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Coalesced Bainite

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Abstract. There is increasing evidence of a tendency to form unusually coarse plates of bainite at large driving forces and relatively low transformation temperatures. It seems that separately nucleated platelets which are in the same crystallographic orientation coalesce during prolonged growth. This leads to a markedly bimodal distribution of plate thicknesses, with the fine plates about $0.2\,\mu$m thick and the larger plates many micrometers thick. The latter are detrimental to the toughness of strong steels.

1. Introduction and Observations

There have been reports since 1979 of bainitic microstructures containing a pronounced bimodal size–distribution of plates [1, 2, 3, 4, 5, 6]. A few coarse plates can be observed on an optical scale, whereas the remaining microstructure consists of much finer plates which can only be resolved using transmission and high–resolution scanning electron microscopy. Some of the observations are based on wrought steels whereas others are from weld metals – we begin with the former.

Fig. 1a is an optical micrograph showing a layer of grey phase decorating the austenite grain boundary, together with the fine sheaves of bainite, in a sample of steel which was partially transformed into bainite during isothermal heat treatment. Transmission electron microscopy has shown the grey layer to consist of fine platelets of bainite which have formed adjacent to each other by nucleation at the austenite grain surface. Because they are all identically–oriented, they coalesce into a single unit [2]. The formation of this grain boundary bainite only happens at large driving forces and at relatively low transformation temperatures. This is because the partitioning of carbon from the supersaturated ferrite to austenite is then relatively slow, permitting the platelets to form without any intervening austenite [2]. These coarse layers have the overall form of allotriomorphs, but there is no doubt that they form by the combination of individual platelets [2, 7]. Fig. 1b shows vividly a higher resolution image with a bimodal size–distribution of bainite in another alloy to be described later.

The microstructure has caused some concern in the context of 300M, which is an ultrahigh–strength steel used in the quenched and tempered martensitic condition [3], Table 1. The alloy has a high hardenability – 10 cm diameter sections can be made martensitic by air cooling from

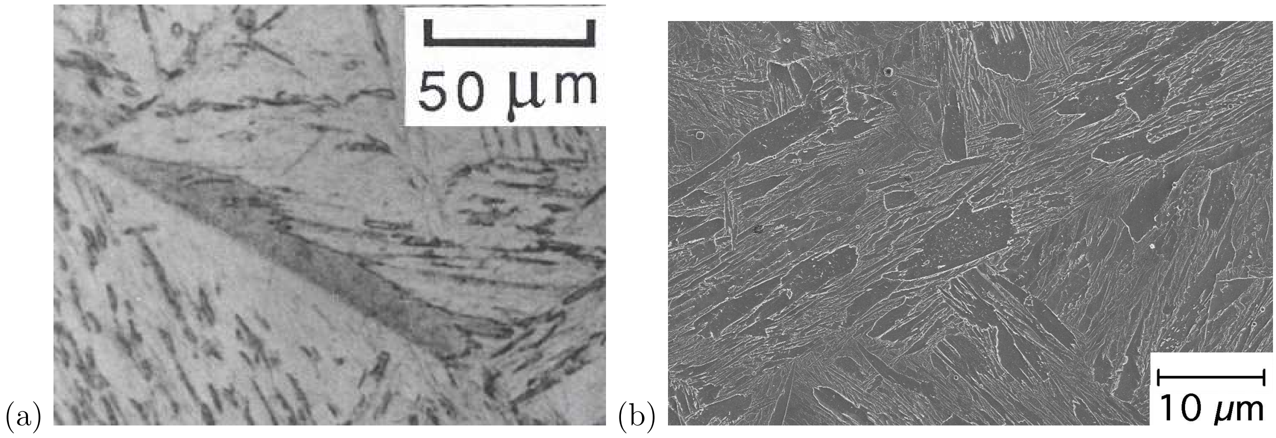

Fig. 1: (a) Optical micrograph showing coarse bainite at the austenite grain boundary in a wrought alloy sample partially transformed to bainite [1]. (b) FEG–SEM image showing bimodal distribution of plate sizes in a weld metal [5, 8, 9, 10].

the austenitisation temperature. However, optical microscopy revealed the surprising presence of allotriomorphs, which on detailed examination turned out to be the grain boundary bainite described above.

A later investigation [4] revealed a similar phenomenon in a wide variety of steels with compositions listed in Table 1, with clear evidence that the coarse plates formed by the coalescence of finer platelets. Fig. 2 shows a sheaf of bainite initiating as many identically oriented platelets at an austenite grain boundary, with each platelet separated by a retained austenite film. The platelets later merge into a single coarse crystal, ending at the point marked ‘A’. The films of austenite disappear along the length of the sheaf, resulting in a homogeneous plate. This is what is meant by *coalesced bainite.*

The question then arises as to what happens to the excess carbon in the bainitic ferrite given that the austenite which originally separated the sub–units is eliminated in the coalescence process. The excess carbon can either precipitate within the ferrite as cementite – as has been reported for the coarse plates in both steels [2, 3] and weld metals [5]. The extent of precipitation naturally depends on the carbon concentration of the steel [10]. The excess carbon can also partition into the residual austenite, but because of the thickness of the coarse bainite, only the regions close to the α/γ interface are able to contribute to the partitioning. The central regions of the coarse plate can relieve their excess carbon by the precipitation of cementite, leaving a precipitate–free zone at the peripheries of the plate. This is precisely what is seen in high–resolution micrographs of coalesced bainite in weld metals [5], Fig. 3.

Notice also that in Fig 2, the film of austenite around the coalesced part of the plate is much thicker than those separating the individual sub–units at the end opposite to ‘A’. This is because a thicker plate is a larger source of carbon available to partition into the adjacent austenite [11].

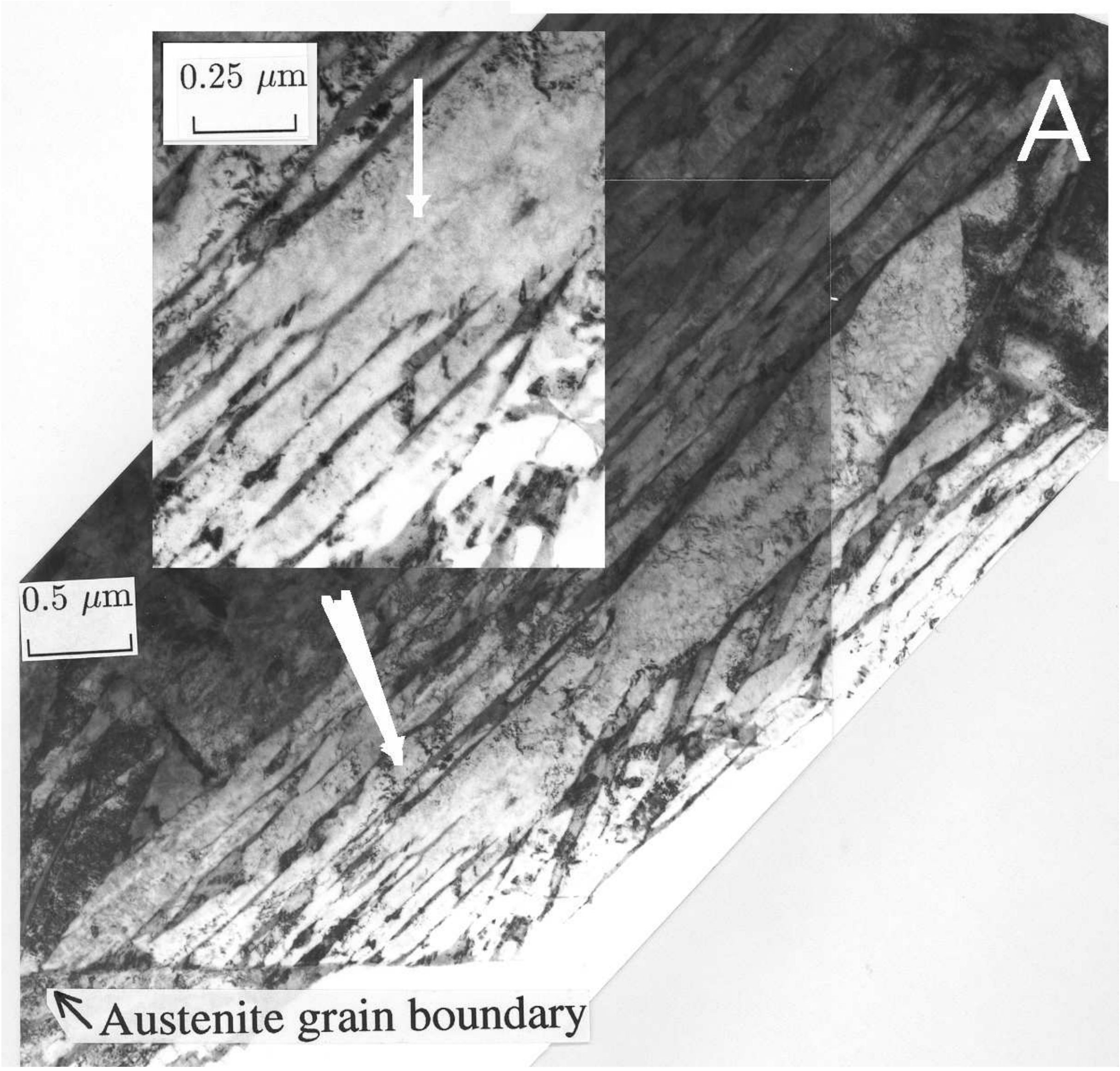

Fig. 2: Formation of coalesced bainite, beginning at the austenite grain boundary. The inset shows at a higher magnification, the disappearance of the austenite film as coalescence proceeds as the plates grow, until at the tip marked 'A', the plate is a single, thick unit. Transmission electron micrographs. [4].

2. Mechanism

Coalesced bainite evidently occurs when adjacent small platelets of bainite ("sub–units") merge to form a single, larger plate. Two conditions have been proposed to be necessary for its occurrence [4]:

(i) Since adjacent sub–units of bainite have an identical crystallographic orientation, they can in principle merge seamlessly. However, a thicker plate is associated with a greater strain energy due to the shape deformation accompanying the formation of bainite. There must

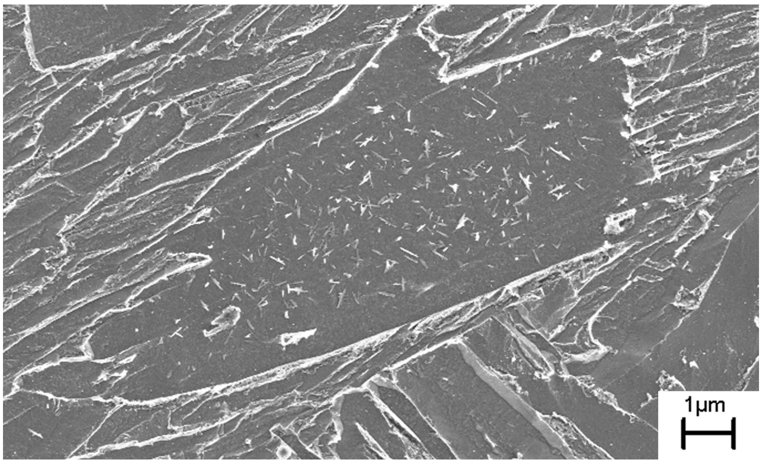

Fig. 3: Precipitate–free zone in a coarse plate of coalesced bainite in steel weld metal [5, 8].

therefore be an adequate driving force (chemical free energy change) to sustain the greater strain energy associated with the coarser plate. This is consistent with the observation that the coarse plates form at large driving forces. An analysis using a theory for elastically accommodated plates [12] has shown reasonable consistency between the driving force and expected strain energy [4].

(ii) As seen in Fig. 2, the coalescence process requires a certain length to establish. This is because the adjacent platelets are at first separately nucleated at the austenite grain boundaries. The nucleation process is not co-ordinated between the different platelets so there is an opportunity to reject excess carbon to form the intervening films of austenite. However, the platelets then can grow at a faster rate [13] and advance into fresh austenite, leading to coalescence before the carbon has an opportunity to partition. A requirement for coalescence is therefore that the lengthening of sub–units must be allowed to proceed without hindrance. This implies that coalescence is only possible at the early stages in the transformation of austenite, when growth cannot be hindered by impingement with other regions of bainite. A large austenite grain size must assist the process of coalescence.

Note that it may not be essential for the development of coalesced bainite to begin at an austenite grain surface. All that is required is for identically oriented platelets to develop in close proximity at about the same time.

It is likely that the mobility of carbon plays a role in making coalescence feasible. A retardation of the partitioning of carbon into the residual austenite should make it easier for plates to coalesce. This may partly explain why coalesced bainite tends to occur at low transformation temperatures; all observations to date have been for temperatures less than approximately 400°C.

There is a further observation applicable to continuous cooling transformations, in which reactions preceding bainite are suppressed by alloying. A greater quantity of coalesced bainite is then obtained at a slow cooling rate whereas rapid cooling gives more martensite.

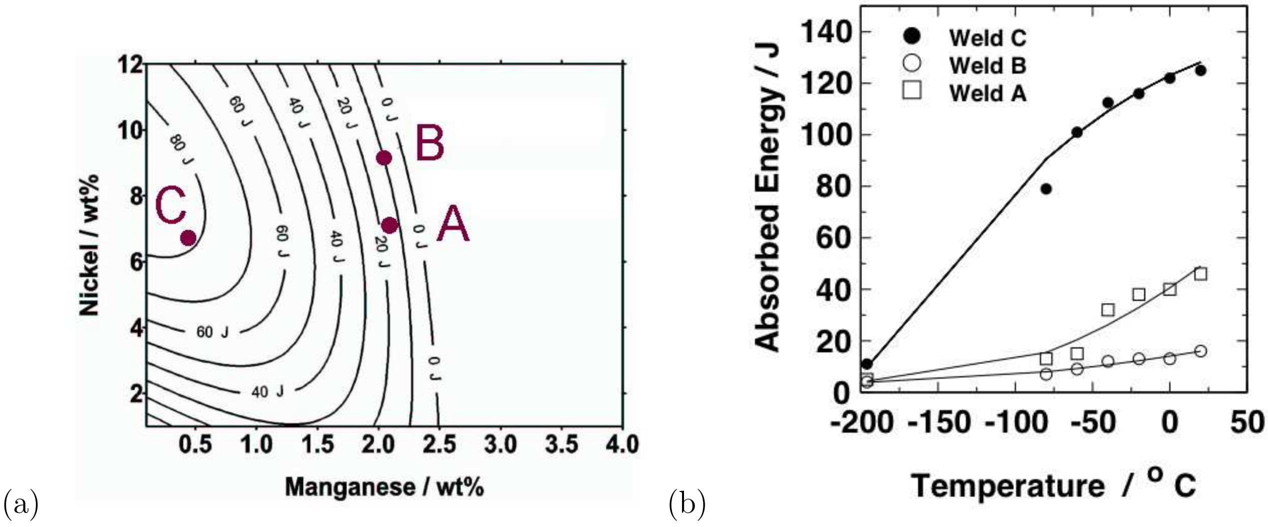

Fig. 4: (a) Contours showing the combined effect of manganese and nickel on the calculated toughness for -60°C, of weld metal produced using arc welding with a heat input of 1 kJ mm^{-1}, with a base composition (wt%) 0.034 C, 0.25 Si, 0.008 S, 0.01 P, 0.5 Cr, 0.62 Mo, 0.011 V, 0.04 Cu, 0.038 O, 0.008 Ti, 0.025 N, and an interpass temperature of 250°C. (b) Full results for welds A, B, and C.

3. Coalesced Bainite in Weld Metals

Experiments have now confirmed that the coarse, coalesced bainite appears in weld metals alloyed such that the bainite forms at temperatures close to the martensite–start temperature [6, 8, 9, 10]. It leads to a dramatic deterioration in toughness, which can be avoided by careful modifications of composition, for example, by reducing the manganese concentration when both nickel and manganese concentrations are high.

The onset of coalescence has been able to provide a physical explanation of the dependence of the toughness of weld metals on the nickel and manganese concentrations.

Murugananth and co–workers [14, 15] compiled a neural network model which revealed that in strong welds, a large concentration of nickel reduces the toughness when the manganese concentration is also large. In contrast, there is a remarkable improvement in the Charpy properties when nickel is increased whilst keeping the managanese content small. This is illustrated in Fig. 4, where the contour plot shows the impact energy at $-60\,^{\circ}$C for welds A (7Ni–2Mn), B (9Ni 2Mn) and C (7Ni-0.5Mn); the details are described elsewhere [14, 15, 16]. Experiments confirmed these empirical predictions but the mechanism of the interaction between Mn and Ni came later through the efforts of Keehan and coworkers. The welds with the relatively poor toughness always contained the coarse coalesced bainite, whereas the low–Mn high–Ni welds with much better toughness did not.

Table 1: Chemical compositions in wt%, of steels and weld metals in which coalesced bainite has been observed.

C	Si	Mn	Ni	Cr	Mo	V	Reference
0.43	2.02	3.0					[1, 2]
0.42	1.64	0.79	1.84	0.79	0.36	0.08	[3]
0.095	1.63	1.99		1.97			[4]
0.1	1.77	2.12	2.0				[4]
0.27	1.98	2.18		1.9			[4]
0.27	2.01	2.16	2.07				[4]
0.26	1.85	2.10					[4]
0.26	1.93	2.04		1.02			[4]
0.46	2.10	2.15					[4]
0.44	2.13	2.14		0.5			[4]
0.032	0.25	2.02	7.23	0.47	0.63		[8]
0.031	0.27	2.11	9.23	0.48	0.64		[8]
0.08	0.23	0.56	10.51	1.13	0.29		[6]
0.061	0.22	1.21	8.6	0.46	0.41		[6]
0.030	0.4	0.61	6.11	0.16	0.38	0.018	[10]
0.061	0.34	0.56	6.84	0.15	0.35	0.014	[10]
0.011	0.38	0.53	7.04	0.14	0.40	0.016	[10]

4. Summary

Coalesced bainite begins as a series of adjacent, identically oriented platelets of ferrite only marginally separated by films of austenite. These early stages involve the development of the nucleus into a particle which can grow rapidly, thus permitting the partitioning of carbon. As the platelets lengthen, and assuming there is nothing to stop them from lengthening, they accelerate and coalesce. The carbon is then trapped in the ferrite, either to precipitate later or to partly partition into the residual austenite. Such coalescence can only occur when the driving force available is sufficient to sustain the greater strain energy associated with the coarser plates.

The coarse bainite is now known to be detrimental to toughness.

5. Future Work

It is appropriate to suggest experiments to determine the true three–dimensional shape of coalesced bainite. This is important in assessing the thermodynamic energy balances involved in its formation. Isothermal transformation experiments are likely to yield better defined information on both the shape and the coalescence process.

The role of carbon concentration, including its mobility, needs to be studied systematically since it is essential for the growing particle to trap the carbon so as to allow the films of austenite separating the individual platelets to be eliminated.

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