

On the Symmetry Among the Diffusional Transformation Products of Austenite

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Information on the diffusional transformation products of austenite in high-carbon steels is reviewed and supplemented with new microscopic studies. A comparison with transformation products in low-carbon steels indicates that there is a symmetry with pearlite in the middle, where ferrite and cementite are equal partners, and with acicular ferrite or cementite on each side. They both form with a surface relief, and at lower temperatures, each one is the leading phase in a eutectoid microstructure, bainite and inverse bainite, respectively. However, there is an asymmetry because at low temperatures bainite appears in high-carbon steels but inverse bainite never appears in low-carbon steels. At a constant high carbon content, there is another kind of symmetry, which is related to temperature. At intermediate temperatures the eutectoid reaction results in spherical nodules in which the cementite constituent originates from Widmanstätten plates. It turns spiky at both higher and lower temperatures with the leading phase in the spikes being cementite at higher temperatures and ferrite at lower temperatures. In the first kind of symmetry, there is an abrupt change among the three reaction products; in the second kind of symmetry, there is a gradual change. Accepting that all the eutectoid microstructures form by diffusion of carbon, one may explain the existence of both symmetries by the variation of the ratio of the supersaturations of ferrite and cementite with carbon content and with temperature.

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I. INTRODUCTION OF THE TERM INVERSE BAINITE

WHEN Hillert in 1957^[1] developed and extended Zener's^[2] theoretical analysis of diffusional growth of pearlite and Widmanstätten plates, he proposed also that there should be a symmetry among the eutectoid transformation products of austenite in the Fe-C system. Pearlite is the result of cooperative growth of ferrite and cementite where the two phases behave as equal partners. It is favored by a close-to-eutectoid composition. Bainite forms with ferrite as a leading phase in the main growth direction, which is identical to the growth direction of Widmanstätten ferrite. Bainite is favored by low carbon content. For symmetry reasons, he suggested that there should be a third eutectoid product, which is favored by high carbon content and has cementite as the leading phase in the favorable growth direction of Widmanstätten cementite. He observed this microstructure and called it inverse bainite because the two phases had exchanged roles compared with bainite.

According to this picture, the protruding tips of the ferritic constituent of bainite should be identical to Widmanstätten ferrite, and the protruding tips of the cementite constituent of inverse bainite should be identical to Widmanstätten cementite. In summary, the two phases should be able to cooperate during growth and form relatively regular pearlite if none of them has a favorable orientation relation to the parent austenite. If the first phase to form has a favorable orientation relation, then it can start to develop as Widmanstätten plates; in a subsequent two-phase structure, it would become the leading phase in the growth direction of the plates.

II. DIFFUSIONLESS OR DIFFUSIONAL GROWTH OF BAINITE

Inverse bainite has been discussed only a few times during the elapsed 50 years, mainly by Aaronson and coworkers,^[3-5] and the idea of symmetry among the diffusional transformation products of austenite has not been discussed subsequently. To some extent, this may be caused by the focus on a conflicting idea about the nature of bainite, which also stems from Zener.^[2] He proposed that a plate of bainitic ferrite forms by a rapid, diffusionless shear mechanism, much like martensite. Support for a shear mechanism related to the martensitic transformation was soon obtained from the observation by Ko and Cottrell^[6] that bainite forms with

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a shape change that gives rise to a surface relief when a plate forms in the surface layer of a specimen. Today, the surface relief is often taken as an indication that the Fe lattice is transformed from face-centered cubic to base-centered cubic by a displacive mechanism. There is a tendency to emphasize the similarity to martensite by implying that displacive growth of bainitic ferrite makes the transformation rapid, which prevents carbon diffusion during growth. However, Ko and Cottrell reported that the growth of bainite is slow enough to be explained by carbon diffusion, and several reports have indicated the slow growth of bainite plates. The proponents of diffusionless growth must still argue for rapid growth, and generally they have explained the slow experimental growth as the macroscopic result of many short consecutive steps of such high velocity that there is not sufficient time for diffusion of carbon during a step.^[7,8] Evidently, the idea of symmetry among the transformation products of austenite could not be reconciled with a diffusionless mechanism for bainitic ferrite because it is not possible to imagine that a unit of inverse bainite can form primarily as a plate of low-carbon cementite. It has been difficult to argue for the idea of symmetry because of the popularity of the diffusionless, displacive mechanism.

However, it was shown recently that there is much metallographic evidence against the diffusionless mechanism of bainite formation.^[9] Furthermore, it has also been emphasized that the hypothesis of diffusionless growth of bainitic ferrite but diffusional growth of Widmanstätten ferrite cannot be reconciled with the fact that the transformation to ferrite does not continue by yielding Widmanstätten ferrite when the formation of bainitic ferrite has stopped because of the so-called incomplete nature of that reaction.^[10] The problem disappears if all acicular ferrite grows with the same diffusional mechanism. It seems that the rapid diffusionless mechanism may no longer be justified. Accepting diffusional growth without discussing whether the Fe lattice of bainitic ferrite forms by a slow displacive mechanism or by a mechanism of more reconstructive character, it now seems possible again to open the question of possible symmetry among the transformation products of austenite. That is the purpose of the current study.

III. POSSIBLE REASONS FOR DEVIATION FROM FULL SYMMETRY

Bainite is defined many ways. To avoid misunderstandings, bainite will here be defined as the kind of eutectoid mixture of ferrite and cementite that forms under conditions where ferrite is the leading phase in the main growth direction and has a tendency for plate-like growth because of some orientation relation of ferrite to the parent austenite. Similarly, inverse bainite will be defined as the eutectoid mixture of ferrite and cementite that forms under conditions where cementite is the leading phase in the main growth direction and has a tendency for plate-like growth because of some orientation relation of cementite to the parent austenite.

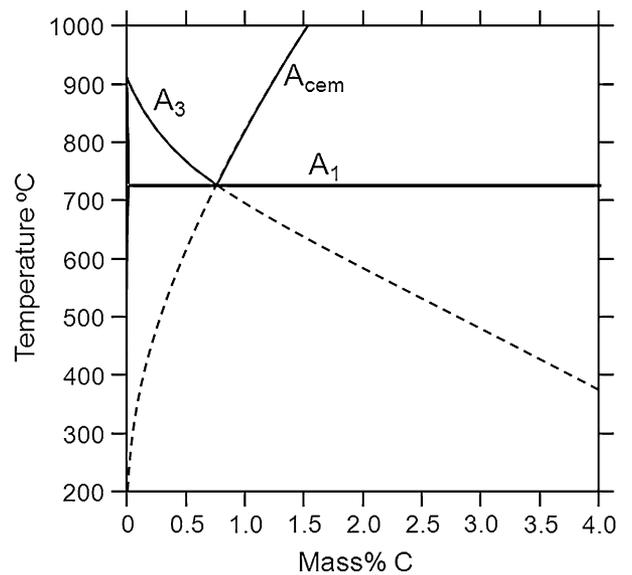


Fig. 1—Extrapolated solubility lines for ferrite and cementite in Fe-C austenite, according to the TCFE6 database.^[11]

However, it should be realized that the phase diagram is not symmetric. Figure 1 shows the solubility limits for ferrite and cementite in austenite, and they are extrapolated below the eutectoid temperature A_1 using the Thermo-Calc Databank System (Thermo-Calc Software, Stockholm, Sweden)^[11] equipped with the database TCFE6. Thus, full symmetry among the diffusional transformation products cannot be expected to hold in all details. First, the fraction of ferrite in the eutectoid mixture is approximately seven times as large as of cementite. Second, the slopes of the A_3 and A_{cem} lines in the Fe-C phase diagram are different. The supersaturation of austenite with respect to ferrite will increase faster at decreasing temperature than the supersaturation with respect to cementite.

Ever since a second paper was published by Ko,^[12] it has been realized that not only bainite but also Widmanstätten ferrite gives rise to a surface relief, which could be a reason for the deviation from symmetry of the diffusional transformation products of austenite unless Widmanstätten cementite also gives rise to a surface relief. In fact, Figure 2, which is a reproduction of an unpublished series of micrographs by Speich,^[13] demonstrates that Widmanstätten cementite gives rise to surface relief. Symmetry, thus, applies to this feature. That observation was confirmed recently by Yan and Zhang.^[14]

IV. SOURCE OF INFORMATION

The current study of symmetry between the diffusional transformation products of austenite will be based on a large number of micrographs from isothermal treatments, and many of them have been reproduced from old literature, which reflects the fact that much information for testing the idea of symmetry has been available for a long time. Important inspiration for



Fig. 2—Metallographic evidence of surface relief caused by Widmanstätten cementite formed during 300 s at 923 K (650 °C). Upper: interferogram; Middle: etched; Lower: unetched, oblique illumination. 400 times magnification. From Speich.^[13]

the current study comes from an extensive series of studies of commercial plain carbon steels with 0.18, 0.55, 0.86, 1.18, and 1.65 mass pct C carried out by Modin and Modin.^[15–17] Their results from high-carbon steels were not published in the open literature but were collected finally in a metallographic atlas that was published privately with limited circulation.^[17] Several of their micrographs for the steel with 1.65 mass pct C are reproduced in the current report. It should be mentioned that this steel contained 0.48 mass pct Cr, which at that time was a common addition to plain carbon steels with high carbon contents to prevent graphitization during the production.

A wealth of information is available on the isothermal decomposition of austenite in low-carbon steels, but for high-carbon steels without considerable alloy additions, remarkably few studies are available. Greninger and Troiano^[18] in 1940 published a study of carbon steels with carbon contents up to 1.78 mass pct C and demonstrated that pearlite was replaced by a spiky product between 823 K and 723 K (550 °C and 450 °C) that was described as “spiky pearlite” (Figure 3(a)). In turn, it was replaced by a nodular product with smooth contours at 573 K (300 °C) (Figure 3(b)). Fan-like units resembling separate sectors of such nodules were observed by Hultgren^[19] in a steel with 0.97 mass pct C and 2.91 mass pct Cr. He called it “smooth pearlite” (Figure 4). More recently, fan-like units have been observed several times, *e.g.*, by Nilan^[20] in a study of the transformation of austenite in a pure Fe-C alloy

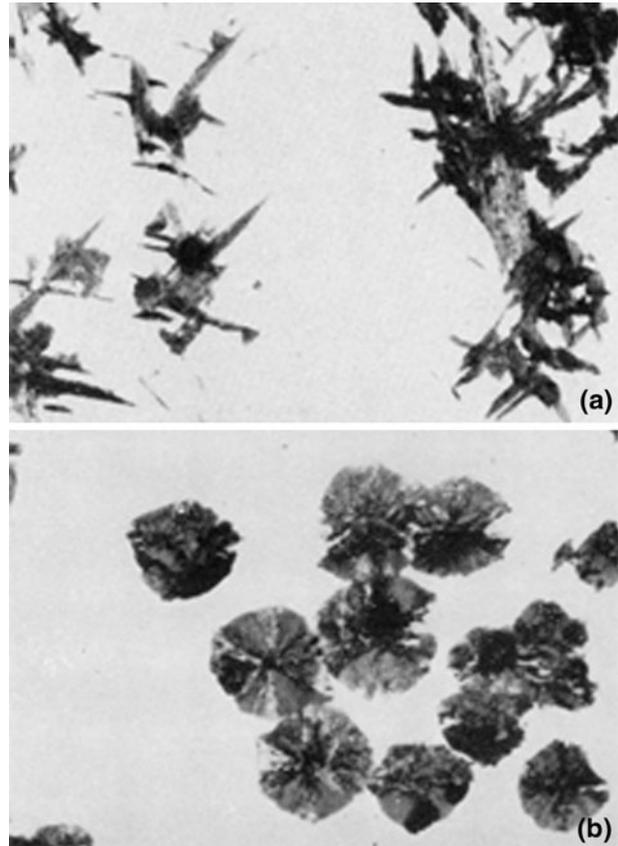


Fig. 3—Light micrographs at 750 times magnification of steel with 1.78 mass pct C. (a) “Spiky pearlite” formed after 10 s at 723 K (450 °C). (b) “Pearlite nodule” formed after 2100 s at 573 K (300 °C). From Greninger and Troiano.^[18]

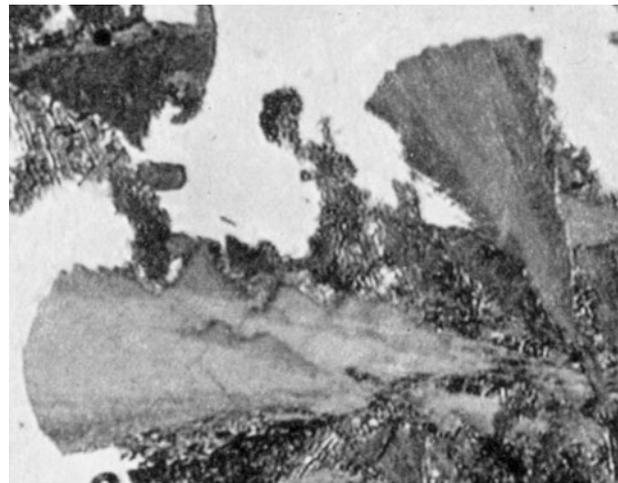


Fig. 4—“Smooth pearlite” formed after 2 h at 648 K (375 °C) in steel with 0.97 mass pct C. Light micrograph at 1500 times magnification. From Hultgren.^[19]

under high pressure. See the electron micrograph in Figure 5. He called this structure “columnar bainite.”

In a discussion of the paper by Greninger and Troiano,^[18] Vilella^[21] claimed that there is a continuous series of microstructures between 723 K and 573 K

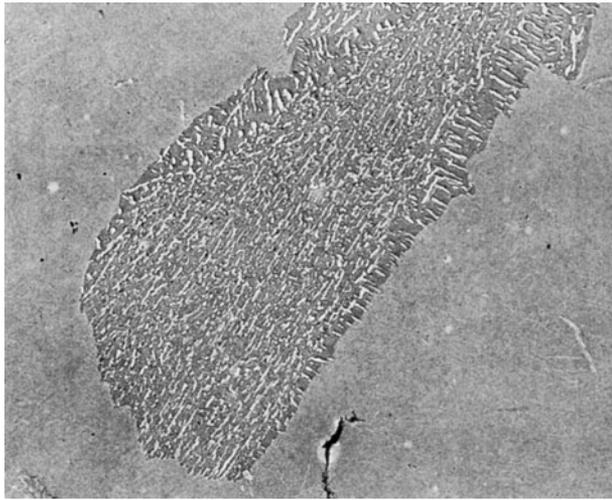


Fig. 5—"Columnar bainite" formed at 563 K (290 °C) and 30 kbar in steel with 0.82 mass pct C. Electron micrograph on plastic replica at 4000 times magnification. From Nilan.^[20]

(450 °C and 300 °C). The changes of structure with temperature in high-carbon steels have been studied in more detail with ordinary light microscopy and with electron microscopy of carbon replicas by Modin and Modin^[17] and by Spanos *et al.*^[5]

To test the idea of symmetry among the transformation products of austenite, it seemed essential to interpret the microstructures of what has been called spiky pearlite, smooth pearlite, and columnar bainite in a high-carbon steel. The current analysis was based initially on micrographs from the steel with 1.65 mass pct C presented by Modin and Modin.^[17] The study of steels with 0.95 and 1.12 mass pct C and about 2 mass pct Mn by Spanos *et al.*^[5] was also of much help. To supplement their results, a commercial steel with 1.67 mass pct C, which is similar to the one used by Modin and Modin and originating from the same time period, was employed in the current work. The steel was delivered in soft annealed condition and 1.0-mm-thick specimens were cut. The specimens were austenitized for 10 minutes at 1373 K (1100 °C) in argon, treated isothermally in a Bi-Sn melt, and quenched in brine. The specimens were polished subsequently using consecutive steps of 55, 9, and 3 μm diamond suspension and final polishing with 0.05 μm Al_2O_3 suspension. The specimens were examined in an ordinary light microscope and a field-emission gun (FEG) scanning electron microscope (SEM) LEO 1530, operating at 5 kV and with a working distance of about 5 mm. Usually, Modin and Modin used picral to etch ferrite for light microscopy and nital when electron microscopy of carbon replicas were used. They applied electrolytic etching in 10 pct chromic acid in water for etching cementite. In the current work, nital was used generally, but another etching method designed for etching carbides^[22] was used for cementite in a few cases. That will be mentioned in the related figure legends. The chemical compositions of several of the alloys referred to in this article are given in Table I.

Table I. Alloy Compositions in Mass Percent

	C	Mn	Si	Cr	Mo	Ni
Greninger <i>et al.</i> ^[18]	1.78	0.18	0.15	0.12		0.10
Oblak <i>et al.</i> ^[8]	0.69	0.85	0.70	0.85	0.81	1.80
Spanos <i>et al.</i> ^[5]	0.95	1.93	<0.01			
Spanos <i>et al.</i> ^[5]	1.12	1.82	0.003			
Hultgren ^[19]	0.97			0.91		
Speich ^[13]	1.12		0.022	3.35		
Warlimont ^[23]	1.17		0.016			4.9
Modin <i>et al.</i> ^[17]	1.65	0.24	0.01	0.48		0.01
Current work	1.67	0.22	0.27	0.47		
Okamoto and Oka ^[24]	1.80	0.01	0.05			

V. CHARACTERISTICS OF UPPER AND LOWER BAINITE

To compare microstructures formed in high-carbon steels, it is necessary first to define the various types of bainite formed at lower carbon contents. When a hypoeutectoid Fe-C alloy with a sufficiently low carbon content is austenitized and then isothermally treated just above the eutectoid temperature, *i.e.*, A_1 , most grain boundaries will be covered by allotriomorphic ferrite. However, some grain boundaries will be covered by groups of many parallel Widmanstätten plates of ferrite growing into the interior of the grains. Sometimes, a group of parallel Widmanstätten plates will develop on each side of a grain boundary and give the appearance of a fishbone. Such groups will also form below A_1 , but after some time, cementite may nucleate somewhere, most probably in contact with allotriomorphic ferrite, and the two phases may develop into pearlite. When impinging on a group of parallel Widmanstätten plates of ferrite, pearlite may grow into the interspaces between the ferrite plates if the spaces are wide enough. The final mixture of ferrite and cementite will contain ferrite of two different crystalline orientations. As the transformation temperature is decreased, the interspaces between the Widmanstätten plates of ferrite will be thinner, and it will be more difficult for the efficient cooperation between the two phases that is a necessary condition for lamellar pearlite to grow. Instead, the eutectoid reaction degenerates by the cementite growing into the spaces alone and initiating the ferrite plates to thicken. A unit of upper bainite will form, and it has only one ferrite orientation. That should be a useful supplement to the definition of bainite to avoid including the composite microstructure of Widmanstätten ferrite and pearlite. A unit of upper bainite formed in this way has a skeleton of many parallel plates of ferrite and has been described as "feathery bainite."

On other occasions, in particular at somewhat lower temperatures, single plates of ferrite may extend from grain boundaries or originate inside the austenite grains. They may gradually give rise to parallel plates, possibly by the interaction of cementite that is formed first in contact with the first plate. A sheaf of ferrite plates with rows of cementite particles marking the interspaces between previous plates of ferrite will develop. Usually,

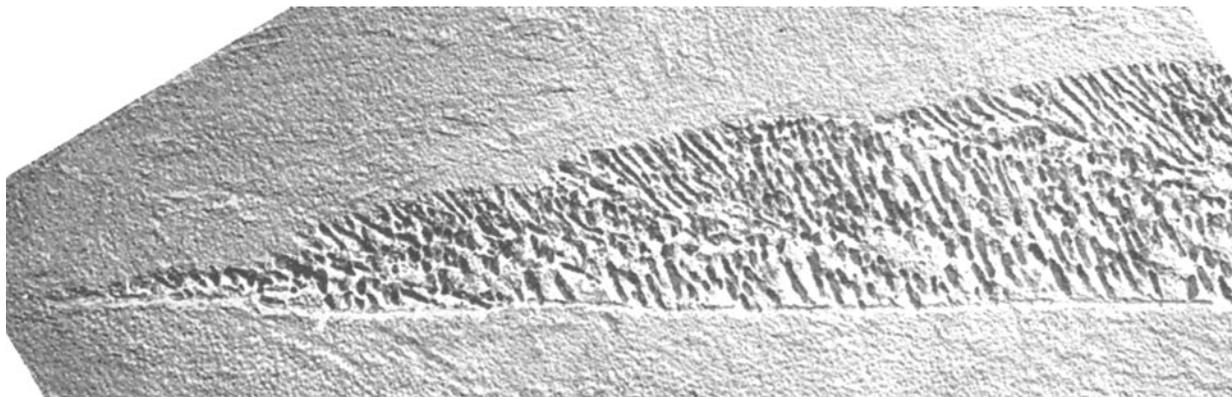


Fig. 6—Lower bainite formed at 618 K (345 °C) in alloyed steel with 0.69 mass pct C. 10,000 times magnification. From Oblak and Hehemann.^[8]

however, the number of parallel plates is limited. This microstructure is also regarded as upper bainite, and it will be referred to as “ordinary upper bainite” to be distinguished from feathery bainite. At even lower temperatures, the single plates of ferrite can cooperate with the cementite by growing together more or less perpendicular to the plate and with none of the phases being a leading phase. The side of the unit will be rather smooth, and the result is called lower bainite. Figure 6 is a reproduction of a classic example of a single unit of lower bainite from Oblak and Hehemann.^[8] At a high carbon content, this cooperation will result in a lamellar structure. At lower carbon contents, the volume fraction of cementite will be too low to form complete cementite lamellae, and they will appear as parallel platelets inside a ferritic matrix, at least in a metallographic section.^[9]

VI. CHARACTERISTICS OF INVERSE BAINITE

The purpose of the current study was to test to what extent the reactions are similar in high-carbon Fe-C alloys with cementite playing the role of ferrite. For the steel with 1.65 mass pct C, Modin and Modin^[17] reported Widmanstätten cementite and pearlite down to 823 K (550 °C), but at 773 K (500 °C), there was a drastic change. Pearlite was replaced completely by an acicular structure (Figure 7). A similar structure was studied by Kinsman and Aaronson^[3] using electron microscopy (Figure 8). It consists of parallel Widmanstätten plates of cementite and the interspaces are filled with a two-phase mixture that certainly consists of ferrite and cementite, but it does not resemble the well-organized lamellar structure of pearlite. Furthermore, when the fine two-phase mixture in a few cases has been able to grow ahead of the primary plates of cementite, it continues to grow with an acicular shape and seems to have the same favorable growth direction as the primary plates of cementite. See the arrows in Figure 8. In the current study, it was identified as a kind of inverse bainite because it grows preferentially in the direction of the primary plates of cementite.

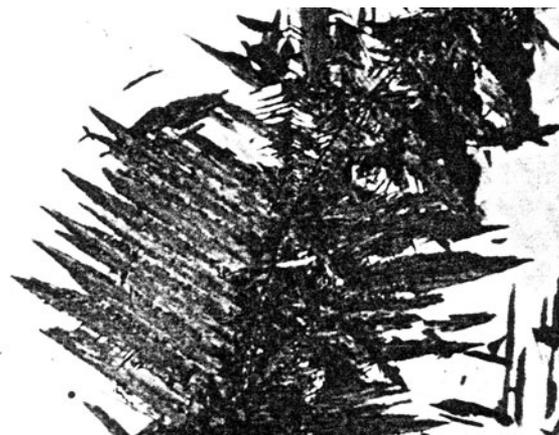


Fig. 7—“Needle-like structure” (inverse bainite) formed after 25 s at 773 K (500 °C) in steel with 1.65 mass pct C. Light micrograph at 700 times magnification. From Modin and Modin.^[17]

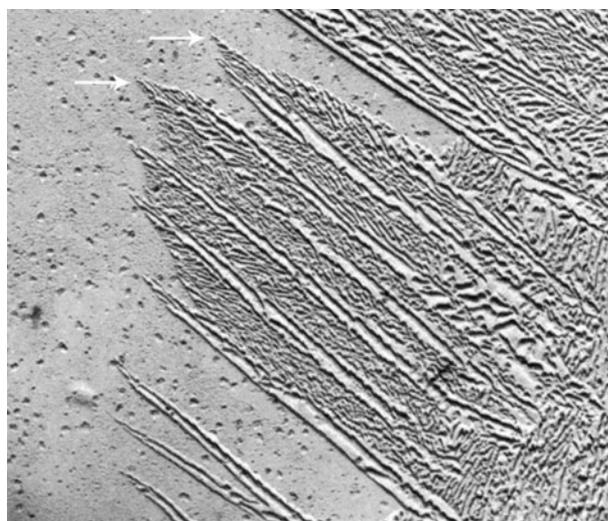


Fig. 8—Acicular eutectoid (inverse bainite) between plates of cementite, formed after 1 s at 823 K (550 °C) in steel with 1.34 mass pct C. The arrows mark inverse bainite ahead of the cementite plate. Electron micrograph on plastic replica at 12,000 times magnification. From Kinsman and Aaronson.^[3]

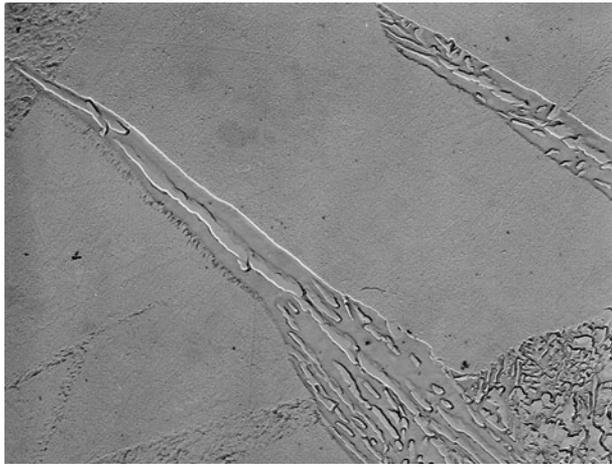


Fig. 9—Acicular eutectoid formed after 90 s at 723 K (450 °C) in steel with 1.17 mass pct C. Electron micrograph on plastic replica at 8000 times magnification. Left-hand half: Layers of ferrite are covering a Widmanstätten plate of cementite. The thicker layer at the bottom is inverse bainite. Upper right corner: Thin acicular unit of inverse bainite. From Warlimont.^[23]

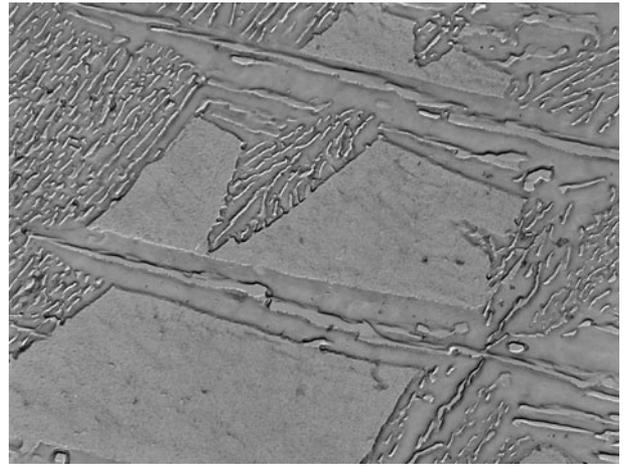


Fig. 10—Similar to Fig. 9. Unit of inverse bainite in the middle shows branching of cementite. 16,000 times magnification.

The acicular growth is again demonstrated in Figures 9 and 10, which are electron micrographs from a discussion by Warlimont^[23] and were taken on a steel with 1.17 mass pct C and 4.9 mass pct Ni at 723 K (450 °C). The left-hand half of Figure 9 shows a long primary plate of cementite that has been covered by a layer of ferrite on each side. This reaction could have resulted in a counterpart to the kind of upper bainite, originating from the fishbone arrangement of Widmanstätten ferrite, if the plates of cementite had been close enough. In the lower part of Figure 9, the layers have grown thicker and consist of the nonpearlitic two-phase mixture with cementite plates in the same main direction as the primary plate. This seems to be the initial stage for formation of the inverse bainite observed between the primary cementite plates in Figure 8. The acicular growth of this structure when it has left the primary cementite plate behind is illustrated well by the unit in the middle of Figure 10.

Provided that it is the cementite constituent of this acicular two-phase structure that has an orientation relation to austenite, it seems natural to propose that it has formed by branching of the primary plate and has inherited the favorable orientation relation to the parent austenite. The colony in the middle of Figure 10 illustrates branching and also it indicates that cementite is the leading phase at the tip. Of course, the cementite constituent in this unit does not originate from the coarse plate just above it, but in the third dimension, it is probably connected to the large colony at the upper left corner.

Figure 11 from Modin and Modin,^[17] again from 773 K (500 °C), illustrates that this acicular two-phase mixture, just as pearlite, can grow between primary plates of cementite when the interspaces are wide. Two tips of one of the acicular units are shown at a higher magnification in the insert. They are similar to the tip of the unit in the middle of Figure 10 and also give the

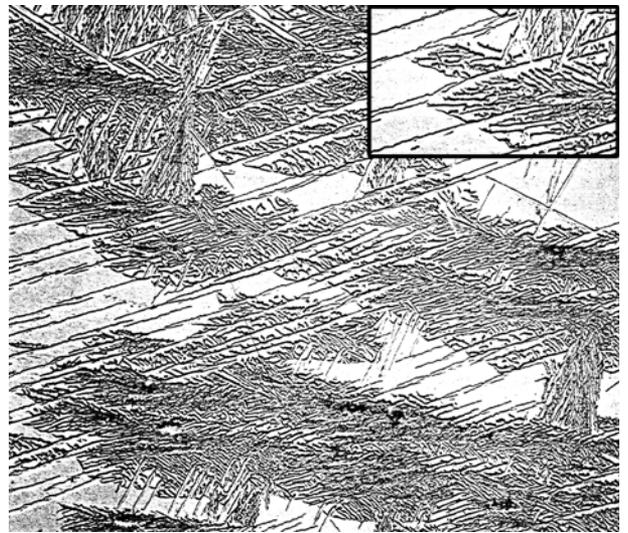


Fig. 11—Acicular units of inverse bainite growing through region with primary plates of Widmanstätten cementite. Formed after 25 s at 773 K (500 °C) in steel with 1.65 mass pct C. 3000 times magnification. Insert from same region, 5500 times magnification. From Modin and Modin.^[17]

impression that cementite is the leading phase at the tips, but one could hope for better evidence. Anyway, it is evident that the interface to austenite is smooth except for the tip, and if cementite is the leading phase at the tip, it does not lead much. It seems that the two phases behave almost as equal partners in this structure but not as in pearlite because the favored growth direction is governed by one of the constituents, cementite. It is now proposed that this kind of inverse bainite should be regarded as “ordinary inverse bainite.” The composite microstructure in Figure 8, which has formed in two steps, where the first step is simply the formation of parallel plates of Widmanstätten cementite and the interspaces have later been filled with ordinary inverse bainite, might simply be regarded as a composite microstructure.

In a laboratory alloy with 1.7 mass pct C, which is isothermally transformed at 723 K (450 °C), Hillert^[1] found an example in which the parallel plates of cementite, which originated from a grain boundary, were spaced densely and the following eutectoid reaction degenerated and resulted in pure ferrite between the cementite plates (Figure 12). The corresponding cementite precipitated evidently as an additional layer on the sides of the primary plates of cementite. That microstructure could be regarded as the counterpart of the kind of upper bainite that is sometimes called feathery bainite. It seems that this kind of inverse bainite is rare. It might be called “feathery inverse bainite” even if it has not been observed on both sides of a grain boundary.

Modin and Modin found spiky nodules at 723 K (450 °C) (Figure 13) that are similar to what Greninger and Troiano reported (Figure 3(a)). The spiky nodules are groups of acicular units similar to the ones in Figures 7 and 11 but are nucleated in the interior of an austenite grain and have different favorable growth directions, probably because each nodule contained several cementite crystals from an early stage.



Fig. 12—Inverse bainite as counterpart of feathery bainite in Fe-1.7 mass pct C after 3 s at 723 K (450 °C). Electron micrograph of plastic replica at 12,000 times magnification. From Hillert.^[1]



Fig. 13—Spiky nodules of inverse bainite formed after 60 s at 723 K (450 °C) in steel with 1.65 mass pct C. Light micrograph at 600 times magnification. From Modin and Modin.^[17]

The electron micrographs by Modin and Modin reveal that some of the sharp tips are now smoother and even blunt as in the center of Figure 14 (see short arrow). The interior structure of such units is rather fan like and seems to be the same structure as in Figure 4 by Hultgren^[19] and Figure 5 by Nilan^[20]; it may be called “fan-like inverse bainite.” Other acicular units in Figure 14 (see the longer arrow) are not as blunt but definitely are less pointed than those in Figures 8, 10, and 11.

VII. CHARACTERISTICS OF NODULES

At 673 K (400 °C), the tendency of acicular units to form in clusters is much stronger, and some clusters are as spherical as well-developed pearlite nodules close to the eutectoid temperature if not restricted by primary Widmanstätten plates of ferrite or cementite. An example from Modin and Modin^[17] is shown in Figure 15,

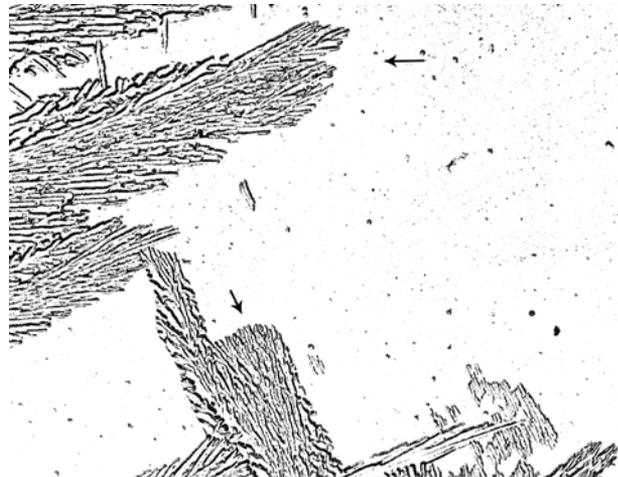


Fig. 14—Inverse bainite with a unit of fan-like eutectoid in the middle, formed after 60 s at 723 K (450 °C) in steel with 1.65 mass pct C. 9000 times magnification. From Modin and Modin.^[17]

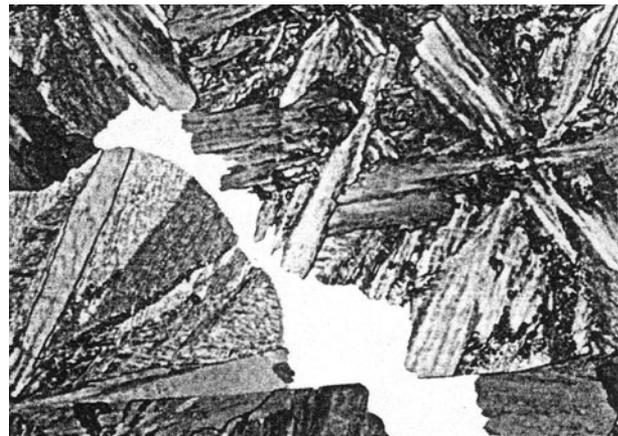


Fig. 15—Nodules of fan-like eutectoid formed after 240 s at 673 K (400 °C) in steel with 1.65 mass pct C. Light micrograph at 650 times magnification. Nodules have not been able to cross horizontal twin boundary. From Modin and Modin.^[17]

where the acicular shape is less evident. One nodule has even a spherical growth front, but the others show blunt growth fronts of individual fan-like units. Modin and Modin also found such nodules at 623 K (350 °C) (Figure 16). A reasonable explanation of this change might be that the orientation relation, which caused acicular growth, has disappeared. However, it is an important observation in Figure 15 that the growth of some nodules has stopped at a twin boundary close to and parallel with the lower side of the micrograph. That was not the only such observation. It is evident that at least one constituent in these nodules still has an orientation relation to the parent austenite grain and that it is so important that growth stopped completely when the orientation relation could not be established to the austenite lattice of the twin. Thus, it might still be justified to regard it as a kind of inverse bainite.

Of course, one may ask for subsequent indications that cementite still plays a leading role in the fan-like units and in the spherical nodules that consist of fan-like units. Figure 17 from Modin and Modin^[17] gives such

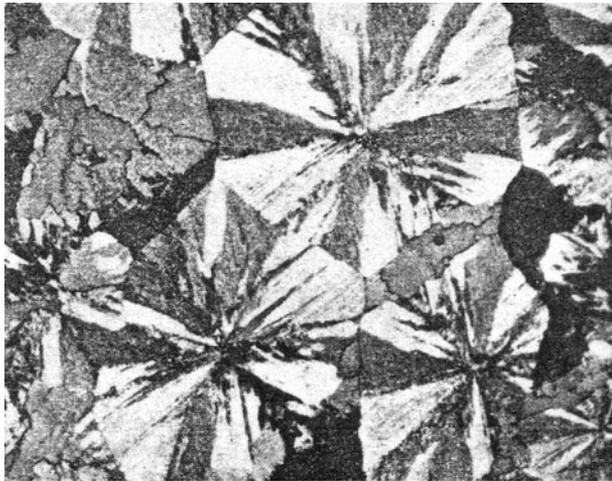


Fig. 16—Nodules of fan-like eutectoid formed after 2 h at 623 K (350 °C) in steel with 1.65 mass pct C. Light micrograph at 650 times magnification. Probably etched in nital to reveal differences in orientation of ferrite. From Modin and Modin.^[17]

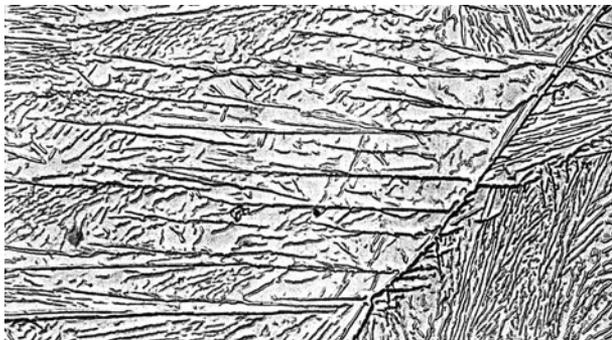


Fig. 17—Series of parallel Widmanstätten plates of cementite starting to branch. Formed after 240 s at 673 K (400 °C) in steel with 1.65 mass pct C. 4000 times magnification. From Modin and Modin.^[17]

an indication. It is an electron micrograph from 673 K (400 °C) and illustrates a strong tendency of branching of primary Widmanstätten plates of cementite originated at an austenite grain boundary. There, the plates started in the fashion normal for Widmanstätten cementite. Figure 18 from the same study illustrates that this branching has been more efficient at 623 K (350 °C), and the fan-like structure has developed there quickly from the primary plates. These observations support the proposal that cementite is still the leading phase and controls the favored growth direction and that it has developed directly from Widmanstätten cementite. However, the cementite constituent of the fan-like structure hardly could have developed without interaction with ferrite, and it seems possible that much of the branching of cementite plates has been triggered by the appearance of ferrite. In fact, it was proposed recently that the formation of the series of ferrite plates in sheaves of upper bainite, which were found inside austenite grains in low-carbon steels, is also triggered by the appearance of the second eutectoid phase, in that case cementite.^[9]

Surprisingly, these micrographs illustrate that Widmanstätten plates of cementite can form branches within a range of angles from its initial direction. It is interesting to note that already in Figure 8, there are at least two plates of Widmanstätten cementite with a slightly different direction than the majority: one close to the upper side and one close to the lower side of the micrograph. The ability of Widmanstätten cementite to change its growth direction will be further considered in the discussion.

Figure 16 demonstrates that different sectors of a nodule etch differently; this fact was noted already by Spanos *et al.*,^[5] who accounted it to the etching reagent, nital, being sensitive to the crystalline orientation of the sectioned surface of the ferrite constituent. It seems that each sector of a nodule has a single ferrite orientation, but that should not be taken as an indication that it has a particularly favorable orientation relation to the parent austenite. It is well known that a colony of pearlite has a uniform ferrite orientation as well as a uniform cementite orientation; in that case, none of



Fig. 18—Beginning of fan-like growth by branching of cementite plates. Formed after 600 s at 623 K (350 °C) in steel with 1.65 mass pct C. 4000 times magnification. From Modin and Modin.^[17]

them should have a special orientation relation to the parent austenite.^[25]

The upper half of Figure 19 shows a sector with a much coarser structure than in the rest of the nodule. In reality, it has certainly the same lamellar structure, *e.g.*, as shown in the lower part of the micrograph. The difference might be caused by the upper part being sectioned almost parallel to the planes of the lamellae. It is evident that the lamellae in each sector are almost parallel to each other; in this case, the lamellae are parallel also to the plane of the section. Whatever branching mechanism is operating, it does not result in a large change of growth direction and it does not seem to increase much within a sector. It seems that the angle between the lamellae on the two sides of a fan-like sector is rather limited. In any case, the fan-like structure has formed by edgewise growth, and if it were to be compared with bainite, it should be compared with upper bainite because it grows mainly in the favored direction of the leading phase, supposedly cementite. It should not be compared with the thickening of lower bainite where the units thicken by the two phases growing side by side and more or less perpendicular to the favored growth direction of the leading phase, ferrite, in a fashion reminding much of pearlite.^[9] This characteristic was illustrated in Figure 6.

The possibility that cementite with an orientation relation to the austenite has the dominant influence on the growth of the fan-like structure is supported by the observation that, even when a sector is growing alone, there is only a weak tendency of widening sideways. This is most evident in Figure 4 where two fan-like units have been able to retain their fan-like shape without their sideways extension being restricted by other units. Figure 5 illustrates that some thickening is possible by the formation of cementite plates in a completely new direction. However, this results in considerably slower growth, supposedly because it is a less favorable growth direction for cementite. That behavior reminds of the sideways growth of lower bainite, which is illustrated in Figure 6.

Figure 20 shows the growth front of a fan-like structure at high magnification and it indicates that

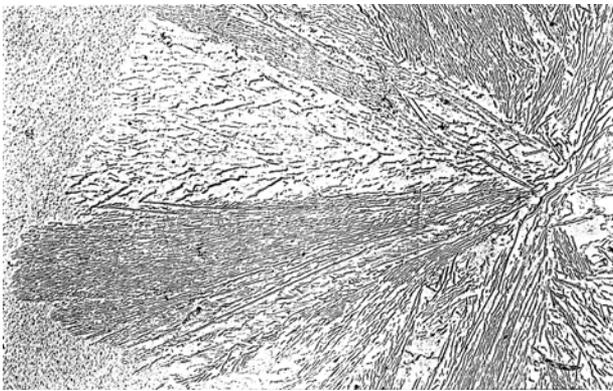


Fig. 19—Nodule with sectors of fan-like eutectoid formed after 600 s at 623 K (350 °C) in steel with 1.65 mass pct C. 5000 times magnification. From Modin and Modin.^[17]

the cementite constituent is sticking out somewhat into the parent austenite, supporting the idea that cementite is the leading phase. In view of these indications, it is concluded that cementite is the leading phase in the acicular as well as fan-like eutectoid microstructure. All these observations give strong support for the proposal to characterize the fan-like microstructure as inverse bainite, which should include nodules that consist of fan-like units. It is proposed that all such variants are called “fan-like inverse bainite.”

VIII. COMPETITION BETWEEN FERRITE AND CEMENTITE

At 573 K (300 °C), there are still several spherical nodules of the fan-like eutectoid in the interior of the austenite grains. In addition, a new phenomenon appears. The light micrograph in Figure 21 from Modin and Modin^[17] shows that the spiky nodules from the higher temperatures seem to have reappeared, but the spikes now have a somewhat triangular shape and there are arms in four main directions. Spanos *et al.*^[5]

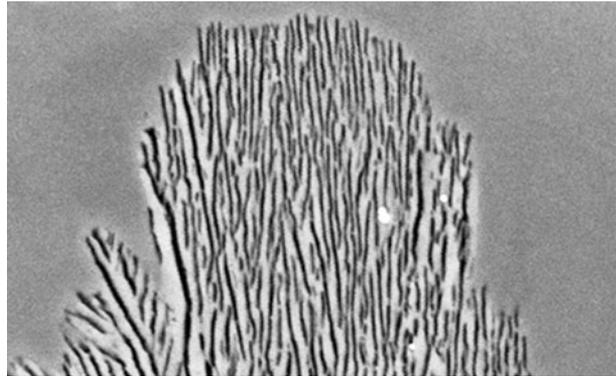


Fig. 20—Growth front of fan-like eutectoid formed after 360 s at 623 K (350 °C) in steel with 1.67 mass pct C. Etched for carbides. SEM at 24,000 times magnification.

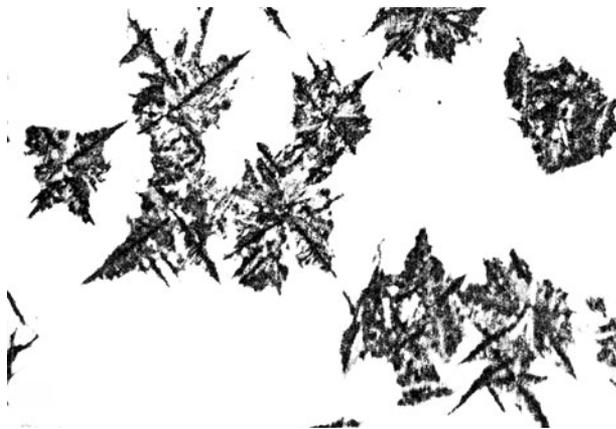


Fig. 21—Spiky nodules formed after 2 h at 573 K (300 °C) in steel with 1.65 mass pct C. Light micrograph at 550 times magnification. From Modin and Modin.^[17]

presented a similar microstructure. These spiky nodules are different from those formed at higher temperatures, such as those in Figure 13. There are still many spherical nodules, but some of them also have spikes, some of which are very small (Figure 22). The spikes might here be related to the occasional observation of plates of ferrite within the nodules, as evidenced by the long plate free of black platelets of carbide, as indicated by an arrow in Figure 23. An electron micrograph from Modin and Modin^[17] demonstrates that such plates of ferrite can protrude into the parent austenite (Figure 24).

In addition to the triangular spikes originating from nodules, such as the ones in Figure 21, there are also thin spikes that do not seem to thicken very much. The electron micrograph of Figure 25 shows two such cases. At the lower left corner, a thin plate of ferrite (light gray) is protruding far into the parent austenite, and some parallel plates of cementite (black) have nucleated on its side. This could have developed into a structure similar to Figure 23 at a later stage if not interrupted by quenching. The longer spike in Figure 25 consists of a two-phase mixture and indicates that the primary plate of ferrite has thickened by simultaneous growth with cementite. However, the cementite constituent consists of parallel platelets, and some of them are sticking out into the parent austenite although not as far as for the first case. It seems that both phases in this two-phase

mixture have a favorable orientation relation to the parent austenite.

It is now proposed that the triangular spikes in Figure 21 have formed by a primary plate of ferrite, which has later been covered by a layer of inverse bainite developed by branching from small plates of cementite. The angle of the triangular spikes in Figure 21 suggests

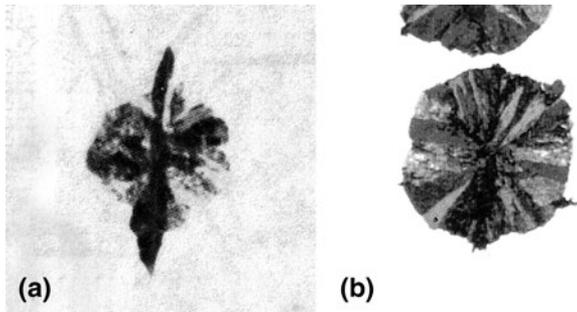


Fig. 22—Nodules of fan-like eutectoid with spikes. (a) Formed after 500 s at 623 K (350 °C) in Fe-1.12 mass pct C. Light micrograph at 900 times magnification. From Spanos *et al.*^[5] (b) Formed after 2 h at 573 K (300 °C) in steel with 1.65 mass pct C. Light micrograph at 700 times magnification. From Modin and Modin.^[17]

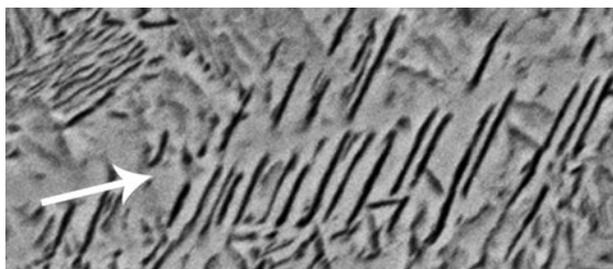


Fig. 23—Acicular eutectoid with a central plate of ferrite (white plate indicated by arrow) between two sets of parallel plates of cementite (dark). Formed after 1 h at 573 K (300 °C) in steel with 1.67 mass pct C. Etched for carbides. SEM at 22,000 times magnification.

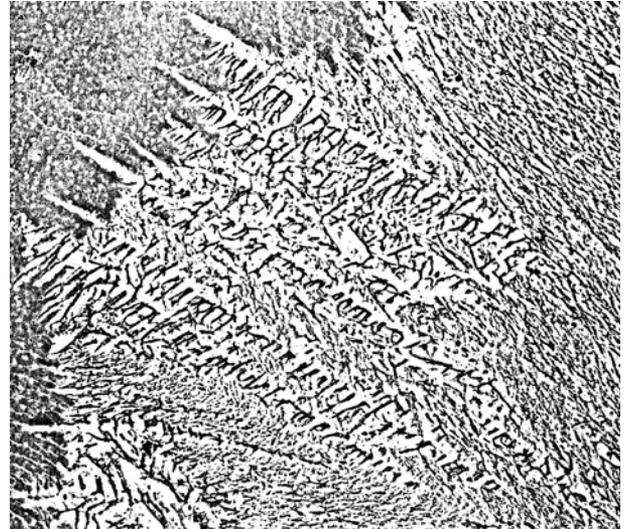


Fig. 24—Protruding plates of ferrite from a nodule of mainly fan-like eutectoid, formed after 2 h at 573 K (300 °C) in steel with 1.65 mass pct C. 7000 times magnification. Etched electrolytically with 10 pct chromic acid in water to show cementite. Electron micrograph of plastic replica at 7000 times magnification. From Modin and Modin.^[17]

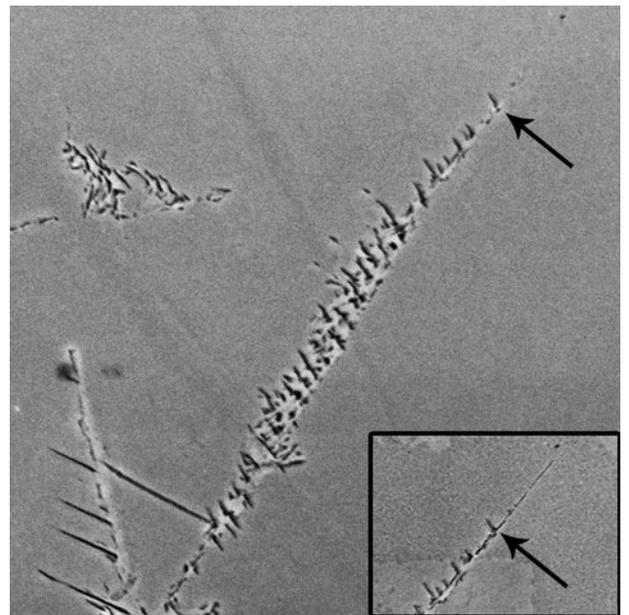


Fig. 25—Two thin spikes with a central plate of ferrite (white) and shorter plates of cementite (dark). Formed after 1 h at 573 K (300 °C) in steel with 1.67 mass pct C. Etched for carbides. Additional etching in nital was applied in the insert. Two arrows mark the same platelet of cementite. SEM at 12,000 times magnification.



Fig. 26—Spiky nodules formed after 2 h at 548 K (275 °C) in steel with 1.67 mass pct C. Light micrograph at 900 times magnification.

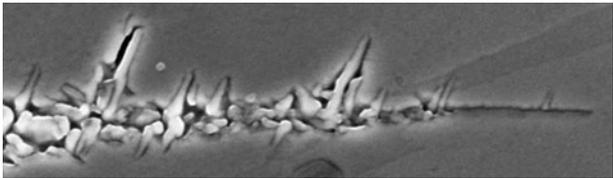


Fig. 27—Plate of ferrite with short cementite plates nucleated on the side. Formed after 2 h at 548 K (275 °C) in steel with 1.67 mass pct C. SEM at 26,000 times magnification.

that the plate of ferrite has lengthened at least twice as fast as the inverse bainite on its side has thickened.

The specimen shown in Figure 25 had been etched for carbides, which appear black in the SEM. Ferrite seems slightly whiter than the austenitic background. The specimen was then etched directly in nital without intermediate polishing, and both ferrite and cementite then appeared black. Please view the insert. It reveals a protruding plate of ferrite not shown initially, which indeed was the leading phase during the primary growth in that direction. It is very thin and is sticking out much further than indicated without the second etching. (The two arrows in Figure 25 point at the same platelet of cementite.)

The tendency of nodules to form thinner spikes increased at 548 K (275 °C) (Figure 26). The SEM micrograph in Figure 27 shows such a spike at a higher magnification. Contrary to Figure 25, the specimen was now etched in nital and ferrite appears black. The primary plate of ferrite is shown better, and the thickening, occurring by the primary ferrite being covered by small platelets of cementite (now white), is evident. One can even observe that the ferrite starts to cover a side of two platelets of cementite.

IX. LOWER BAINITE IN HIGH-CARBON STEELS

At 523 K (250 °C), the thin acicular units dominate almost completely, and in the light microscope, they look like lower bainite (Figure 28). There are hardly any massive units of the two-phase mixture. By SEM microscopy, it was confirmed that there is a primary

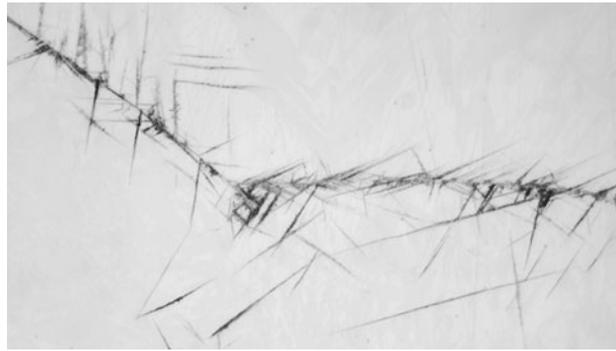


Fig. 28—Acicular precipitate formed after 4 h at 523 K (250 °C) in steel with 1.67 mass pct C. Light micrograph at 900 times magnification.

plate of ferrite that is very thin; here, they might be very long. Figure 29 gives several examples of how the thickening process is initiated by cooperation with cementite. It seems that the platelets of cementite, after being nucleated on the plate of ferrite, first grow alone into the austenite but they do not grow long. They seem to become imbedded by sideways growth of ferrite originating from the primary plate of ferrite. The units eventually seem relatively smooth when they have thickened (Figure 29(f)). The right-hand part of Figure 29(e) demonstrates that the primary plate of ferrite can no longer be discerned when the unit has thickened to a mixture of ferrite and cementite. This may be explained by ferrite being dissolved by etching and cementite at lower levels then becoming visible. Figure 27 is another example of the same phenomenon. There is no doubt that the lengthening of these units is governed by the formation of a thin plate of ferrite. In that respect, it should seem natural to regard them as bainite and even as lower bainite because they are so long and thin, and they thicken by the growth of a mixture of ferrite and cementite. However, their two-phase mixture (illustrated in Figure 29) does not resemble the two-phase mixture found in lower bainite (illustrated in Figure 6). They may simply be called “irregular lower bainite.”

Before the primary plates of ferrite start to thicken together with cementite platelets, one could expect them to be straight because, presumably, they form because of a specially favored interface to the parent austenite. However, in Figure 29, the free ferrite plates are often wavy, but that might be caused by some plastic deformation of the austenite matrix during the metallographic preparation. It should further be emphasized that the white platelets of cementite in Figure 29 often have a dark contour, *e.g.*, in Figure 29(a). This may be caused by electron shadowing or some etching effect on the austenite. On the other hand, the dark layer on the left-hand side of the longest platelet of cementite in Figure 27 looks different and was interpreted as a layer of ferrite. In several micrographs of Figure 29, it is not possible to decide what is a thin layer of ferrite or just a dark contour.

At 473 K (200 °C), the thin acicular units, which are shown for 523 K (250 °C) in Figure 29, were still

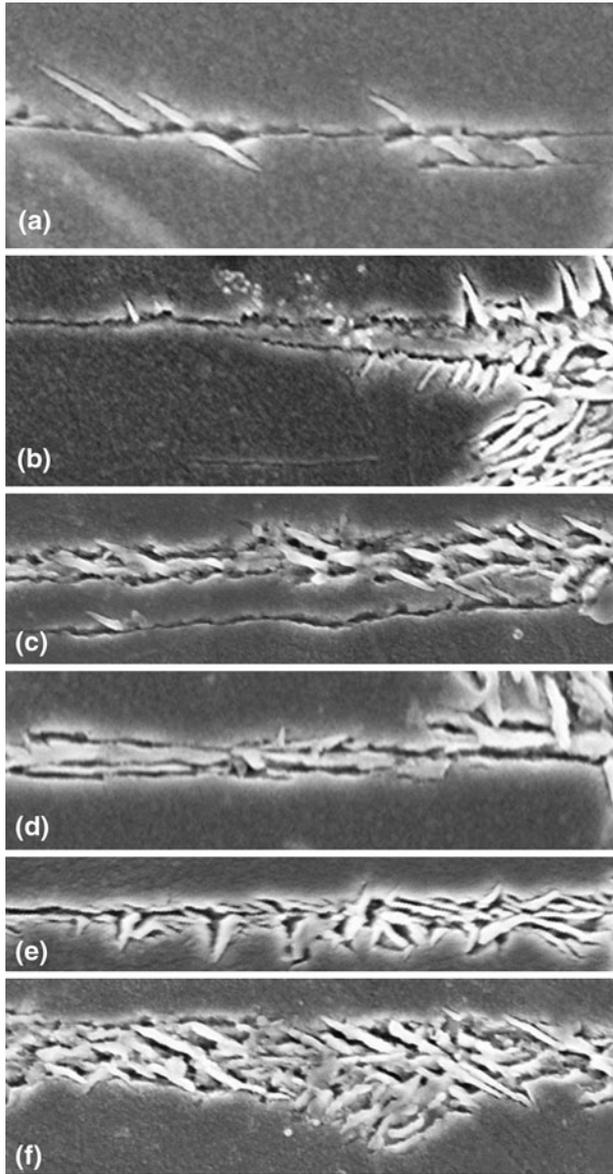


Fig. 29—Long plates of ferrite with cementite platelets nucleated on the sides, formed after 4 h at 523 K (250 °C) in steel with 1.67 mass pct C. SEM at (a,b,c,e) 22,000 times magnification. (d) 38,000 times magnification. (f) 34,000 times magnification.

present but the overall microstructure was completely different because plates resembling high-carbon martensite in a zigzag pattern predominated (Figure 30). They appear white in the SEM micrograph of Figure 31 where athermal martensite, formed on the final quenching from 473 K (200 °C), is observed as black units in the austenitic background. Black and white units have similar shapes and both occur in zigzag patterns. This phenomenon has been observed already by Oka *et al.*^[26] for a steel with 1.87 mass pct C. It is, thus, difficult to avoid the conclusion that the white isothermal product is somehow related to the black martensite. If the white product were isothermal martensite, then it should be tempered because of the long treatment of 4 days at 473 K (200 °C) and have an internal structure similar to athermal martensite tempered for the same time and

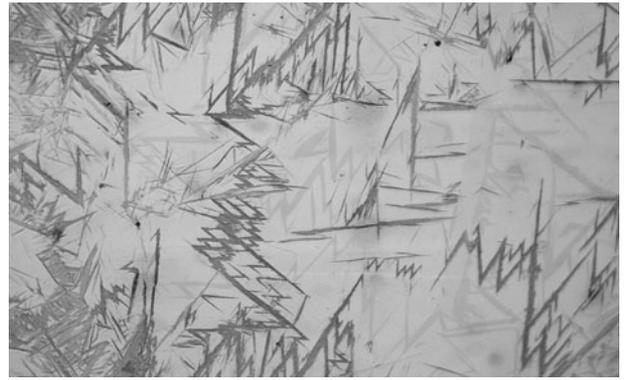


Fig. 30—Zigzag pattern and athermal martensite in the austenitic background formed after 96 h at 473 K (200 °C) and quenching of steel with 1.67 mass pct C. Light micrograph at 400 times magnification.

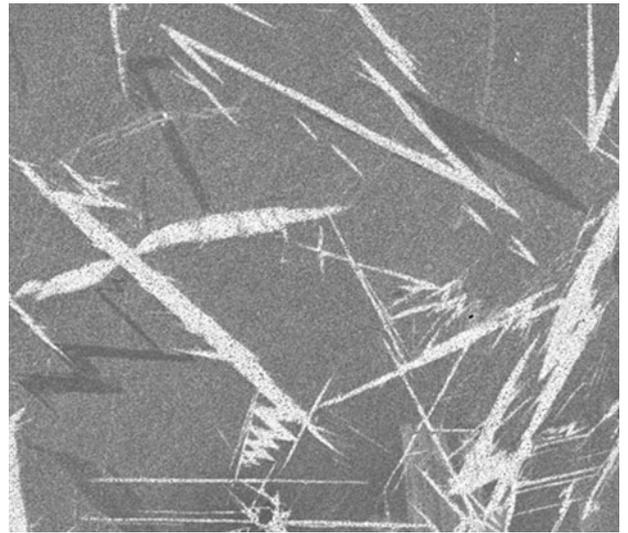


Fig. 31—Zigzag pattern and thin needles of bainite after 96 h at 473 K (200 °C) in steel with 1.65 mass pct C. Some athermal martensite (dark) is observed in the background. SEM at 1200 times magnification.

temperature. To check this, a specimen was quenched directly into brine to form some athermal martensite and then tempered for 75 hours at 473 K (200 °C). It was found that all the athermal martensite had been covered by a layer of a two-phase mixture (Figures 32(a) and (b)), which did not at all look as the tempered martensite. Okamoto and Oka^[24] made a similar experiment with a steel of 1.80 mass pct C and finished by annealing at 423 K (150 °C). They found a layer of a fine lamellar two-phase structure, which they identified as bainite. In fact, Kuteliya^[27] reported already in 1969 that, when athermal martensite in a steel with 1.6 mass pct C was annealed at 423 K (150 °C) for 100 hours, it would be surrounded by a layer of bainite. It seems safe to regard the two-phase mixtures in Figure 32(a) and (b) as bainite. They certainly did not at all look as the tempered martensite; all the two-phase mixture in Figure 32(a) and part of it in Figure 32(b) was similar to the irregular bainite in Figures 27 and 29.

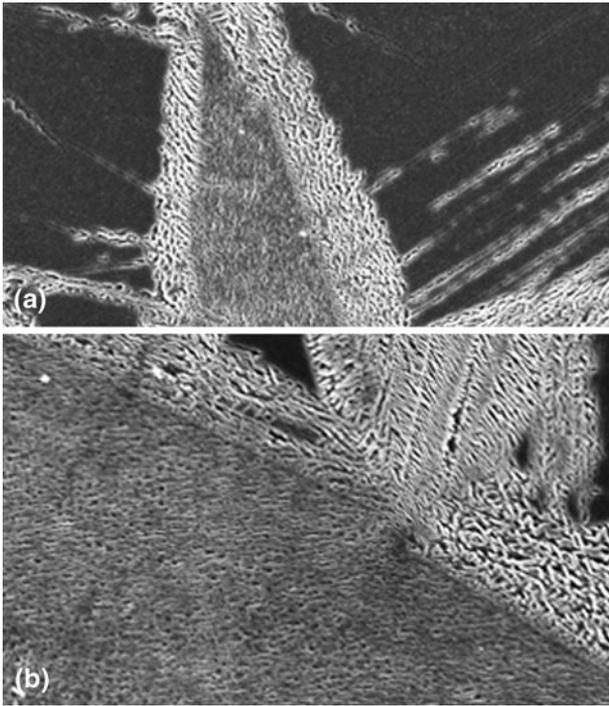


Fig. 32—Athermal martensite formed in steel with 1.67 mass pct C by quenching, then covered with layers of bainite by annealing for 75 h at 473 K (200 °C). (a) Thin black lines represent thin plates of ferrite formed during annealing. Cementite (white) has started to form on their sides. SEM at 6000 times magnification. (b). Layer with two kinds of bainite. The lower left half is tempered martensite. SEM at 8500 times magnification.

In Figure 32(b), there was also a more regular, lamellar type. It might be called lamellar, lower bainite. Some of the lamellar two-phase structure gives an impression of having a central plate of cementite (white). That part is magnified in Figure 33, and it is revealed that there is not really a central plate of cementite. Oka *et al.*^[26] have published a similar transmission electron microscopy (TEM) picture that supports the absence of a cementite midrib.

Figure 34(a) shows the internal structure of the last leg in a zigzag pattern. It also gives the impression of having a central plate of cementite (white), but again the higher magnification in Figure 34(b) does not support that interpretation. An alternative explanation could be that there was a primary plate of ferrite that is no longer visible because it has been dissolved by etching as explained in connection to Figures 27 and 29(e). Even though the plate in Figure 34 was selected for a closer study because it represented the last leg in a zigzag pattern, a close inspection seems to indicate that two short legs in zigzag positions are about to develop on the lower side of the tip. Another last leg was instead inspected and is presented in Figure 35. The hope was to view the leading phase, presumably ferrite as in Figure 27. However, this is less evident in Figure 35. The resolution is not sufficient, but it seems that there is not a long protruding plate of ferrite. Cementite appears close to the tip, and it does not show the tendency of forming small platelets. This may be taken as an

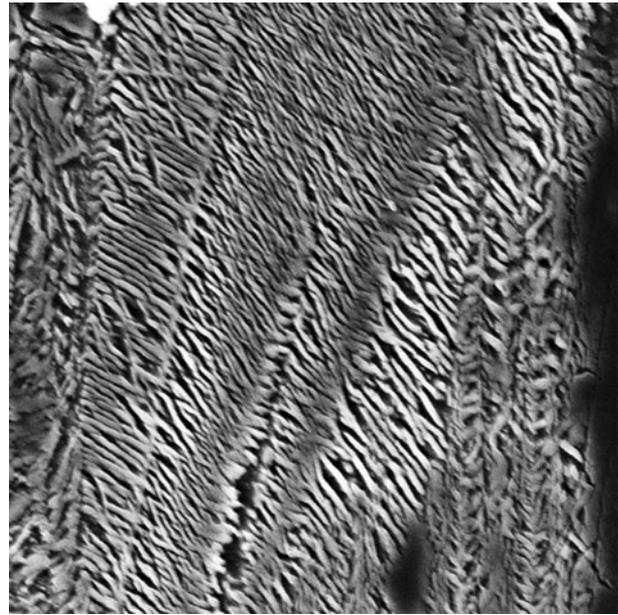


Fig. 33—Magnification of upper part of Fig. 32(b) showing bainite with a central line. SEM at 21,000 times magnification.

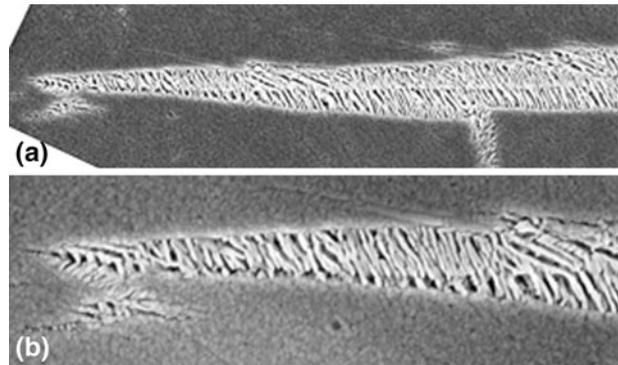


Fig. 34—(a) Lower bainite in the last leg of a zigzag pattern formed after 75 h at 473 K (200 °C) in a steel with 1.67 mass pct C. SEM at 9000 times magnification. (b) Magnification of same, showing a step in the interface to austenite. SEM at 19,000 times magnification.



Fig. 35—Last leg of a zigzag pattern formed after 96 h at 473 K (200 °C) in a steel with 1.67 mass pct C. SEM at 30,000 times magnification.

indication that the crystalline orientation of cementite in the zigzag pattern is not related favorably to the orientation of the parent austenite.

Figure 36 is from a knee in another zigzag pattern. In both legs, there is a weak indication of a central line, and they seem to meet on the line of symmetry between the two legs. It may be suggested that they represent the position of the leading edge during the formation of the

legs. For some reason, the growth direction of the leading edge was changed suddenly, and a second leg started to grow in the new direction. It is proposed that sideways growth could start just behind the leading edge of the primary plate and result in the more or less lamellar structure by cooperation with the other eutectoid phase. That structure is best shown in the lower half of the lower leg in Figure 36, probably because the lamellae are there roughly perpendicular to the polished section of the specimen. In the upper leg, the structure seems more irregular, but close to the tip of the knee, one can view the sides of a few cementite lamellae that are almost parallel to the section. It seems safe to conclude that at least most of the two-phase mixture in both legs is lamellar. Evidently, the two-phase mixture in Figures 34(a) and (b) is also lamellar, and the same holds for most of the two-phase mixtures in Figure 33. These lamellar two-phase mixtures resemble the two-phase mixture of lower bainite illustrated in Figure 6.

It is now proposed that both types of two-phase structure should be identified as lower bainite. They both differ from ordinary lower bainite, the irregular type by not being lamellar and the lamellar one by, at least often, forming with a zigzag pattern. The differences from ordinary lower bainite could be accentuated by the term “high-carbon lower bainite.” Otherwise, the terms irregular and lamellar lower bainite may be preferred.

When trying to explain the zigzag pattern, one should consider an additional observation. The lamellar structure often has straight and parallel interfaces to the parent austenite (Figures 34(a) and (b)). Even more important, the straight interfaces in Figure 36 extend all the way to the tip of the knee between the two legs in a zigzag pattern. The distance of growth from the intersections of the two central lines to the tip is roughly three times as long as the perpendicular growth distance from the central line to the interface. It is not possible to explain the straight interfaces by the lamellar growth starting at almost the same time along the whole length of the central line and occurring with the same growth rate. It is difficult to avoid the conclusion that a strong crystallographic feature acts to stabilize the straight interface and can contribute some additional driving

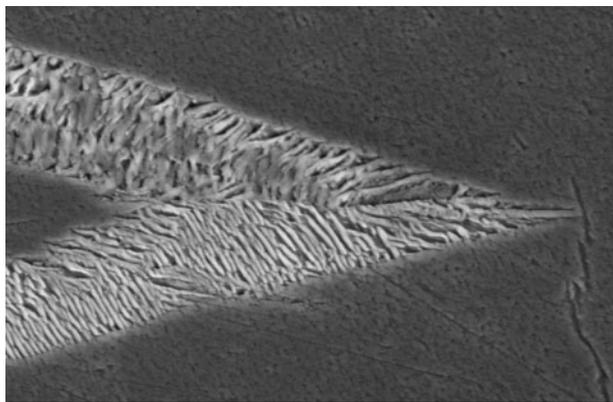


Fig. 36—A knee in a zigzag pattern formed after 96 h at 473 K (200 °C) in a steel with 1.67 mass pct C. SEM at 16,000 times magnification.

force for straightening the interface. Because it is believed that ferrite is the leading phase and because its volume fraction is much larger than of cementite, one might suspect that the decisive factor for the straight interface to austenite is related somehow to the orientation relation between ferrite and the parent austenite.

X. THIN PLATE ISOTHERMAL MARTENSITE

Modin and Modin^[17] went directly from 573 K to 473 K (300 °C to 200 °C) and observed a drastic change at 473 K (200 °C). The nodules had disappeared, both the spherical ones and the spiky ones. Instead, there were plate-like units of different thicknesses (Figure 37). Many of the thicker ones had flat and parallel interfaces to the parent austenite. In the light microscope, the thin ones resembled the thin spikes at 523 K (250 °C) in Figure 28. The thick plates resemble so-called thin-plate isothermal martensite (TIM), which has been studied in detail by Okamoto and Oka^[24,28] in their steel with 1.80 mass pct C.

Okamoto and Oka obtained TIM by austenitization followed by a long isothermal treatment at 373 K (100 °C), and it was certainly an isothermal product. After metallographic preparation at room temperature, they observed that TIM was usually surrounded by leaf-like athermal martensite, making it look much like an ordinary midrib in martensite, although it was more accentuated. Electron diffraction revealed the presence of epsilon carbide in the TIM, whereas the athermal martensite had not yet precipitated any carbides because it had not been tempered. Then they showed that athermal martensite, formed by quenching, will precipitate epsilon carbide when tempered at 423 K (150 °C). The presence of epsilon carbide in TIM could be taken as an indication that TIM is a kind of martensite formed isothermally just above the M_s temperature for the steel, which was estimated to 346 K (73 °C). However, austenitization followed by isothermal treatment at 423 K (150 °C) produced plates with a lamellar two-phase structure and with a well-developed central plate (Figure 38). Okamoto and Oka^[28] proposed that this plate of TIM had later been covered by layers of lower bainite, similar to the covering of athermal martensite

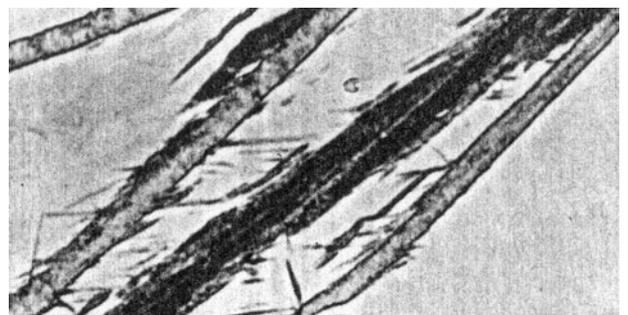


Fig. 37—Plate-like precipitations of different thicknesses formed after 72 h at 473 K (200 °C) in a steel with 1.65 mass pct C. Light micrograph at 1800 times magnification. From Modin and Modin.^[17]

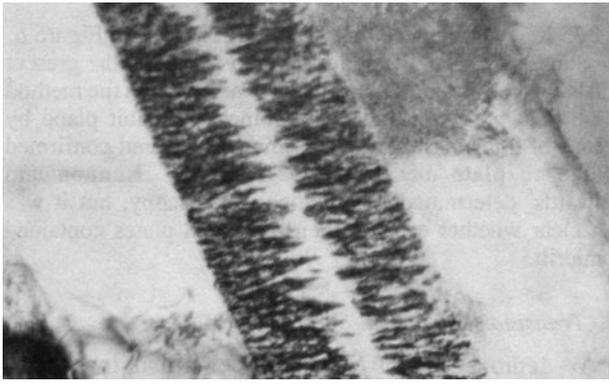


Fig. 38—Lower bainite with a central plate formed after 120 h at 423 K (150 °C) in steel with 1.80 mass pct C. TEM. Magnification not given. From Okamoto and Oka.^[24]

during tempering. The explanation why TIM was not observed in the current study may be that it forms only in a narrow range of temperature.

XI. DISCUSSION

A. Symmetry with Respect to Carbon Content

Strong indications have been presented supporting the suggestion that a counterpart of bainite can form in high-carbon steels. It has been called inverse bainite because cementite is the leading phase instead of ferrite as in bainite. There is an important symmetry among the eutectoid microstructures in Fe-C alloys with respect to the effect of carbon content. It is explained easily by accepting that all the eutectoid transformations occur under diffusion of carbon. The ratio between the supersaturations with respect to ferrite and cementite should then control whether bainite or inverse bainite is favored.

B. Competition between Bainite and Inverse Bainite

The interesting consequence of this simple approach is that it explains why bainite should be the favored transformation product at sufficiently low temperatures even if the carbon content is high. This result is understood from the asymmetry of the Fe-C phase diagram. For a eutectoid steel at 673 K (400 °C), the supersaturation with respect to cementite is about 0.6 mass pct C, but for ferrite, it is approximately 3.5 mass pct C. At lower temperatures, the difference will be even higher. Furthermore, the fact that ferrite is closer than cementite to the carbon content of the parent austenite favors the growth of ferrite because less diffusion of carbon is required. The occurrence of bainite at low temperatures in high-carbon steels and the complete absence of inverse bainite in low-carbon steels may be regarded as a break of symmetry, but it is explained without actually introducing any new transformation mechanism.

Today, it is not possible to predict the border line in the Fe-C phase diagram between the regions of bainite

and inverse bainite because it is not well known what additional driving force is required for the growth of plates of ferrite or cementite as the leading phase. According to a simple model, the growth of the leading phase can be approximated as the growth of a Widmanstätten plate. In that case, it should be sufficient to know the additional driving force required for growth of the edge when the sides of the plate are in some coherency with the parent austenite. It should also be necessary to treat the diffusion around the edge with sufficient accuracy to compare the effect of the composition difference between parent and daughter phase, which is much larger for cementite than ferrite. A first step toward increased understanding would be to determine the border line experimentally.

C. Symmetry with Respect to Temperature

As demonstrated by the current results for high-carbon steels, inverse bainite may form spiky nodules, but with decreasing temperature, the spikes turn fewer and less pronounced and become more or less spherical nodules. At even lower temperatures, spikes appear again. There is another kind of symmetry, but it is now related to temperature. Because cementite is the leading phase at the higher temperatures and ferrite at the lower temperatures, a hypothetical temperature where there are no spikes should define the border between the inverse bainite and bainite. The current work gives some indication of a point on the border, but unfortunately, the steel examined by Modin and Modin and the steel in the current experimental study both contained about 0.5 mass pct Cr.

D. Comparison with Predicted B_s

Starting from high transformation temperatures, the bainitic spikes first appeared between 623 K and 573 K (350 °C and 300 °C). It might be interesting to compare with predicted values of the bainite start temperature B_s . There are at least two methods to predict B_s . One is based on Zener's hypothesis of diffusionless growth of bainitic ferrite.^[2] Bhadeshia^[29] added an additional energy requirement of 400 J/mol. When evaluated with the thermodynamic database TCFE6,^[11] the result was 445 K and 440 K (172 °C and 167 °C) for the two steels with 1.65 and 1.67 mass pct C. This does not compare favorably with the appearing of bainitic spikes. The other method is from Hillert^[30] and is based on diffusion-controlled growth of Widmanstätten ferrite subjected to an additional energy requirement that depends on temperature. That energy requirement was revised recently,^[31] and the revised method yielded 610 K and 607 K (337 °C and 334 °C) when applied to the two steels, *i.e.*, within the experimental range of uncertainty from the appearance of bainitic spikes.

E. Lower Bainite in High-Carbon Steels

Two kinds of microstructures in the high-carbon steels have been identified as lower bainite: the irregular kind and the lamellar kind. Both are shown in

Figure 33. Early stages of the irregular kind are presented in Figure 29 and indicate that not only ferrite, which is the leading phase, but also cementite has some orientation relation to the parent austenite. This fact might explain why cementite is less able to collaborate with the ferrite to form a well-organized lamellar structure during the thickening of these bainitic units. From the current metallographic evidence, it could be proposed that cementite in the lamellar kind of lower bainite in high-carbon steels has no special orientation relation to the parent austenite and might be more closely related to lower bainite in low-carbon steels. In fact, such a conclusion is supported by the results of Oka *et al.*,^[26] who studied the orientation relations in the lamellar type of lower bainite. They found that the ferrite constituent has a K-S relation to the matrix austenite, but for the cementite constituent, they only reported an orientation relation to the ferrite. Unfortunately, they did not report on the irregular type of lower bainite.

It is interesting that the cementite lamellae in the lamellar kind of lower bainite, which are usually very parallel to each other, sometimes have a tendency to suddenly switch to another direction. An example is given to the right on the upper side of the unit in Figure 34(b) and twice in Figure 34(a). That is probably connected to small steps in the bainite/austenite interface and may be caused by a change of growth direction at the steps. On the other hand, in the lamellar bainite in Figure 33 the cementite lamellae seem to switch back and forth between two growth directions. In fact, the same phenomenon has been observed in pearlite.^[25,32] It is now proposed that this is the result of an orientation relation between cementite and ferrite that favors primarily one direction but can secondarily favor another direction if it is closer to the growth direction of the two-phase mixture.

F. Branching of Cementite Plates

One might wonder how it is possible that the cementite constituent of inverse bainite, with a favorable orientation relation to the parent austenite, can change its growth direction as much as indicated by the two-phase mixture in the middle of Figure 10. One possibility should be mentioned, although it seems less likely. Cementite is anisotropic and might have a tendency of growing as plates even without a strict orientation relation. That is illustrated in Figure 39. Figure 39(a) shows that cementite from a eutectic colony in white cast iron has been able to continue to grow into a primary dendrite arm of austenite, which is now mainly fine pearlite. However, it bends gradually during growth, and because of the application of polarized light, Figure 39(b) can illustrate that the cementite lattice rotates at the same time. It seems that the orientation relation was not perfect, but the cementite crystal has had an ability to adjust its lattice orientation during growth and, thus, change the direction of the plate-like growth. It might also be concluded that the broad face of the Widmanstätten plate of cementite is determined primarily by its own lattice and only secondarily by the lattice of the parent phase. Figure 40 shows another

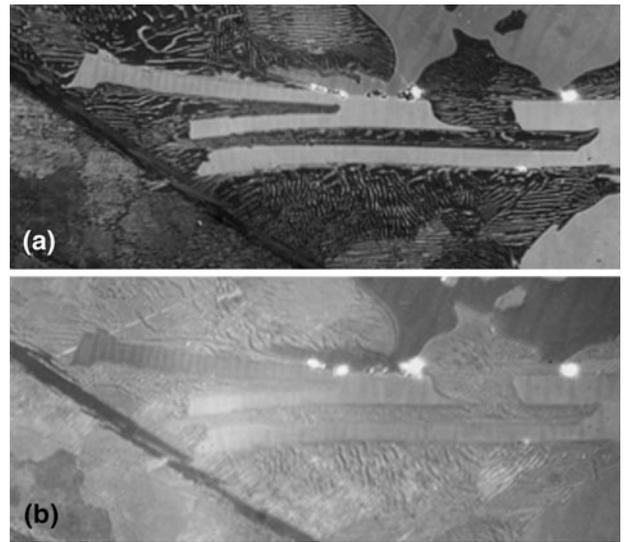


Fig. 39—(a) Widmanstätten cementite formed from ledeburitic cementite in white cast iron. Light micrograph at 1800 times magnification. (b) Same area in polarized light with crossed nichols. The banded structure reveals magnetic domains. The change of contrast reveals rotation of lattice.

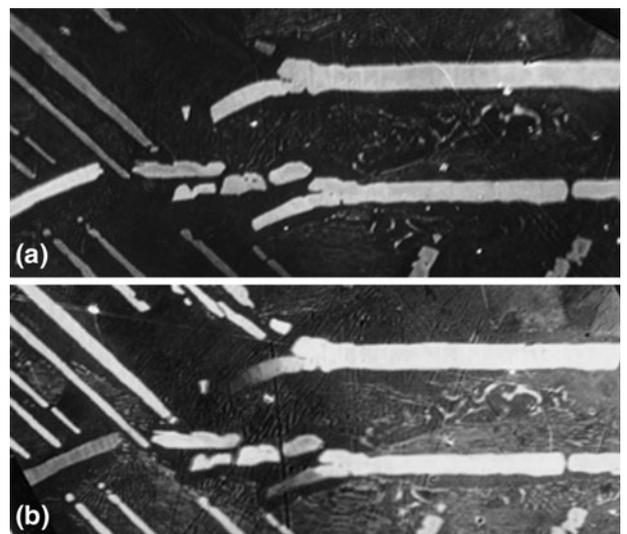


Fig. 40—(a) Widmanstätten cementite impinging on an austenite twin boundary, which was vertical and in the middle of the picture. Light micrograph at 1800 times magnification. (b) Same area in polarized light with crossed nichols. The change of contrast on the other side reveals rotation of lattice.

example in which two Widmanstätten plates of cementite have impinged on a twin boundary in the austenite. Ordinarily, one should expect a Widmanstätten plate to stop there, but in this case, the cementite plates have continued to grow into the new austenite grain, although with a slightly different growth direction. As in the previous case, its crystalline orientation was not perfect for fitting into the new austenite twin. The polarized light in Figure 40(b) reveals that cementite was again able to rotate its lattice gradually, presumably to improve the orientation relation to the new twin.

XII. SUMMARY

Widmanstätten cementite in high-carbon steels forms with a shape change and gives a surface relief just as Widmanstätten ferrite does in low-carbon steels. It is proposed that they form with the same mechanism, which must then be under diffusion of carbon.

Pearlite forms below the A_1 temperature, but in high-carbon steels, it is replaced by an acicular eutectoid at approximately 773 K (500 °C) with cementite as the leading phase. It is the counterpart of bainite in low-carbon steels and is regarded as inverse bainite. There is thus symmetry related to carbon content with the two acicular microstructures: one on each side and with pearlite in the middle, which has no leading phase.

When nucleated inside the austenite grains, the acicular units form spiky nodules. With decreasing temperature, the acicular units change to fan-like units with a flat growth front, and the spiky nodules turn spherical. At even lower temperatures, the nodules again turn spiky and the spikes form around a primary plate of ferrite. This microstructure may be regarded as a kind of bainite, although the cementite also has an orientation relation to the parent austenite. The presence of spiky nodules on both sides of spherical nodules is another kind of symmetry, which is now related to temperature.

Finally, the nodules vanish completely and the spikes develop into thin plates looking like ordinary lower bainite in the light microscope. At sufficiently low temperature they form in a zigzag pattern.

Most of the changes of microstructure of the eutectoid products in high-carbon steels with temperature are gradual and are explained by the ratio of the supersaturation with respect to ferrite or cementite increasing gradually at decreasing temperature. The role of leading phase is switched gradually from cementite to ferrite, and they behave almost as equal partners in the spherical nodules.

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