ISIJ International, Vol. 35 (1995), No. 8, pp. 937–945

Review

Ferritic Microstructures in Continuously Cooled Low- and Ultralow-carbon Steels

George KRAUSS and Steven W. THOMPSON

Advanced Steel Processing and Products Research Center, Colorado School of Mines, Golden, Colorado 80401, U.S.A.

(*Received on March 20, 1995; accepted in final form on May 26, 1995*)

This paper reviews the various ferritic microstructures produced by austenite decomposition in continuously cooled low-carbon and ultralow-carbon steels and irons. Various terminologies used to identify the different ferritic microstructures are presented and related to several classification systems which have been developed for bainitic and ferritic microstructures in steels. Microstructural aspects are emphasized and discussed relative to transformation kinetics and mechanisms of austenite transformation to various morphologies of ferrite.

KEY WORDS: austenite decomposition; ferrite classification; bainite classification; ferrite in low-carbon steels; ferrite in ultralow-carbon steels; continuous cooling; ferrite–austenite microstructures.

1. Introduction

Microstructures in commercial low-carbon sheet and plate steels typically consist of equiaxed ferrite grain structures.1) Cementite may also be present as dispersed pearlite colonies in hot-rolled steels, or as dispersed spheroidized particles in cold-rolled-and-annealed sheet steels. Recent commercial development of interstitial-free (IF) or vacuum-degassed steels has completely eliminated cementite from the microstructure of cold-rolled-and-annealed sheet steels, and additions of Ti and Nb to IF steels completely remove carbon from interstitial solid solution in ferrite and control crystallographic texture.2,3) Annealed ferritic microstructures in low-carbon and IF steels have very high formability but low strength.

The requirement for steels of higher strength with high toughness or high formability has led to recent intensive examination of continuously cooled microstructures in low-carbon and ultralow-carbon steels.4) In contrast to the equiaxed ferritic microstructures of conventionally hot-rolled or cold-rolled-and-annealed steels, the ferritic microstructures formed by decomposition of austenite in the new steels, by virtue of alloying or rapid cooling, often assume non-equiaxed morphologies. The temperature range in which the non-equiaxed morphologies of ferrite form is intermediate to those at which austenite transforms to equiaxed ferrite/pearlite and martensite, and therefore is the same as that in which bainitic microstructures form in medium-carbon steels. However, the low-carbon steel ferritic microstructures formed at intermediate temperatures differ in variety and form from classical bainitic microstructures. In addition to recent developmental activity, non-equiaxed ferritic microstructures have been applied in pipe-line steels5) and described in the welding literature.6) Also, considerable previous effort has been devoted to characterizing the fundamental structures and mechanisms of austenite transformation in irons and very-low-carbon steels. This effort has recently been reviewed by Wilson.7)

The purpose of this paper is to review the characteristics of the various ferritic microstructures which form in low- and ultralow-carbon steels. Various bainite and ferrite classification systems which have been used to classify intermediate-temperature-range austenite transformations to ferritic microstructures are also presented and compared. The presentation of these considerations should provide a framework for the intensifying discussion of microstructural evolution in modern low-carbon high-strength steels.4)

2. Bainite and Bainite Classification Systems

Davenport and Bain8) introduced bainitic microstructures to the world by high-resolution light microscopy of steel specimens isothermally transformed at temperatures between those at which pearlite and martensite formed. Etching differences established the microstructures as different from pearlite and martensite, and eventually the unique ferrite–cementite aggregates became known as bainite in honor of Bain's pioneering efforts.9,10) Two different morphologies of bainite which form in medium-carbon steels, as described below, were designated upper and lower bainite by Mehl in 1939.11)

From the early recognition of bainite as a unique microstructural constituent of steels, the non-lamellar combination of ferrite and cementite has been an important characteristic of bainite. Aaronson12,13) strongly advocates the generalized microstructural definition of bainite as the product of a non-lamellar, non-cooperative mode

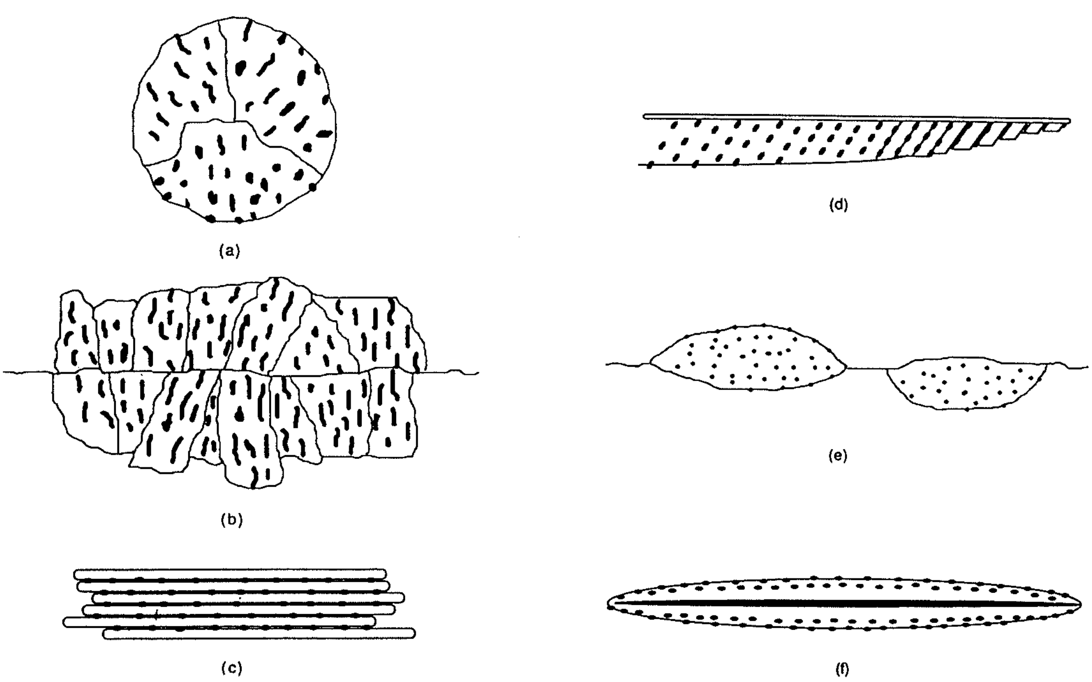

Fig. 1. Schematic illustrations of various ferrite (white)–cementite (dark) bainite morphologies. (a) Nodular bainite, (b) columnar bainite, (c) upper bainite, (d) lower bainite, (e) grain boundary allotriomorphic bainite, and (f) inverse bainite (from Ref. 13)).

of eutectoid decomposition of a parent phase. In steels, the eutectoid phases are ferrite and cementite, and six morphologies of ferrite and cementite are now recognized as bainite by Aaronson and his colleagues.[13] **Figure 1** shows these morphologies schematically. Upper bainite, Fig. 1(c), consists of sheaves or groups of parallel ferrite crystals, in the form of laths or plates, with discontinuous interlath cementite particles. In lower bainite, Fig. 1(d), ferrite crystals contain fine carbides at angles around 55 to 60 degrees to the long axis of the ferrite. In a high-manganese steel, lower bainite has recently been shown to form by the growth of secondary ferrite plates from a common ferrite spine, with the carbide precipitation occurring in austenite adjacent to the secondary ferrite plates.[14]

In many low-carbon and alloy carbon steels, however, cementite is not associated with intermediate-temperature austenite transformation.[15] Therefore, broader classifications of bainitic-type microstructures have been proposed which incorporate microstructures without cementite. For example, Ohmori *et al.*[16,17] recognize that the ferrite of upper bainite in low-carbon steels will always have a lath-like morphology, but that bainite may be carbide-free (BI), with austenite retained between laths, or that carbides may be present between ferrite laths (BII) or within ferrite laths (BIII). **Table 1** lists the bainite morphologies in the Ohmori *et al.* system, and **Fig. 2** shows the isothermal transformation regions where the three types of upper bainite formed in a low-carbon Cu–Ni–Cr–Mo steel.[17]

Bramfitt and Speer have proposed the general classification system for bainite shown in **Fig. 3**.[18] Three major types of bainite, all based on an acicular morphology of the ferrite, are presented. The differences in the various types of bainite are dependent on the type and association of other phases with ferrite in the bainitic structures. In the B_2 and B_3 morphologies, the Bramfitt–Speer system recognizes that martensite may transform from austenite retained between ferrite crystals. This phenomenon is frequently observed in continuously cooled low-carbon steels, and partially transformed interlath austenite is commonly referred to as the martensite–austenite (M/A) constituent of ferritic or bainitic microstructures. The Bramfitt–Speer bainite classification system is the most comprehensive proposed to date for bainites with acicular morphologies of ferrite, but as discussed in the next sections, does not describe all of the ferritic microstructures observed in continuously cooled low-carbon steels.

Table 1. Morphology of bainite in isothermal transformation.

Microconstituent	Criteria	
	Ferrite morphology	Carbide distribution
Ferrite	Lath-like	Acicular ferrite (carbide free)
Upper bainite	BI BII BIII	Lath interface
Lower bainite	Plate-like	Within grain

3. Ferritic Microstructures: General Considerations

In continuously cooled low-carbon and ultralow-carbon steels, the dominant decomposition product of austenite is ferrite. Some of the parent austenite is invariably not transformed and as noted earlier, the austenite may

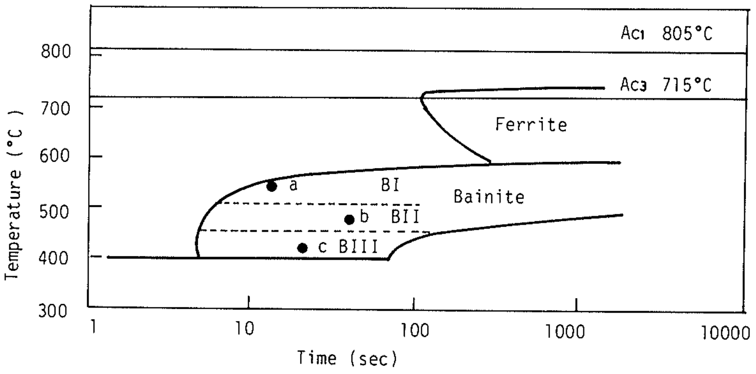

Fig. 2. Schematic representation of isothermal transformation diagram and the temperature regions of the formation for three forms of upper bainite for a low-carbon steel according to Ohmori *et al.* (from Ref. 17)).

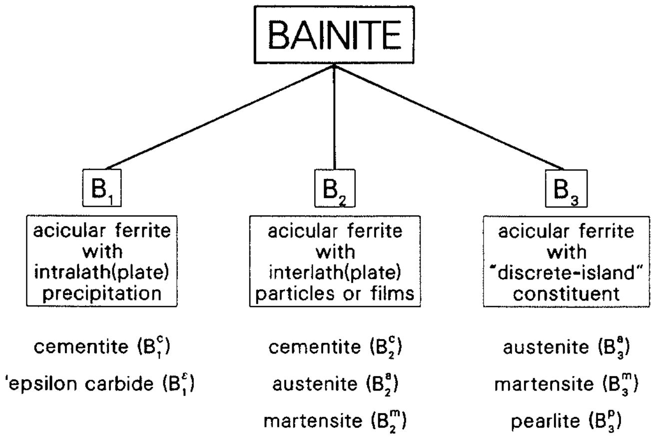

Fig. 3. Proposed morphological classification system for bainite according to Bramfitt and Speer (from Ref. 18)).

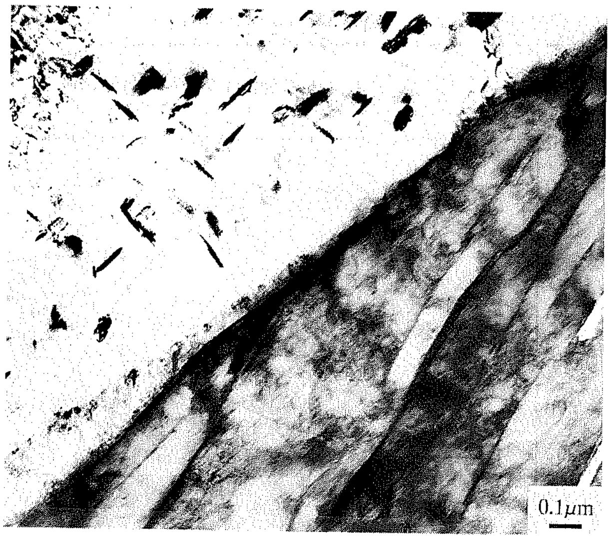

Fig. 4. Cementite precipitation in a large autotempered lath of martensite in a 0.075C–3.0Mn–1Cr steel cooled at 1°C/s. (Courtesy of C. C. Tseng, Colorado School of Mines)

be retained to room temperature or partially transformed to produce the M/A constituent. The ferrite may take many morphologies, and retained austenite or M/A constituent mirrors by default the shapes of the ferrite crystals. Therefore none of these forms of ferrite fit the microstructural definition of bainite as presented in Fig. 1, although lath or acicular morphologies of ferrite are incorporated into the bainite classifications of Ohmori *et al.*16,17) and Bramfitt and Speer.18) The general reaction of austenite to ferrite implies rejection of carbon into retained austenite, according to the dynamic solubility limits of ferrite. At very high cooling rates, even in very-low-carbon steels or irons with sufficient hardenability, austenite may transform to martensite which is well characterized in the literature.7,19) Sometimes the martensite is autotempered, reflecting both the high M_s temperatures of low-carbon steels, and the fact that the martensite at the temperature of formation was supersaturated with carbon.20) **Figure 4** shows cementite precipitates in a coarse autotempered martensite lath produced by cooling a steel containing 0.075 C, 3.0 Mn, and 1.0 Cr at 1°C/s.

The many types of ferrite which form in low-carbon steels are the subject of the balance of this paper. In addition to the relatively well-characterized forms of ferrite which form from austenite at high temperatures, types of ferrite which form from austenite at intermediate temperatures are now commonly observed in continuously cooled low-carbon steels. The recent interest has been driven by studies of a series of low-carbon and ultralow-carbon steels produced by the ISIJ Bainite Research Group,21,22) and evaluation of low-carbon high-strength-low-alloy (HSLA) steels developed for U.S. Navy ship plate applications.23) Independent of the latter recent efforts, the International Institute of Welding (IIW) has recognized the variety of ferritic microstructures which may form in low-carbon steel welds and weld heat-affected zones, and has established metallographic procedures to estimate the amount of each type of ferritic structure in welded specimens.24) Also, studies of austenite transformation in the 1960s and 1970s established many fundamental aspects of transformation mechanisms and structures in pure irons and low-carbon steels. Wilson7) and Maki25) have written comprehensive recent reviews of austenite-to-ferrite transformation in the latter ferrous alloys, evaluating transformation start temperature plateaus as a function of cooling rate for various transformation mechanisms. Recently, Yada has also categorized temperature ranges for various transformations in a number of low-carbon steels.26)

Figures 5 and **6** show, respectively, continuous-cooling-transformation (CCT) diagrams for an ultralow-carbon steel investigated by the ISIJ Bainite Committee22) and an HSLA plate steel evaluated by Thompson *et al.*27) The composition of the ultralow-carbon steel is given in the figure, and the HSLA steel contained (in mass%)

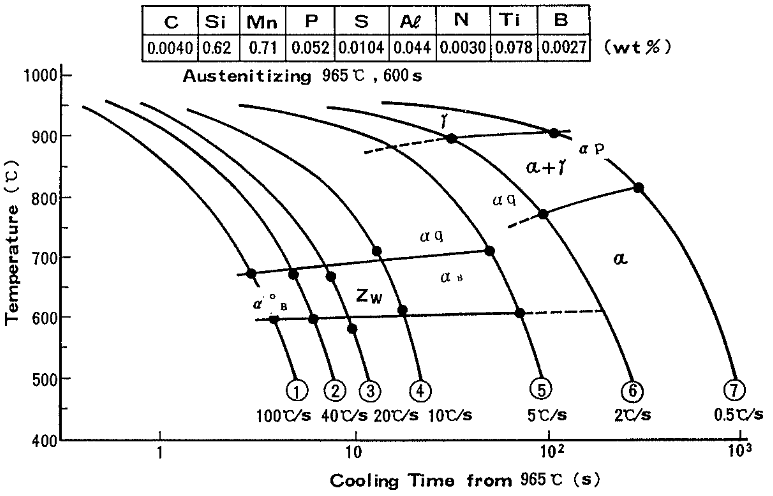

Fig. 5.
Continuous-cooling-transformation diagram for an ultra-low-carbon steel (by S. Sayanaji in Ref. 22)).

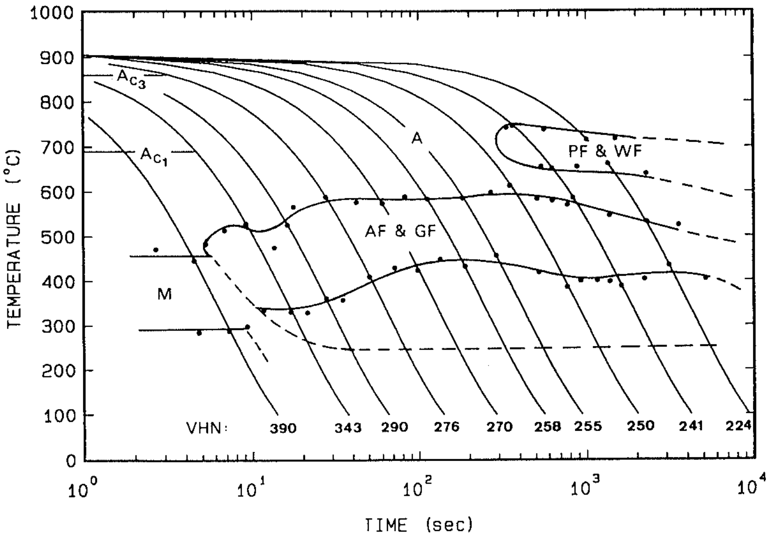

Fig. 6.
Continuous-cooling-transformation diagram of HSLA steel containing, in mass%, 0.06 C, 1.45 Mn, 1.25 Cu, 0.97 Ni, 0.72 Cr, 0.42 Mo (from Ref. 27)).

Table 2. Symbols and nomenclature for ferritic microstructures according to ISIJ bainite committee.[22)]

Symbol	Nomenclature
I_0 Major matrix-phase	
α_p	Polygonal ferrite
α_q	Quasi-polygonal α
α_w	Widmanstätten α
α_B	(Granular bainitic) α
α_B°	Bainitic ferrite
α'_m	Dislocated cubic martensite
II_0 Minor secondary phases	
γ_r	Retained austenite
MA	Martensite–austenite constituent
α'M	Martensite
aTM	Auto-tempered martensite
B	BII, B2: upper bainite Bu: upper bainite B_L: lower bainite
P′	Degenerated pearlite
P	Pearlite
Θ	Cementite particle

0.06 C, 1.45 Mn, 1.25 Cu, 0.97 Ni, 0.72 Cr and 0.42 Mo. In both steels, dependent on alloying and hardenability, intermediate temperature transformations play an important role in austenite decomposition. The various types of ferrite which form in the phase fields in the diagrams are labeled with the ISIJ Bainite Committee notation, as reproduced in **Table 2**, and in the HSLA steel diagram are identified by the letters PF, WF, AF and GF, which stand for polygonal ferrite, Widmanstätten ferrite, acicular ferrite and granular ferrite, respectively. Each type of ferritic microstructure will be discussed below.

As noted above, in addition to CCT diagrams, the various austenite transformation mechanisms and product microstructures have been fundamentally related to temperature ranges of formation and isothermal transformation diagrams. For example, as shown in **Fig. 7**, Wilson[7)] has related continuous-cooling-arrest temperatures for various austenite decomposition mechanisms in low-carbon irons to independent C-curves on time-temperature-transformation (TTT) diagrams. He reasons that each transformation product has a unique transformation-start temperature plateau over a range of cooling rates established by the mechanism of the transformation. At a critical cooling rate, which corresponds to the nose of a C-curve on a TTT diagram, a given mechanism is suppressed, and transformation shifts to a lower temperature at which transformation proceeds by another mechanism.

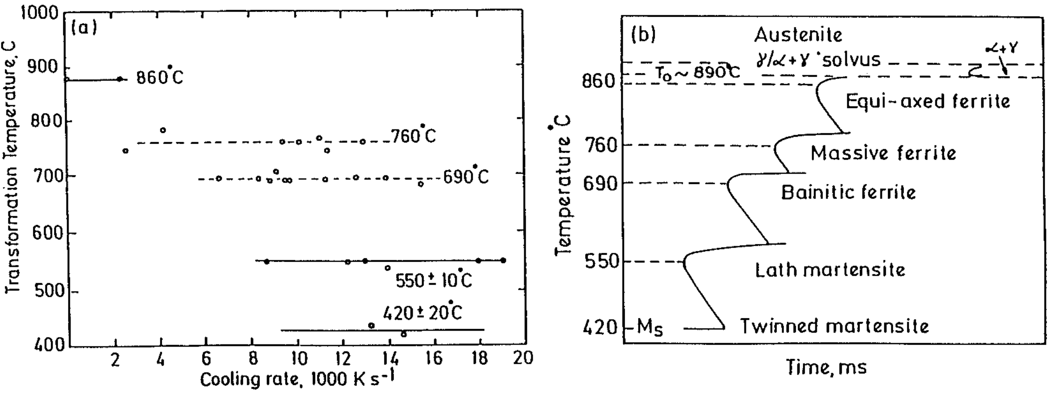

Fig. 7. (a) Transformation start temperatures as a function of cooling rate and (b) associated transformation curves for various transformation products in an iron containing 0.011% C (from Ref. 7)).

4. Ferritic Microstructures: Specific Types

The following sections briefly describe the various types of ferritic microstructures which have been observed in continuously cooled low-carbon irons and steels. Each type of microstructure may be described by several terms, depending on the classification system or terminology used by investigators, and the following discussion will attempt to cross reference the various terms used for a given structure if possible. In many cases the characterization of the austenite decomposition products is not yet complete, and considerable work is still necessary to couple transformation mechanisms and kinetics to microstructural evolution.

5. Polygonal or Equiaxed Ferrite

The ferritic microstructure which forms at the highest temperatures and slowest cooling rates in low-carbon steels is nucleated as grain-boundary allotriomorphs and grows into equiaxed grains. In view of the equiaxed grain geometry, this type of ferrite is referred to as equiaxed or polygonal ferrite (PF), and is designated α_p in the ISIJ bainite committee notation. The IIW system terms this morphology as primary ferrite, and distinguishes primary ferrite nucleated on grain boundaries and in grain interiors as PF(G) and PF(I), respectively.[24)]

Polygonal ferrite is readily identified in the light microscope and is characterized by very low dislocation densities and the absence of substructure, as revealed by the transmission electron microscope (TEM). **Figure 8** shows an example of polygonal ferrite in homogenized HSLA-80 steel isothermally transformed at 675°C for 500 s.[28)] The dark-etching regions of the microstructure are martensite which formed on quenching after the 500-s isothermal hold. Due to impingement, there is considerable grain-boundary curvature in the isothermally formed ferrite in Fig. 8, but the ferrite grain boundaries are smooth and continuous on the scale of the light microscope.

Wilson[7)] reviews evidence for nucleation of equiaxed ferrite at austenite grain corners. Thus the ferrite interfaces cross original austenite grain boundaries, and the parent ausenite grain structure is rendered indistinguishable in specimens largely transformed to polygonal ferrite. In contrast, in specimens only partially transformed to polygonal ferrite, the network of ferrite grain-boundary allotriomorphs clearly outlines the parent austenite grain-boundary structure. Growth of polygonal ferrite is controlled by rapid substitutional atom transfer across partially coherent boundaries and long-range diffusion of carbon atoms which are rejected from the growing ferrite. Partitioning of substitutional alloying elements may occur at the interfaces of polygonal ferrite, a phenomenon which may cause significant reductions in growth rates of grain-boundary ferrite allotriomorphs.[29-31)]

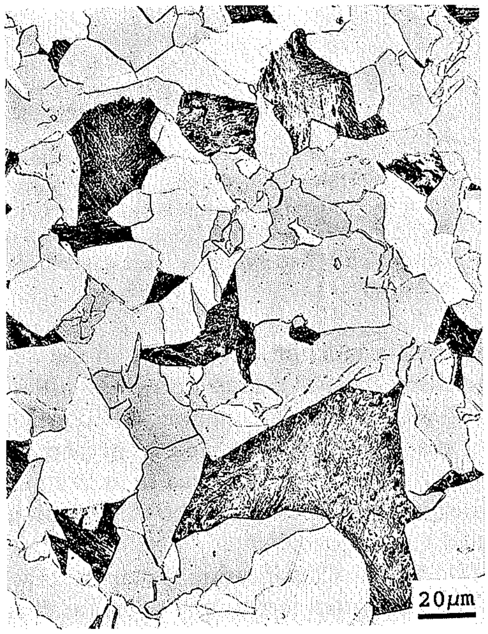

Fig. 8. Polygonal ferrite (light grains) formed in HSLA-80 steel (composition in text) isothermally transformed at 675°C for 500 s. The dark structures are martensite formed during quenching after isothermal holding. Light micrograph. (Courtesy of M. Kumar, Colorado School of Mines)

6. Widmanstätten Ferrite

Coarse, elongated crystals of ferrite are almost universally referred to as Widmanstätten ferrite (WF). **Figure 9** shows examples of Widmanstätten ferrite formed by isothermal transformation of austenite in an homogenized HSLA-80 steel held at 600°C for 100 s. The WF appears uniformly white, with no evidence of sub-

Fig. 9. Widmanstätten ferrite (large elongated white grains) formed in HSLA-80 steel isothermally transformed for 100 s at 600°C. Dark areas are martensite formed during quenching after isothermal hold. Light micrograph. (Courtesy of M. Kumar, Colorado School of Mines)

Fig. 10. Widmanstätten ferrite saw-teeth with low dislocation densities and copper precipitates in a copper-containing HSLA steel cooled at 0.1°C/s (from Ref. 27)). TEM micrograph.

structure within individual crystals, and the dark areas are martensite formed during quenching after the isothermal hold. The most common WF crystals, which nucleate at austenite grain boundaries or from polygonal ferrite allotriomorphs, are referred to as Widmanstätten side-plates, according to the Dubé classification system advocated by Aaronson.[32)]

The ISIJ Bainite Classification system uses the symbol α_w for Widmanstätten ferrite, and notes the characteristic lath-like or plate-like shape of this form of ferrite. Widmanstätten ferrite is further described as "mostly recovered", perhaps to indicate the absence or minimal presence of a dislocation substructure. The IIW system appears to describe Widmanstätten ferrite within the category of regions of two or more parallel laths of ferrite of high aspect ratio, greater than 4 : 1, and in general assigns the term Ferrite with Aligned Second Phase, FS(A), to these regions of microstructure. Specifically, Widmanstätten ferrite side-plates would be identified as FS(SP).

The mechanisms by which Widmanstätten ferrite forms are still under discussion. There is general agreement that WF forms at faster cooling rates and at the next lower range of temperatures than equiaxed ferrite. However, there are several explanations for the mechanisms by which Widmanstätten ferrite forms. Ohmori and his coworkers[33)] have characterized the surface relief associated with isothermal Widmanstätten ferrite formation in an ultralow-carbon 3% Mn, 1% Cr steel, and conclude that Widmanstätten ferrite nucleates *via* a diffusional mechanism and grows *via* a displacive mechanism. On the other hand, Kinsman and Aaronson[34)] argue that the surface relief associated with Widmanstätten ferrite formation can be produced by diffusional ledge mechanisms of growth. In copper-containing low-carbon steels, the present authors show that Widmanstätten ferrite growth may be accompanied by precipitation of copper particles at interfaces between Widmanstätten ferrite crystals and austenite.[27)] Therefore, evidence is provided not only for interstitial atom diffusion, as required by ferrite formation, but also for substitutional atom diffusion during the growth of Widmanstätten ferrite. **Figure 10** shows a TEM micrograph of Widmanstätten ferrite saw-teeth in a copper-containing HSLA steel.[27)] Low dislocation densities and copper precipitates are present in the WF, consistent with high temperatures of transformation and diffusion-controlled mechanisms of growth.

7. Quasi-polygonal or Massive Ferrite

In very-low-carbon steels and irons, it is possible by rapid cooling to go from single-phase austenite to single-phase ferrite without a composition change. Cooling, however, must be rapid enough to minimize partitioning in the intervening two-phase ferrite–austenite field. Under these conditions, the microstructure formed consists of relatively coarse ferrite grains, and therefore, is referred to as massive ferrite. The ferrite grains, however, have irregular grain boundaries and often show etching evidence of substructure. **Figure 11** shows an example of massive ferrite in an ultralow-carbon steel containing 0.005% C and 3% Mn. This microstructure is also termed quasi-polygonal ferrite, α_q, in the ISIJ Bainite Committee notation, and similar to polygonal ferrite, crosses prior austenite grain boundaries.

As reviewed by Wilson,[7)] the massive transformation has been in the past a subject of extensive academic

Fig. 11. Quasi-polygonal ferrite formed in ultralow-carbon steel containing 0.005 C and 3 Mn cooled at 50°C/s. (Courtesy of C. C. Tseng, Colorado School of Mines) Light micrograph.

investigation. Practical interest is now expressed because continuously cooled low-carbon steels with quasi-polygonal ferrite microstructures show the potential of excellent combinations of strength and ductility.[4] Because the parent austenite and product ferrite involved in a massive transformation ideally have the same composition, the transformation can be accomplished by short-range diffusion across transformation interfaces.[35] However, interstitial or substitutional atom partitioning may occur at the migrating interfaces,[36] causing irregular growth and the jagged boundaries of massive ferrite crystals. In contrast to polygonal ferrite, massive ferrite, as shown by transmission electron microscopy, contains a high dislocation density, dislocation subboundaries, and apparently even M/A constituent[37,38] Such a substructure correlates with low yield-to-ultimate-strength ratios and high strain-hardening rates of low-carbon steels with quasi-polygonal microstructures.[39]

8. Bainitic or Acicular Ferrite

With increasing cooling rates, the austenite of low-carbon and ultralow-carbon steels transforms to much finer ferrite crystals than described above. The most commonly used terms for the resulting ferritic microstructures are bainitic ferrite, α_B°,[22] and acicular ferrite, AF.[5,24,27] The transformation temperatures for the formation of these ferritic microstructures are clearly in the intermediate temperature range, as shown in the continuous-cooling-transformation diagrams of Figs. 5 and 6. Although the austenite decomposition is only to ferrite, coexisting with retained austenite or M/A constituent, the microstructural arrangement of acicular-shaped ferrite crystals in groups of parallel laths is included in the Ohmori *et al.* bainite classification as BI bainite and in the Bramfitt and Speer bainite classification as B_2, acicular ferrite with interlath austenite. Thus the literature describes the fine nonequiaxed ferritic intermediate-temperature austenite transformation product as both ferrite and bainite.

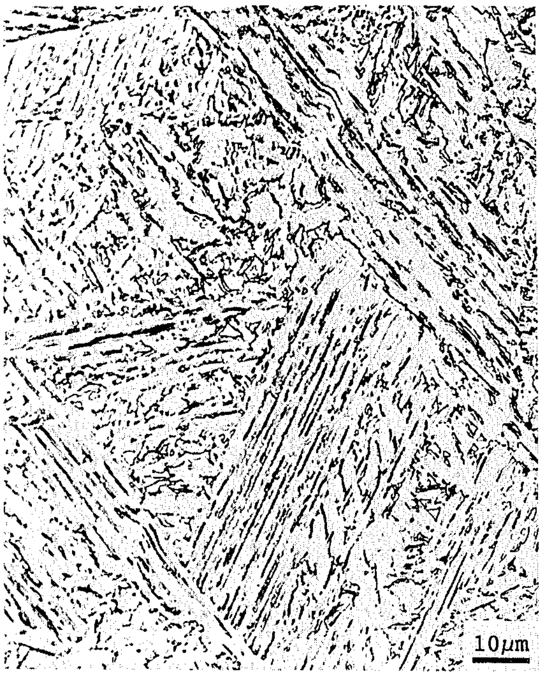

Fig. 12. Acicular ferrite formed by isothermal transformation of copper-containing HSLA-80 steel transformed for 5 000 s at 500°C. (Courtesy of M. Kumar, Colorado School of Mines) Light micrograph.

Figure 12 shows a light micrograph of acicular ferrite formed in HSLA-80 steel isothermally transformed at 500°C for 5 000 s. The most prominent features of the microstructure are the aligned, elongated, parallel islands of retained austenite or M/A constituent within the prior austenite grains, and the fact that the austenite grain boundary structure is conserved, as emphasized by the ISIJ ferrite classification system. The matrix which contains the elongated particles is featureless in the light micrograph.

Complete characterization of bainitic or acicular ferrite requires TEM, and many good examples of TEM characterization have been published in the literature.[4,22,27] The TEM shows that the matrix structure consists of many fine, elongated ferritic crystals with a high dislocation density. In a given region, the ferrite crystals are parallel and have almost the same crystallographic orientation. As a result, the ferrite crystal boundaries are low-angle and do not respond to etching, explaining the apparent absence of matrix boundaries in light micrographs. Austenite or M/A constituent is retained between the ferrite laths, and therefore by default assumes the elongated or acicular morphology observable in light micrographs.

In weld metal of low-carbon content, acicular ferrite is considered to consist of fine, elongated crystals of aspect ratio less than 4 : 1.[24] However, in contrast to sheet- and plate-steel microstructures, adjacent acicular ferrite crystals are not parallel, a situation which results from the nucleation of several ferrite crystal variants

Fig. 13. Granular ferrite formed by continuous cooling of a modified-A710 steel (composition in text) at a rate of 1°C/s. (Courtesy of B. Kloberdanz, Colorado School of Mines) Light micrograph.

from oxide particles distributed throughout the weld metal. As a result, the welding literature regards intragranular nucleation as a major characteristic of acicular ferrite. Many questions regarding the mechanisms of nucleation and growth of bainitic ferrite, continuing from arguments regarding the importance of shear and diffusion in the bainite literature, must yet be resolved.

9. Granular Ferrite or Granular Bainitic Ferrite

Granular bainitic ferrite, α_B,[22] or granular ferrite, GF,[27] has many similarities to bainitic or acicular ferrite, but there appear to be morphological differences which merit a separate category of austenite-to-ferrite transformation. Microstructures consisting of granular bainite also form in the intermediate austenite transformation range, as shown in the CCT diagrams, Figs. 5 and 6. Although acicular and granular ferrites form over the same transformation temperature range, the cooling rates which form granular ferrites appear to be somewhat slower than those which form acicular ferrites.

Figure 13 shows a light micrograph of granular ferrite formed during continuous cooling of a modified-A710 steel (0.033 C, 1.44 Mn, 1.20 Cu, 2.19 Ni, 0.67 Cr, and 0.46 Mo) at a rate of 1°C/s. Similar to acicular ferrite microstructures, the microstructure of granular ferrite consists of dispersed retained austenite or M/A particles in a featureless matrix which may retain the prior austenite grain boundary structure. However, in contrast to the acicular ferrite microstructures, the dispersed particles have a granular or equiaxed morphology. TEM shows that the ferritic matrix consists of fine ferrite crystals, containing high densities of dislocations, separated by low-angle grain boundaries.[27] As for acicular ferrite microstructures, the low-angle boundaries explain the insensitivity of the matrix ferrite crystals to etching for light microscopy. The ferrite crystals have granular or equiaxed shapes which cause enclosed retained austenite or M/A regions, by default, to have the granular or equiaxed shapes resolvable in light micrographs.

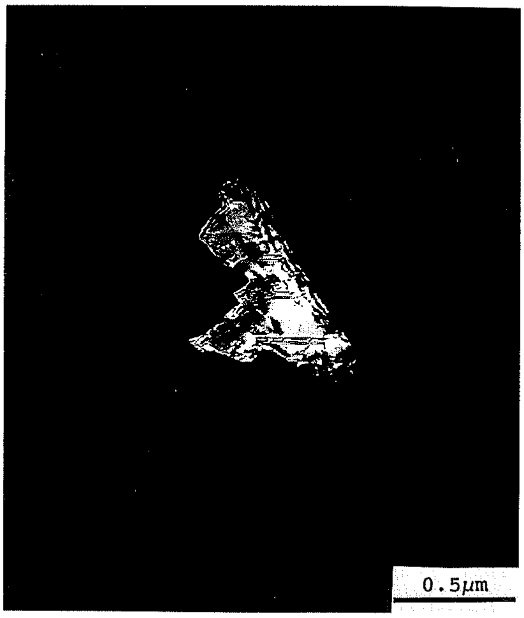

Fig. 14. Equiaxed island of retained austenite in granular ferrite of modified-A710 steel cooled at 2.5°C/s (from Ref. 27)). TEM micrograph; dark field illumination with austenite diffraction beam.

The nucleation and growth mechanisms of granular ferrite have been explored much less than those of bainitic or acicular ferrite. Nevertheless, there is evidence that the granular ferrite crystals grow by a diffusion-controlled ledge mechanism. **Figure 14** shows a TEM micrograph of a retained austenite island in a modified-A710 steel specimen transformed to granular ferrite.[27] The retained austenite crystal is roughly equiaxed in shape and defined by ledge interfaces with the surrounding ferrite. Granular ferrite is the same microstructure referred to as granular bainite by Habraken and Economopoulous.[15] Bramfitt and Speer attempted to incorporate it into their classification system by incorporating a category of bainite consisting of acicular ferrite with "discrete-island" constituent, but it is difficult to see how secondary phases can assume equiaxed morphologies in a matrix of acicular ferrite.

10. Summary

This paper has described the various ferrite microstructures which form by austenitic transformation in low-carbon and ultralow-carbon steels and irons. Of necessity it has reviewed pertinent literature regarding bainite and ferrite transformation, microstructure, and morphology, in addition to presenting evidence from the authors' investigations. The review is far from exhaustive, and instead is directed to questions regarding ferrite formation in the context of the 1994 Tokyo conference "New Aspects of Microstructures in Modern Low Carbon High Strength Steels". Considerable new information regarding the evolution of microstructure and properties of continuously cooled low-carbon steels was presented at that conference, and the reader is referred to the Abstract book and subsequent papers from that conference for a wealth of new information. It is clear that there are many scientific questions regarding the mechanisms by which the various ferritic microstructures form[12,13,40,41] and some confusion regarding characterization and terminology of the various microstructures. These questions will be addressed in future research which, because of the Tokyo conference, can now be more clearly defined.

Acknowledgements

Research on microstructural evolution in high-strength low-carbon steels at the Colorado School of Mines is supported by the Advanced Steel Processing and Products Research Center, an NSF Industry/University Cooperative Research Center, by the Office of Naval Research under contract number N00014-91-J-1862, and 1992 and 1993 summer student grants from Sumitomo Metal Industries, Ltd., and Kobe Steel, Ltd. We gratefully acknowledge this support, and we thank Ms. Mimi Martin and Mr. C. C. (Frank) Tseng for assistance with manuscript preparation.

REFERENCES

1) W. C. Leslie: The Physical Metallurgy of Steels, McGraw-Hill, New York, (1981).
2) Metallurgy of Vacuum-Degassed Steel Products, ed. by R. Pradhan, TMS, Warrendale, PA, (1990).
3) Physical Metallurgy of IF Steels, ISIJ, Tokyo, (1994).
4) Symposium Book, New Aspects of Microstructures in Modern Low Carbon High Strength Steels, ISIJ, Tokyo, (1994).
5) Y. E. Smith, A. P. Coldren and R. L. Cryderman: Toward Improved Ductility and Toughness, Climax Molybdenum Co., Ann Arbor, MI, (1971), 119.
6) O. Grong and D. K. Matlock: *Int. Met. Rev.*, **31** (1986), 27.
7) E. A. Wilson: *ISIJ Int.*, **34** (1994), No. 8, 615.
8) E. S. Davenport and E. C. Bain: *Trans. AIME*, **90** (1930), 117.
9) H. K. D. H. Bhadeshia: Bainite in Steels, The Inst. Mater., London, (1992).
10) N. F. Kennon: *J. Austral. Inst. Met.*, **18** (1973), No. 2, 57.
11) R. F. Mehl: Hardenability of Alloy Steels, ASM, Metals Park, OH, (1939), 1.
12) H. I. Aaronson: The Mechanism of Phase Transformations in Crystalline Solids, The Inst. Met., London, (1969), 270.
13) W. T. Reynolds, Jr., H. I. Aaronson and G. Spanos: *Mater. Trans., JIM*, **32** (1991), No. 8, 737.
14) G. Spanos, H. S. Fang and H. I. Aaronson: *Metall. Trans. A*, **21A** (1990), 1381.
15) L. J. Habraken and M. Economopoulos: Transformation and Hardenability in Steels, Climax Molybdenum Co., Ann Arbor, MI, (1967), 69.
16) Y. Ohmori, H. Ohtani and T. Kunitake: *Trans. ISU*, **11** (1971), 250.
17) H. Ohtani, S. Okaguchi, Y. Fujishiro and Y. Ohmori: *Metall. Trans. A*, **21A** (1990), 877.
18) B. L. Bramfitt and J. G. Speer: *Metall. Trans. A*, **21A** (1990), 817.
19) G. Krauss and A. R. Marder: *Metall. Trans.*, **2** (1971), 2343.
20) R. H. Aborn: *Trans. Amer. Soc. Met.*, **48** (1956), 51.
21) T. Araki, M. Enomoto and K. Shibota: *Mater. Trans. JIM*, **32** (1991), 729.
22) Atlas for Bainitic Microstructures, Vol. 1, ISIJ, Tokyo, (1992).
23) T. W. Montamarano, B. P. Sack, J. P. Gudas, M. G. Vassilaros and H. H. Vanderveldt: *J. Ship Production*, **2** (1986), 145.
24) Document Number IX-1533-88, IXJ-123-87 Revision 2, IIW, (1988).
25) T. Maki: Physical metallurgy of IF Steels, ISIJ, Tokyo, (1994), 183.
26) H. Yada: Final Report of Bainite Research Committee, ISIJ, Tokyo, (1994), 71.
27) S. W. Thompson, D. J. Colvin and G. Krauss: *Metall. Trans. A*, **21A** (1990), 1493.
28) M. Kumar: Isothermal Decomposition of Coarse-Grained Austenite in Low-Carbon, Copper-Containing HSLA-80 Plate Steel, M.S. Thesis, Colorado School of Mines, Golden, CO, (1994).
29) H. I. Aaronson and H. A. Domian: *Trans.-AIME*, **236** (1966), 781.
30) M. Hillert: Solid–Solid Phase Transformations, ed. by H. I. Aaronson, D. E. Laughlin, R. F. Sekerka and C. M. Wayman, TMS, Warrendale, PA, (1982), 789.
31) D. E. Coates: *Metall. Trans.*, **4** (1973), 2313.
32) H. I. Aaronson: Decomposition of Austenite by Diffusional Processes, ed. by V. F. Zackey and H. I. Aaronson, Interscience, N.Y., (1962), 131.
33) Y. C. J. Jung, K. Nakai, H. Ohtsubo and Y. Ohmori: *ISIJ Int.*, **34** (1994), No. 1, 43.
34) K. R. Kinsman and H. I. Aaronson: Transformation and Hardenability in Steels, Climax Molybdenum Company, Ann Arbor, MI, (1967), 33.
35) T. B. Massalski: Phase Transformations, ASM, Metals Park, Ohio, (1970), 433.
36) M. Hillert: *Metall. Trans. A*, **15A** (1984), 411.
37) J. Cawley, C. F. Harris and E. A. Wilson: Symposium Book, New Aspects of Microstructures in Modern Low Carbon High Strength Steels, ISIJ, Tokyo, (1994), 11.
38) K. Shibata and K. Asakura: Symposium Book, New Aspects of Microstructures in Modern Low Carbon High Strength Steels, ISIJ, Tokyo, (1994), 31.
39) G. Krauss and S. W. Thompson: Final Report of Bainite Research Committee, ISIJ, Tokyo, (1994), 97.
40) J. W. Christian and D. V. Edmonds: Phase Transformations in Ferrous Alloys, ed. by A. R. Marder and J. I. Goldstein, TMS, Warrendale, PA, (1984), 293.
41) G. B. Olson, H. K. D. H. Bhadesia and M. Cohen: *Acta Metall.*, **37** (1989), 381.