of austenite with carbon should eventually cause the paraequilibrium precipitation of cementite from austenite in a region adjacent to the bainitic ferrite. At the time, pearlitic cementite was thought to bear a rational orientation relation to the austenite grain into which the pearlite colony grows, and Hultgren proposed, without any evidence, that bainitic cementite should be randomly orientated to the austenite in which it precipitated. This process of ferrite and subsequent cementite precipitation then repeated, giving rise to the sheaf of bainite. Hultgren therefore considered upper bainite to be similar to pearlite but growing under paraequilibrium conditions and different in the orientation relations with austenite.

No explanation was offered for the occurrence of paraequilibrium with bainite, nor for the existence of the various orientation relationships. He admitted the possibility that bainite formed at lower temperatures (later known as *lower* bainite) ‘forms directly’, implying that the bainitic ferrite formed with a supersaturation of carbon, although the mechanism was not discussed.

The model of pearlite formation involving the repeated formation of ferrite and cementite was abandoned when Hillert (1962) demonstrated that a pearlite colony really consists of two interwoven crystals, one of ferrite and the other of cementite. Hillert (1957, 1962) also pointed out an important distinction between pearlite and upper bainite; in the former case, the ferrite and cementite phases grow cooperatively, whereas in the latter case, the plates of bainitic ferrite form first with the precipitation of cementite being a subsequent reaction.

1.2.6 Kinetics

Experiments by Wiester (1932), Hannemann *et al.* (1932–1933) and Forster and Scheil (1936, 1937) indicated that martensite can grow very rapidly in steels, a plate taking a few microseconds to grow right across an austenite grain. Bunshah and Mehl (1953) later measured the growth rate to be as high as 1 km s^{-1} , i.e. about one-third of the velocity of sound in iron. This gave rise to the incorrect impression that martensitic transformation does not involve a ‘nucleation and growth process’. Thus, Smith and Mehl (1942), wondered whether bainitic structures form by a process of nucleation and growth or whether the plates spring full-formed from the matrix lattice ‘as they do in the transformation to martensite’. A nucleation and growth model was

favoured since the sizes of the reacted regions apparently increased with time at the reaction temperature. This was consistent with the work of Wever and his co-workers (1932), who found that in the bainite transformation range, the austenite decomposes relatively slowly. Furthermore, the progress of the bainite transformation could be represented by means of a C-curve on a TTT diagram (Davenport and Bain, 1930), with a well defined incubation period before the beginning of isothermal transformation. Martensitic transformation, on the other hand could not be suppressed by the fastest available quench rates (Troiano and Greninger, 1946); it seemed to form athermally and was represented on the TTT diagram by a family of lines parallel to the time axis (Cohen, 1946). The bainite reaction was found to follow C-curve kinetics even below the M_S temperature (Howard and Cohen, 1948).

It is in this context that Ko and Cottrell (1952) attempted to investigate whether bainite is 'a nucleation and growth reaction, or like martensite, forms in a fraction of a second'. They also wanted to establish whether the transformation leads to surface relief effects similar to those associated with martensitic transformations. Ko and Cottrell were able to demonstrate, through hot-stage light microscopy, that bainite grows relatively slowly and that its formation causes the shape of the transformed region to change, the shape change being characterised qualitatively as an invariant-plane strain (Fig. 1.6). They also noted that unlike pearlite which is not hindered by austenite grain boundaries (Mehl, 1948), bainite growth terminated at austenite twin or grain boundaries. The transformation was therefore similar to martensite, and Ko and Cottrell attempted to identify any clear differences that may exist between martensite and bainite.

It was known already that martensite first forms at a large undercooling below the T_0 temperature, at which ferrite and austenite of identical composition have equal free energy (Zener, 1946; Cohen *et al.*, 1950). Since diffusionless transformation is *thermodynamically* feasible below T_0 , the extra undercooling was believed necessary to account for the strain and to a lesser extent, the interface energy associated with the formation of the martensite plate. Bainite, which forms at higher temperatures, must have a different mechanism consistent with the smaller driving force available at elevated temperatures. Ko and Cottrell argued that a 'coherent nucleus' can develop either into martensite or into bainite depending on the driving force available for transformation, the nucleus developing into martensite below M_S . At the higher temperatures where bainite occurs, 'coherent growth' can only 'take place when the strain due to the density change is relieved'. This could happen if the amount of carbon dissolved in bainite is reduced, either by diffusion from bainite or by precipitation within bainite, or by a combination of these processes, depending on the transformation temperature. It is not clear from their description whether they envisaged initially diffusionless growth, followed by carbon dif-

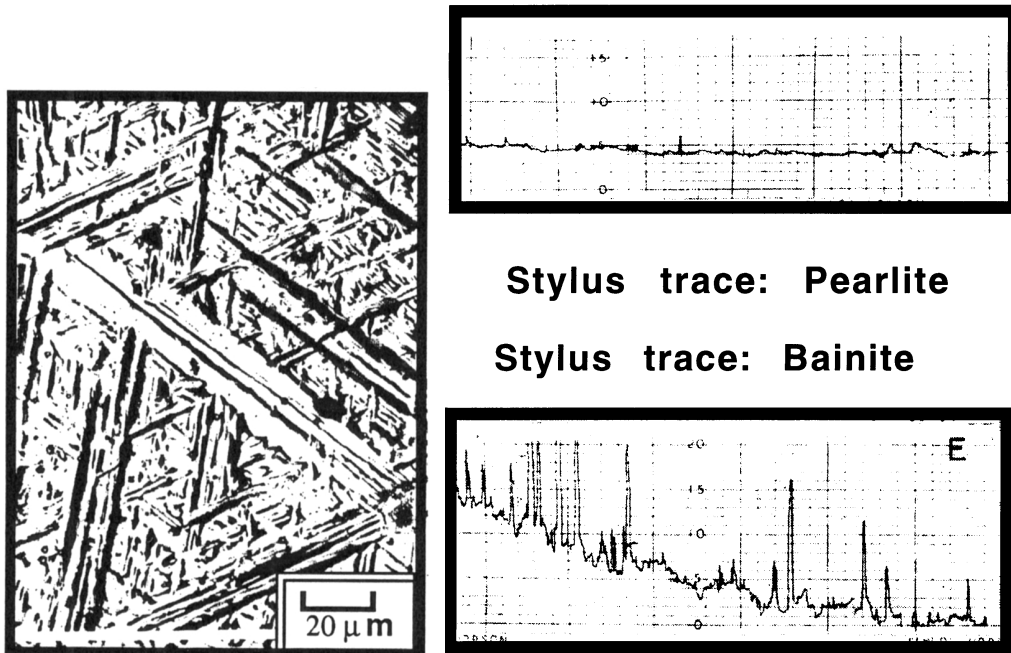


Fig. 1.6 Surface effects observed during the transformation of pre-polished samples of austenite (Ko and Cottrell, 1952): (a) Surface relief due to the formation of bainite; (b) Line traces obtained by traversing a stylus across the surface of a pearlitic and a bainitic sample. Notice the severe upheavals caused by bainite, which contrast with the negligible relief due to pearlite.

fusion to provide the driving force for further growth, or whether the diffusion and interface migration are coupled so that precipitation within the ferrite (for lower bainite) or carbon rejection to the austenite (for upper bainite) takes place at the moving interface. The former mechanism is illogical since the extra driving force is only available after a stage of initial growth to martensite which should not be possible (according to their growth condition) above M_S . Provided there is some way of circumventing the difficulty of forming the initial coherent nucleus (of whatever composition), the second type of growth model would allow bainite to form above M_S , and indeed above T_0 . In some later work, Ko (1953) distinguished between incoherent ferrite and 'acicular ferrite' which he proposed should be regarded as carbon-free bainitic ferrite.

Kriesement and Wever (1956) pointed out that the appearance of bainite changes continuously between upper and lower bainite, and postulated that the microstructure evolves by the repeated and alternating nucleation and growth of lamellae of cementite and ferrite, from austenite. Unlike pearlite,

the growth direction of the macroscopic plate of bainite was supposed to be normal to the plane of the lamellae. Although this particular mechanism has since been shown to be incorrect, they identified clearly the condition necessary for cementite precipitation to occur from residual austenite during the bainite transformation. Cementite precipitates from austenite if the carbon concentration of the latter exceeds that given by the extrapolated $\gamma/\gamma + \theta$ phase boundary.

Although many of the characteristics of bainite, especially the morphology and the shape deformation, had been found to be similar to those of martensite, a different microstructural approach was developed by Aaronson (1962). He used the Dubé morphological classification (Dubé *et al.*, 1958; Heckel and Paxton, 1961) for all non-pearlitic forms of ferrite and attributed the morphological variations to the dependence on the growth kinetics of an interface and to the nature of the site from which a precipitate crystal develops. In particular, plate morphologies were regarded as the result of the formation of immobile, partly coherent, planar interfaces which can grow normal to themselves only by the lateral migration of 'ledges'. In a later discussion of bainite, Aaronson (1969) developed the 'microstructural' definition in which bainite is regarded simply as a non-lamellar two-phase aggregate of ferrite and carbides in which the phases form consecutively, as distinct from pearlite where they form cooperatively. Aaronson stated that according to this definition, the upper limiting temperature of bainite formation should be that of the eutectoid reaction (Ae_1), and he denied that the kinetic B_S temperature has any fundamental significance. In those alloy systems where there seems clear evidence for a separate C-curve for bainite, the bainitic 'bay' and the apparent upper limit of bainite formation (B_S) were attributed to a special effect of certain alloying elements on the growth kinetics. Aaronson equally dismissed the observation of surface relief as a basis for classifying the various forms of ferrite.

1.3 Bainitic Steels: Industrial Practice

In spite of the early optimism about the potential of bainitic steels, commercial exploitation took many years to become established. The steels were not better than quenched and tempered martensitic steels, partly because of the coarse cementite particles associated with bainite and because the continuous cooling heat treatments which were popular in industry, could not in practice produce fully bainitic steels. The use of lean alloys gave mixed microstructures whereas intense alloying led to intolerable quantities of martensite. It was not until low-alloy, low-carbon steels containing boron and molybdenum were introduced by Irvine and Pickering (1958) that fully bainitic steels could be produced in commercial quantities using continuous cooling heat treatments. Nonetheless, martensitic steels dominated the high-strength steel market, with their better

overall mechanical properties and well understood physical metallurgy principles.

Even lower carbon concentrations than conceived by Irvine and Pickering could have led to better bainitic steels, with strength and toughness due to the submicron size grain structure of bainite. However, technology was not in those days sufficiently advanced to cope with the necessarily higher cooling rates required to produce bainite in very low-carbon steels, as the steel left the hot-rolling mill. The first system designed to accelerate cooling of hot sheet steel as it leaves the mill, was at the United Steel Company (UK), probably as a means to reduce the length of the run-out table which allows the strip to cool to a specified temperature before coiling. The faster cooling was achieved using a laminar water jet system (Adcock, 1962). The first papers discussing the metallurgical benefits of accelerated cooling were presented in 1965 (Morgan *et al.*). The technology of accelerated cooling designed to produce partially or wholly bainitic microstructures in very low-carbon, microalloyed steels has been perfected within the last fifteen years or so, with the new class of steels being the cause of much excitement (DeArdo, 1988).

An area of major success for bainite was in sector of creep resistant steels, where the so-called $2\frac{1}{4}\text{Cr}-1\text{Mo}$ steel was known to be one of the best alloys for creep strength and microstructural stability in large components (Miller *et al.*, 1940). The microstructural aspects of the steel may not have been appreciated in those days, but on continuous cooling it transforms into carbide-free upper bainite. In most applications, the microstructure is then heavily tempered at 700°C for several hours in order to relieve any residual stress. The tempering treatment and service at elevated temperatures causes the precipitation of a series of metastable alloy carbides, which together with solid solution strengthening by molybdenum, greatly enhance the creep strength. This particular alloy even now sustains the energy generation industry (Lundin *et al.*, 1982).

1.4 Summary of the Early Research

By the beginning of the sixties, bainite was regarded as a transformation product differing significantly from various forms of proeutectoid ferrite as well as from pearlite and martensite. The results of the early research can be summarised as follows (Fig. 1.7).

Bainite can be obtained by isothermal transformation at all temperatures where the formation of pearlite and proeutectoid ferrite is sluggish, and also at temperatures below the martensite-start temperature. Upper bainite, which forms at high temperatures, was found to consist of sheaves of ferrite plates with cementite particles located between the plates. By contrast, lower bainite was characterised by fine cementite particles within the bainitic ferrite plates in addition to those between the plates.

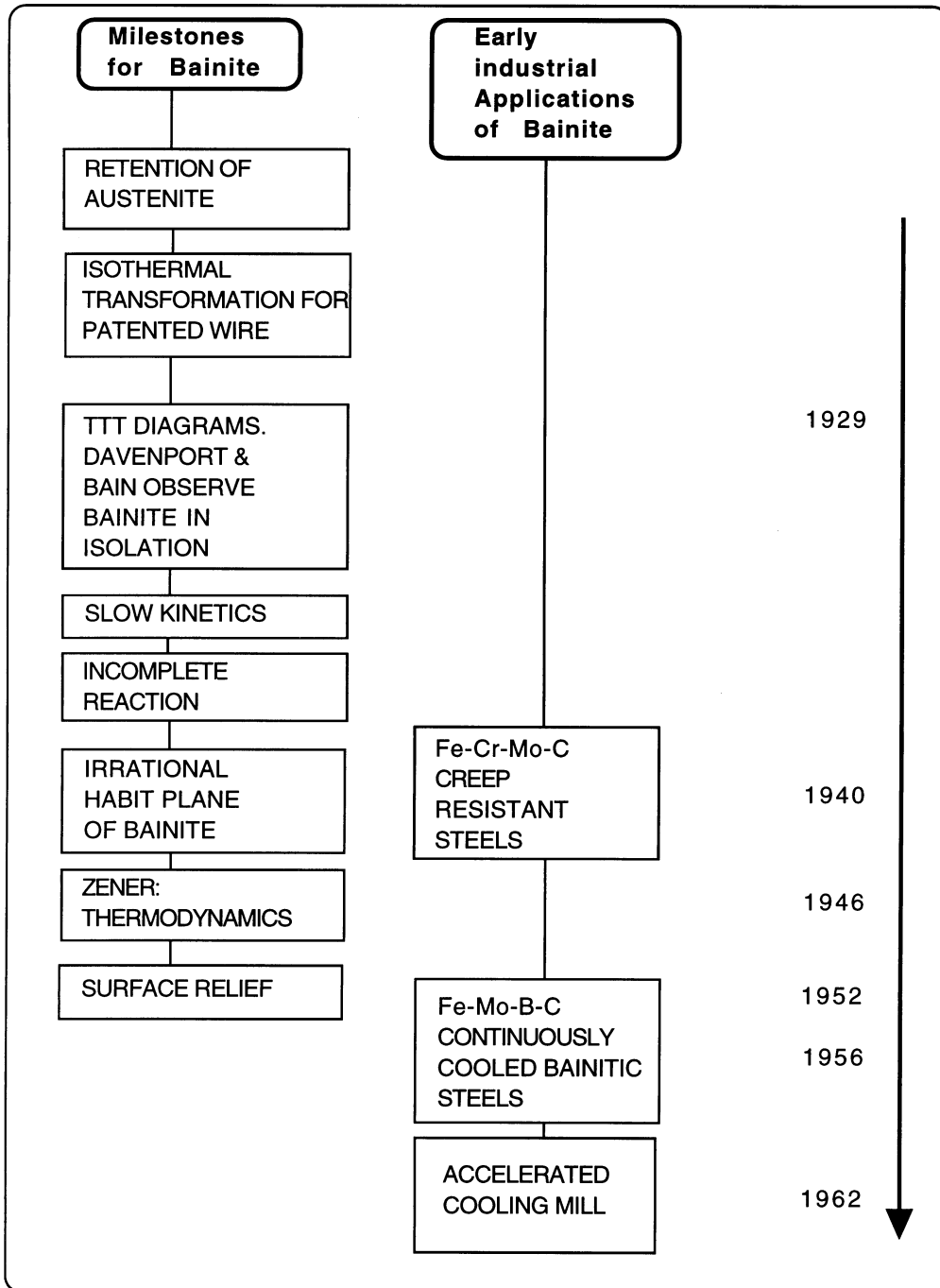


Fig. 1.7 Flow chart illustrating some of the important milestones in the history of bainite

Introduction

Observations using light microscopy indicated that bainite sheaves lengthen at a rate much slower than martensite plates. Bainite sheaves were found to have irrational habit planes, the indices of which differed from those of martensite in the same alloy. The orientation relationship between bainitic ferrite and austenite was on the other hand similar to that between martensite and austenite. Bainite plates were never found to cross austenite grain boundaries and the formation of bainite was, like martensite, observed to cause the shape of the parent crystal to change. This shape deformation is in present day terminology better described as an invariant-plane strain.

In steels where transformation to bainite could be carried out without interference from other reactions, experiments demonstrated that the degree of transformation to bainite decreases (ultimately to zero) and that the time taken to initiate the reaction increases rapidly with increasing isothermal transformation temperature. This led to the definition of a bainite-start temperature (B_s) above which there is no reaction. This temperature was always found to lie well within the (metastable) $\alpha + \gamma$ phase field. Other reactions could follow bainite, but in all cases, the rapid growth of bainite stopped prematurely before the austenite was fully transformed.

The prevailing, albeit rather ill-defined concept of the bainitic reaction as involving a martensitic type interface combined with carbon diffusion-controlled growth had already led to the suggestion of bainitic reactions in non-ferrous alloys. In particular, the observation of surface relief effects apparently combined with compositional changes in the decomposition of some β -phase copper-zinc alloys had been used in a pioneering paper by Garwood (1954-5) to identify this decomposition as bainitic, and the difficulties in accounting for such a reaction in purely substitutional alloys had been emphasised (Christian, 1962). This remains an interesting aspect of transformation theory (Christian, 1997).

The early emphasis on the similarities between bainitic and martensitic transformations still dominated the literature in the 1960s. The contrasting views of Aaronson and co-workers were only beginning to emerge. This led to controversy but also stimulated research. There is now a clear picture of the mechanism of transformation, the quantitative aspects of which have contributed significantly to the design of some remarkable steels.