STEEL
TECHNOLOGY INTERNATIONAL
1989

Editor
Peter H Scholes

SP
G

Cover illustration: Teeming liquid steel from a ladle to the continuous bloom caster at British Steel's Teesside Works

Steel Technology International is distributed on a strictly controlled circulation basis primarily to the senior management of steel manufacturing companies worldwide. These include company board members, executives responsible for research, production, and engineering activities, and works directors. Heads of government agencies and major plant suppliers are also circulated.
Additional copies are available from the publisher at £25.

ABC
MEMBER OF THE AUDIT
BUREAU OF CIRCULATIONS

Production and metallurgy of advanced bainitic steels

H K D H Bhadeshia
University of Cambridge

Careful choice of alloy chemistry and advances in thermal processing conditions have led to high strength steels based on bainitic microstructures. These include rapidly cooled pipeline alloys and the ultra-low carbon bainitic and inoculated ferrite steels with high levels of toughness and weldability.

Bainite was discovered, as a microstructure in its own right, in the late 1920s by Davenport and Bain duirng the course of some pioneering studies on the isothermal transformation of austenite. It was the cause of much excitement because the bainitic samples seemed to display unusual and promising properties. Bain in 1939 went so far as to suggest that the microstructure was found to be "tougher for the same hardness than tempered martensite".

In spite of this early optimisim, many years elapsed before any major commercial exploitation of bainitic steels. There were difficulties in obtaining fully bainitic microstructures in sizeable samples of steel. Industry also preferred continuous cooling heat treatments, and at rates which could not in practice exceed $\simeq 50°Cs^{-1}$. In these circumstances, lean steels gave mixed microstructures of allotriomorphic ferrite and bainite, whereas the more heavily alloyed steels transformed only partially to bainite, some of the residual austenite undergoing martensitic transformation on further cooling.

It was not until low-alloy, low-carbon steels, containing small amounts of boron and molybdenum to suppress allotriomorphic ferrite formation were developed by Irvine and Pickering in the late 1950s that the potential for significant commercial exploitation became realistic. Boron increases the bainitic hardenability.

Other solute additions can, in the presence of boron, be kept at sufficiently low concentrations to avoid the formation of martensite. Steels like these (Alloy 1, Table 1) were found to yield virtually fully bainitic microstructures with very little martensite during normalising heat treatments.

The steels exhibited reasonable combinations of toughness and strength, but in time proved to be unexciting when compared with the best of quenched and tempered martensitic steels. Nevertheless, the physical metallurgy principles established during their development are now being applied in the metallurgical design of a new generation of bainitic steels. The purpose of this article is to summarise recent developments in high-technology, low-alloy steels based on bainitic microstructures. The results discussed are from original work all over the world, but particularly in Australia, Europe, Japan and North America; detailed references can be obtained from the author.

Many of these developments would not have been possible without major advances in steel processing technology. These advances include facilities for accelerated cooling methods which avoid distortion and the problems of nonuniform cooling in thick sections. The technology of controlled rolling which has developed over a period of many years has now been adapted for the production of bainitic microstructures.

No.	C	Si	Mn	Ni	Mo	Nb	Ti	B	Al	N	
1	0.100	0.25	0.50		0.55			0.0030			Early bainitic steel
2	0.081	0.25	1.86	0.20	0.09	0.045	0.016		0.025	0.0028	Accelerated cooled steel
3	0.039	0.20	1.55	0.20		0.042	0.015	0.0013	0.024	0.0030	Accelerated cooled steel
4	0.110	0.34	1.51			0.029					Accelerated cooled steel
5	0.100	0.25	1.00								Bainitic dual phase steel
6	0.020	0.20	2.00	0.30	0.30	0.050	0.020	0.0010		0.0025	ULCB steel
7	0.080	0.20	1.40				0.012		0.002	0.0020	Inoculated acicular ferrite steel

Table 1. Typical compositions of advanced bainitic steels (wt.%).

State of the art methods for introducing a uniform distribution of nonmetallic particles for the production of acicular ferrite steels are under development with much of the information still at the proprietary stage.

Accelerated cooling of control-rolled steels.

Pipeline steels. There is a general demand for a reduction in the wall-thickness and an increase in the diameter of pipelines for gas transmission; thinner walls permit faster and less troublesome girth welding operations, thereby reducing costs. The reduction can be achieved by increasing the strength of the steels used, as long as toughness is not sacrificed in the process.

When thickness considerations are not paramount, an increase in strength has the further advantage that the gas can be transmitted more efficiently under increased pressure ($\simeq 10$MPa).

It is found that if, after thermo-mechanical processing of the kind associated with conventional control-rolling, the steel is cooled from the austenite phase field at a rate which is high enough to reduce the formation of products such as allotriomorphic ferrite, but low enough to avoid substantial amounts of martensite, then a fine grained microstructure which is a mixture of allotriomorphic ferrite and bainite is formed.

The bainite consists of sheaves of platelets of apparent thickness $\simeq 0.9\mu$m, as compared with the equiaxed grains of allotriomorphic ferrite of size $\simeq 5\mu$m. It also has a much higher dislocation density of 1.7×10^{14}m^{-2}, compared with 0.4×10^{14}m^{-2} of the allotriomorphic ferrite. The overal microstructure is thus more refined relative to the conventional control-rolled steels.

The volume fraction of bainite can vary from about 0.2–1.0 depending on chemistry (Alloys 2–4, Table 1) and cooling conditions.

The microstructure described seems to meet the required properties of increased strength without an adverse effect on toughness. The tensile strength of $\simeq 700$MPa is some 50-70MPa higher than that of conventional control-rolled steels and Charpy impact values of $\simeq 160$–200 J at -20°C are frequently quoted. The extra strength is attributed to the fine size of the bainite platelets, although the strength of the allotriomorphic ferrite also increases with the accelerated cooling, for reasons which are not as yet understood.

The steels also do not exhibit a sharp yield point effect, although the advantage of this with respect to pipeline applications is not clear.

The production of the steels is not a continuous process of casting, control-rolling followed directly by accelerated cooling. Instead, cast ingots are first allowed to cool to ambient temperature and then reheated for the thermo-mechanical treatment; this ensures that the coarse austenite grain structure which evolves during ingot cooling is disrupted by transformation to ferrite.

The processing involves the reheating of thick ingots to 1150°C, followed by rolling during cooling of the ingot to 740°C, with the total reduction in thickness being about 625 per cent followed by accelerated cooling to around 450°C before allowing natural cooling. The cooling rates involved are higher, 10–40°Cs^{-1} over the temperature range 800–500°C than those appropriate for normal control-milled steel processes.

The accelerated cooling is achieved in industrial practice by the use of water spray curtains directed on either side of the hot plate in a manner designed to ensure uniform cooling and minimise distortion.

Processing parameters

There are a number of processing parameters which can influence the properties of the final product. For example, a high ingot reheating temperature allows more of the niobium carbonitrides to dissolve in the austenite; the niobium carbonitrides may subsequently precipitate during the $\gamma \rightarrow \alpha$ reaction to give fine dispersions within the ferrite (interphase precipitation), leading to an enhancement of its strength.

The temperature at which the rolling operation finishes is critical in the sense that it should leave the final austenite grains in an unrecrystallised, pancake shape. This ensures a further degree of refinement of the microstructure obtained after transformation.

If the finish rolling temperature is too low (below Ar$_3$), then the allotriomorphic ferrite will itself deform, leading to an increase in strength but at the expense of toughness. For this reason, the deformation should be restricted to the austenite phase.

The steels used in the accelerated cooling operations can have a hardenability high enough to prevent the completion of the bainite reaction during continuous cooling to ambient temperature. Large amounts of martensite can then be found in the microstructure, leading to a drop in toughness and a significant distortion of the plate product. To avoid this, the cooling sprays can be cut off while the steel is in the bainite temperature range, allowing the reaction to proceed to a greater extent, leaving only very small amounts of untransformed austenite.

It is generally recognised that a problem with these steels is that the toughness and microstructure are not maintained in the heat-affected zones created after welding. For cases where their enhanced strength is not needed, the carbon equivalent of the steel could in principle be reduced, thereby improving the weldability. A further difficulty is that the process is not suitable for heavy gauge plates ($\simeq 20$–30mm thickness) since it is then impossible to ensure uniform cooling throughout the depth of the samples; it is often the case that the central regions of such samples transform instead to a ferrite and pearlite microstructure.

With the increased use of continuously cast steels, the problem of solute-segregation at the centres of the rolled products becomes more severe. An advantage of the accelerated cooled steels is that the resulting microstructure of bainite and ferrite is experimentally found to be less sensitive to the segregation, when compared with the gross effect typical of ferrite-pearlite microstructures. These observations have yet to be explained.

In control-rolled steels, heavy gauge plates which are cooled slowly after rolling, have a tendency to develop a coarse ferrite grain structure at the surfaces. This appears to be a consequence of the recrystallisation of ferrite grains deformed by rolling in the $\alpha + \gamma$ phase field, although the fact that recrystallisation only happens at the surface implies that the deformation must have been inhomogeneous. Accelerated cooling has the added advantage that it inhibits these recrystallisation effects.

Steels with a high formability. The oil crises of the 1970s stimulated research which led to the development of the so-called dual phase steels, for applications leading to a reduction in the weight of automobiles in order to make them more fuel efficient. Conventional automobile steels either consisted of mixtures of ferrite and small amounts of pearlite, or wholly of ferrite ("dead" mild steels), with a tensile strength of $\simeq 420$MPa and the high level of formability necessary for the pressing operations so common in automobile manufacture.

A disadvantage with respect to forming operations is that such steels are capable of exhibiting discontinuous yielding behaviour, which can lead to the formation of unsightly stretcher
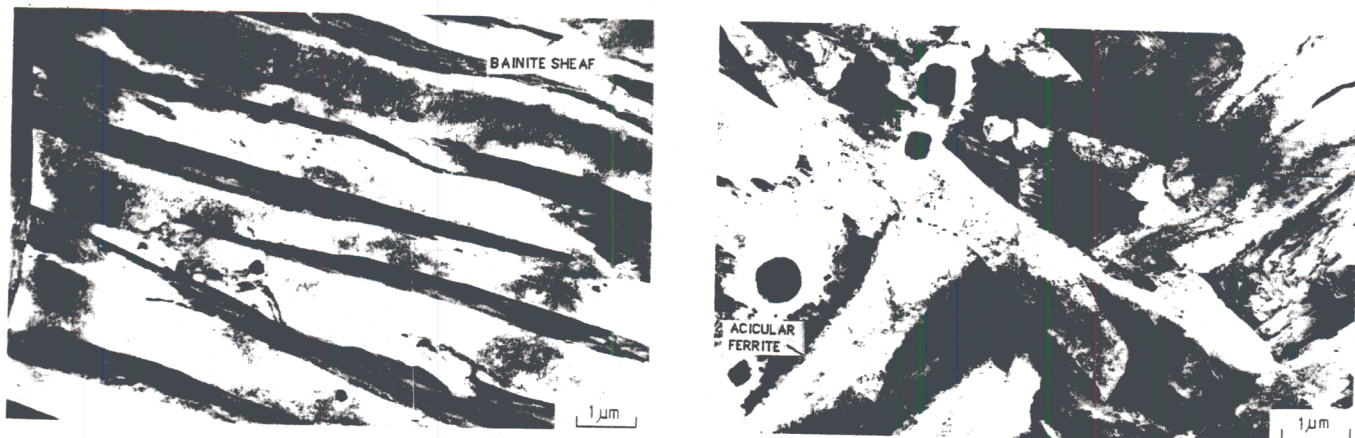
Figure 1. Transmission electron micrographs of microstructures obtained in the same alloy under identical isothermal transformation conditions. Left: small austenite grain size, classical bainitic microstructure consisting of bundles of parallel platelets in the same crystallographic orientation. Right: large austenite grain size, giving an acicular ferrite microstructure.

After Yang

strains on finished products.

Serious attempts have recently been made to design dual phase steels in which the hard phase is bainite instead of martensite. It is claimed that conventional (martensite containing) dual phase steels could benefit from a greater degree of stretch flangeability and also suffer from localised necking in the heat-affected zones of flash butt welds. To produce the microstructure of martensite and ferrite in a continuous process, the final coiling temperature has to be below the M_S temperature, and this is technically difficult to sustain at high mill speeds.

The cooling rate from the austenite phase field also has to be relatively high. In addition, the use of high silicon concentrations and other alloying additions adds to the cost of these dual phase steels, and the high silicon also can lead to undesirable scale on the steel surface.

The new dual phase steels have a simple chemical composition (Alloy 5, Table 1); they are hot-rolled in the austenite phase field to give a fine austenite grains size, cooled rapidly into the bainite transformation region and coiled in that temperature range to promote the formation of bainite.

The allotriomorphic ferrite forms during the coiling operation, and the cooling rate ($40 \rightarrow 100°Cs^{-1}$) determines the volume fraction of bainite (which may vary from 0.2–1.0 depending on the cooling conditions and chemistry). A coiling temperature below the martensite-start temperature can lead to the formation of some martensite as well, giving a triple phase steel.

The steels have properties which seem to compare well with conventional dual phase alloys, and the ferrite+bainite dual phase steels are claimed to have a better weldability, especially if they are microalloyed with niobium. The reasons for the improved weldability are not clear, but may have something to do with the fact that bainite has a lower strength when compared with martensite, so that any loss of strength in the heat affected zone of the welds should be of lesser consequence.

The carbon equivalent of the new steels is also supposed to be lower when compared with conventional dual phase steels.

Ultra-low-carbon bainitic steels. It has long been apparent that good mechanical properties (when compared with martensitic steels) can be obtained in bainitic steels when their carbon concentration is reduced. Otherwise, the coarse cementite particles and relatively large regions of untempered martensite (as a consequence of incomplete transformation to bainitic ferrite) have a severe detrimental effect on the toughness of the steel.

Very high concentrations of substitutional alloying elements can also be detrimental if they limit the possible degree of transformation to bainite. Of course, too low an alloy content reduces the hardenability of the steel, making the production of bainitic microstructure difficult.

A compromise solution adopted in the early days of bainite was that the carbon concentration was reduced to $\simeq 0.1$ wt.%, and boron and molybdenum additions ensured that the hardenability with respect to bainitic transformation was good while that with respect to martensitic transformation was rather low. Using this method, it
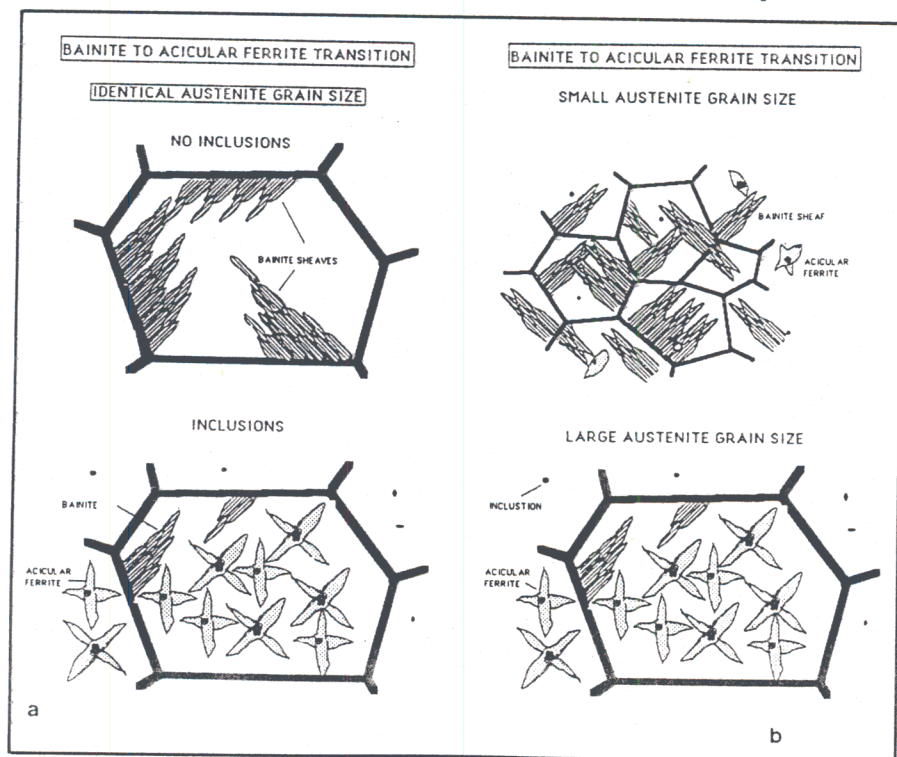

Figure 2. Transition between acicular ferrite and bainite, under identical isothermal heat treatment conditions. (a) The effect of altering the inclusion content; (b) effect of altering the austenite grain size.

was possible to produce virtually fully bainitic steels during continuous cooling transformation.

Recent work has advanced these concepts further, resulting in the development of the so-called ultra-low carbon bainitic (ULCB) steels (Alloy 6, Table 1). The carbon concentration is limited to the range 0.01-0.03 wt.% to ensure the absence of any substantial regions of martensite due to incomplete bainitic transformation, while at the same time the concentration is high enough to react with the niobium microalloying addition to form niobium carbide.

The niobium carbide and TiN serve to prevent austenite grain growth during control-rolling operations, which is an additional, essential feature of these steels. The niobium and titanium additions are also known to be effective in suppressing the formation of $Fe_{23}(CB)_6$, which tends to stimulate the nucleation of allotriomorphic ferrite. Nb and Ti combine with the carbon (which also has a tendency to segregate to austenite grain boundaries) and thereby prevent it from displacing boron from the grain boundaries.

In other respects the steels are similar in concept to the Irvine and Pickering steels; they contain boron and molybdenum to enhance bainitic hardenability, and the titanium also helps to tie up any dissolved nitrogen which would otherwise combine with the boron and render it ineffective.

It is reckoned that the titanium concentration (wt.%) should be about 3.4 times that of nitrogen if the latter is to be fixed. Because of the lower carbon concentrations in ULCB steels, the level of manganese and other substitutional elements such as nickel are higher compared with the Irvine and Pickering steels. The low carbon concentration also ensures that some of the niobium remains in solid solution at typical austenitising temperatures.

ULCB steels are found to have extremely good toughness strength and weldability combinations and have been designated for use in high strength line pipe in Arctic or submarine environments. A possible problem with these steels is in ensuring that the TiN particles which form in the melt are sufficiently small to avoid acting as fracture initiators. The size of the particles can be modified by controlling the cooling rates involved in the solidification process.

Acicular ferrite steels. Acicular ferrite is essentially, intragranularly nucleated bainite; its morphology differs from that of bainite sheaves consisting of parallel platelets, because it nucleates from a point site (an inclusion) rather than from the austenite grain surfaces. This gives rise to a microstructure in which the adjacent ferrite platelets tend to radiate in many directions from the point nucleation (Figure 1). Such clusters of nonparallel platelets lead to an enhancement of toughness since, unlike bainite, any propagating crack encounters plates in many different crystallographic orientation.

Conventional bainite and acicular ferrite can be obtained under identical isothermal transformation conditions in the same (inclusion-rich) steel; in the former case, the austenite grain size has to be small in order that nucleation from grain surfaces dominates and subsequent growth then swamps the interiors of the austenite grains (Figure 2). For the same reasons, acicular ferrite is not usually obtained in relatively clean wrought steels.

Inoculation of steels

Significant attempts have recently been made in industry, particularly by the Nippon Steel Corporation, to inoculate steels with oxide particles in order to induce the formation of acicular ferrite for improved toughness. These attempts are driven by the need to develop steels for the offshore oil and gas industries, steels which are required for service in hostile, deep and cold environments. This in turn requires unprecedented levels of strength and toughness.

The requirements can be met using thermomechanically processed, rapidly cooled bainitic steels, although when these steels are welded, the resulting thermal cycles induce less desirable microstructures in the heat-affected zones.

The problem can in principle be resolved in an elegant way which takes advantage of the coarsening of the austenite grain structure in the heat-affected zones of weld deposits. Low alloy steels containing titanium oxides and nitrides have been developed, in which these phases help nucleate acicular ferrite during cooling of the heat-affected zone after welding (Alloy 7, Table 1). The oxide particles have a diameter of about 2μm, and are introduced during steel making. The oxide particles thought to be effective in nucleating acicular ferrite are believed to be Ti_2O_3, although each inclusion is usually a complex combination of the titanium compounds and phases such as MnS, Al_2O_3, (Mn,Si)O, and so on, in both crystalline and amorphous conditions.

The aluminium concentration of the steel has to be minimal (<30ppm) during steelmaking since the formation of Ti-oxides is otherwise prevented. The nitrogen concentration must be similarly controlled since titanium also forms TiN.

Experimental measurements indicate that the procedure is very successful in enhancing the toughness of the critical regions of the heat affected zones of welds under both laboratory and commercial conditions.

It should be emphasised that the design of such steels also requires that the alloy chemistry be adjusted to avoid the prior formation of phases such as allotriomorphic ferrite, Widmanstätten ferrite, and so on, to leave enough untransformed austenite available for the formation of an effective quantitiy of intragranularly nucleated acicular ferrite. This can be accomplished by the careful use of microalloying elements such as Nb, Mo and B, thereby avoiding a large rise in the carbon equivalent of the steel.

Finally, it is to be noted that prior to the advent of the oxide-inoculated wrought steels just discussed, high-strength low-alloy steels were sometimes called acicular ferrite HSLA steels. This is because they exhibited a microstructure of heavily dislocated laths; this microstructure is more like the low-carbon bainite in which adjacent laths are in the same crystallographic orientation in space and it is probably not useful to call it an acicular ferrite microstructure, given that the latter nowadays carries the implication of intragranular, heterogeneous nucleation. □

Dr Harshad Bhadeshia is a lecturer in physical metallurgy at the University of Cambridge. His main research interest is in phase transformations, particularly in the modelling of microstructural development in metals. He is the author or co-author of two textbooks and about 100 papers and review articles.