Morphology of Proeutectoid Ferrite

JIAQING YIN, MATS HILLERT, and ANNIKA BORGENSTAM

The morphology of grain boundary nucleated ferrite particles in iron alloys with 0.3 mass pct carbon has been classified according to the presence of facets. Several kinds of particles extend into both grains of austenite and have facets to both. It is proposed that they all belong to a continuous series of shapes. Ferrite plates can nucleate directly on the grain boundary but can also develop from edges on many kinds of particles. Feathery structures of parallel plates on both sides of a grain boundary can thus form. In sections, parallel to their main growth direction, plates have been seen to extend the whole way from the nucleation site at the grain boundary and to the growth front. This happens in the whole temperature range studied from 973 K to 673 K (700 °C to 400 °C). The plates thus grow continuously and not by subunits stopping at limited length and continuing the growth by new ones nucleating. Sometimes, the plates have ridges and in oblique sections they could be mistaken for the start of new plates. No morphological signs were observed indicating a transition between Widmanstätten ferrite and bainitic ferrite. It is proposed that there is only one kind of acicular ferrite.

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I. INTRODUCTION

THE morphology of proeutectoid ferrite in steels has attracted much attention ever since Sorby[1] first examined a polished and etched section of a steel specimen almost one and a half century ago. Dubé[2] devised a framework for classifying various shapes. A slightly modified system was then published by Aaronson[3] at the 1960 Conference on The Decomposition of Austenite by Diffusional Processes and recently by Kral.[4] At the same conference Hillert[5] presented another system for classifying shapes of grain boundary nucleated particles, two of which had facets to both grains. See Figures 1 and 2. Dubé's system, as modified by Aaronson, has been widely accepted and in a recent volume on Phase Transformations in Steels[6] there were no less than eight citations. However, they only concern the two-dimensional shapes observed in the plane of polish. In recent years, there have been several reports on the 3D shapes of ferrite particles[7–9] that have yielded valuable information by serial sectioning.

The first detailed study of the orientation relationships between grain boundary nucleated particles of ferrite and the austenite grains was carried out by King and Bell[10] using electron diffraction. In recent years, there have been several studies using laser-scanning confocal microscopy (LSCM)[11,12] and electron back scattering diffraction (EBSD).[13–16] The modern techniques have open up new possibilities for efficient studies of crystallographic aspects of various phase interfaces with ferrite particles and also the role of the orientation relationship between two austenite grains and the direction of their grain boundary on the selection of particle shapes. However, a purpose of the present work was to provide a more thorough analysis of the 2D shapes of grain boundary nucleated ferrite particles to be used as a basis for studies with modern techniques.

In early studies of particle shapes, there was a practical limit caused by the resolution of light optical microscopy (LOM). To facilitate the comparison with old observations and classification systems based thereon, it was decided again to use LOM as the main tool also for the present study of particle shapes at 973 K (700 °C). scanning electron microscopy (SEM) was adopted when the study was extended to lower temperatures. It is interesting to note that also in recent 3D studies with SEM one has often presented the 2D microstructure with LOM.

A second purpose of the present work was to study the role of various particle shapes in the development of a particular microstructure of upper bainite, called feathery bainite.[17] A third purpose was to study the role of nucleation of new ferrite particles in the growth of feathery bainite and sheaves.[18] Finally, a purpose was to study the relation between Widmanstätten ferrite and bainitic ferrite.

II. PREVIOUS CLASSIFICATION SYSTEMS

It is evident from Figures 1 and 2 that facets on ferrite particles play a decisive role in the classification of the shapes. They might originate from the nucleation stage, where low interfacial energy is important, and are then preserved during growth, partly for kinetic reasons. The most well-known faceted precipitate is the Widmanstätten plate that forms in most cases of precipitation from supersaturated solid solutions. In

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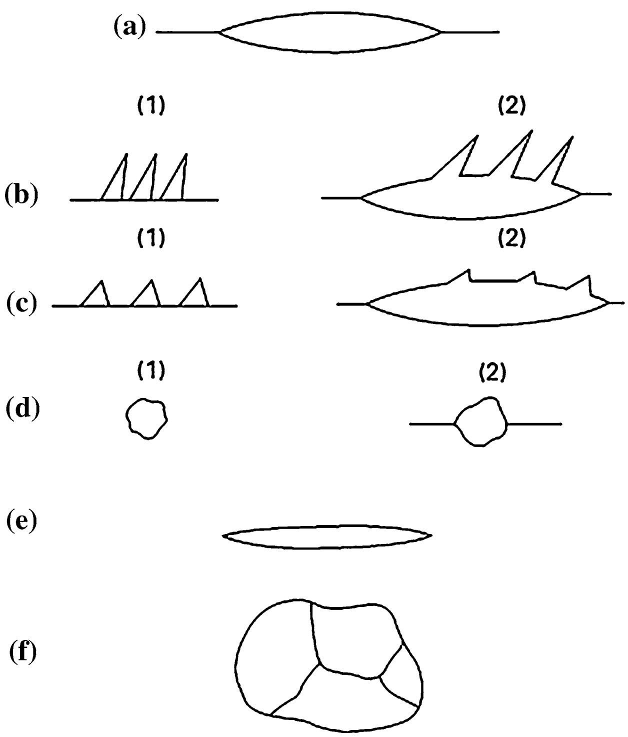

Fig. 1—The Dubé classification system modified by Aaronson[3] and Kral.[4] Reprinted from Ref. [4].

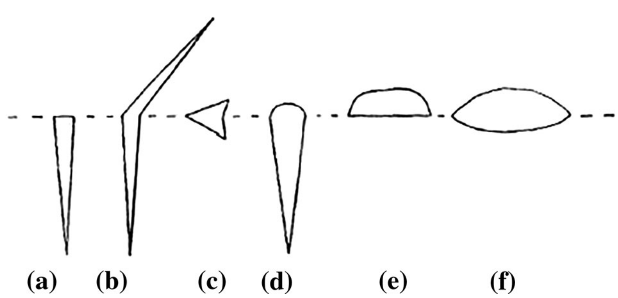

Fig. 2—Hillert's shapes of particles.[5] Reprinted from Ref. [5].

Fe-C alloys, they may nucleate intragranularly, *e.g.*, on non-metallic inclusions or on grain boundaries. However, nucleation on grain boundaries is predominant in the precipitation of ferrite from austenite in Fe-C alloys. It is thus possible to study the development of grain boundary nucleated ferrite without interference from intragranular Widmanstätten plates. The reason is that the driving force for nucleation is relatively small if the difference in composition between the phases is small[19] and it is small for allotropic transformations where it starts as zero for the pure element. It is thus essential that nucleation can be stimulated by the interfacial energy of grain boundaries. Smith[20] discussed this role of a grain boundary and started with the case of a lens-shaped particle on a grain boundary which was incoherent to both grains. That shape was included as case (a) in Figure 1 and case (f) in Figure 2. Aaronson[3] used the name grain boundary allotriomorph. However, Smith then explained that a particle of ferrite, nucleated at a grain boundary, should have a favorable orientation relationship to one of the austenite grains, which would be the decisive factor behind the nucleation due to low interfacial energy. On the other hand, that interface would be partially coherent and have low mobility in addition to low energy. Smith suggested that the nucleus would thus develop into the other grain to which it has a mobile, incoherent interface. Using electron diffraction and an alloy with 20 mass pct Fe in Co, for which austenite is retained at room temperature, Ryder *et al.*[21] 20 years later confirmed Smith's suggestion of orientation relationship for ferrite particles in austenite.

Hillert[22,23] observed particles, which to one grain had a rather flat interface coinciding with the prior grain boundary, Figure 3. He explained the shape with Smith's suggestion and included this shape as case (e) in Figure 2. It is now proposed that case (e) in Figure 2 should be called smithiomorph to honor Smith for his pioneering work on shapes of grains and precipitates. It seems probable that Aaronson[3] regarded smithiomorphs as grain boundary allotriomorphs because he reproduced a micrograph (Figure 44 in Reference 3) but did not include it in his classification system. Today it is common to regard all particles, elongated along a grain boundary, as allotriomorphs. However, the presence of facets in particles of various shapes will be emphasized in the present study. Facets will actually play the key role in the new classification scheme to be proposed. In the discussion, it will be assumed that a facet reveals that the interface has some coherent character, which is accepted as a sign of some kind of orientation relationship. The term allotriomorph will thus be reserved for grain boundary films without facets and, presumably, without any special orientation relationship to the austenite grains.

In Figure 3, there are two smithiomorphs and they seem to have stopped advancing along the grain boundary when they met. This could be a coincidence but could also be due to a resistance to form a high-energy interface between the two ferrite particles compared to the presumed low energy of the facets to the austenite grains. One may wonder about the probability that an austenite grain happens to have a special atomic plane exactly coinciding with the grain boundary and thus allowing a ferrite particle to form a low-energy interface. However, a clue was found when Hillert[23] observed two smithiomorphs joined by a thin and curved film of ferrite which most probably formed on the connecting grain boundary during the final quench, Figure 4. It is proposed that the two smithiomorphs have grown simultaneously along the grain boundary and perpendicular to the plane of polish. However, it seems that the favorable crystallographic plane of each austenite grain was not quite parallel to the initial grain boundary. In order to retain the low-energy interface to their respective austenite neighbor, they forced the grain boundary to move but in different directions and the short piece of grain boundary between them, which is now covered with a thin

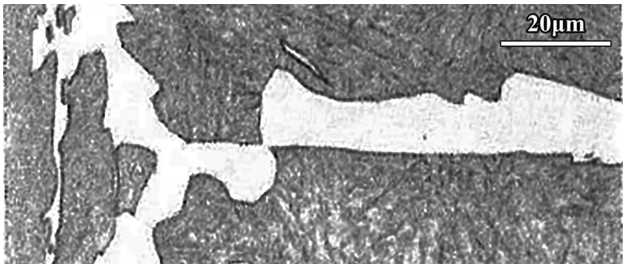

Fig. 3—Two smithiomorphs from Fe-0.56 mass pct C after 20 minutes at 983 K (710 °C). Apparently, they stopped advancing along the grain boundary when they met. Reprinted from Ref. [22].

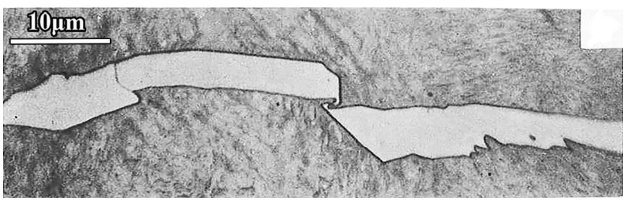

Fig. 4—Two smithiomorphs that may have grown simultaneously and perpendicular to the plane of polish. By retaining a low-energy facet to the opposite grain, each one has forced the grain boundary to move but in different directions. The remaining grain boundary between them is revealed through a fine film of ferrite formed during the quench. Reprinted from Ref. [23].

grain boundary film of ferrite between them, became much curved. The probability that a grain of austenite has a favorable plane within some range of angle to the grain boundary may not be negligible. In addition, there may be several crystalline planes in the austenite lattice that are suitable for a partially coherent interface to ferrite.

It has further been proposed[24] that all shapes with facets, caused by some influence from two phases, should be regarded as dimorphic since their shapes have been affected by the properties of both phases, whereas the shapes of idiomorphs reflect properties of the precipitated phase itself. The latter case is common for precipitates from a gas, liquid, or amorphous phase, which are not crystallized. In a solid matrix, it is very rare that a precipitated particle with a characteristic shape has not been affected by the matrix phase. Most precipitates with at least one facet, which have precipitated inside a solid phase, are thus dimorphic.

Some shapes are characterized by two facets. For a Widmanstätten plate, they are the broad faces which should ideally be parallel. When a plate starts from a grain boundary, Aaronson called it a Widmanstätten sideplate to distinguish it from intragranular Widmanstätten plates. It is interesting that cases (b1) in Figure 1 and (a) in Figure 2 depict a plate with a tip and an angle between the broad faces. With cases (a) and (d) Hillert illustrated that the angle can vary. The presence of an angle is in contrast to the usual description of Widmanstätten plates with two parallel broad faces. It

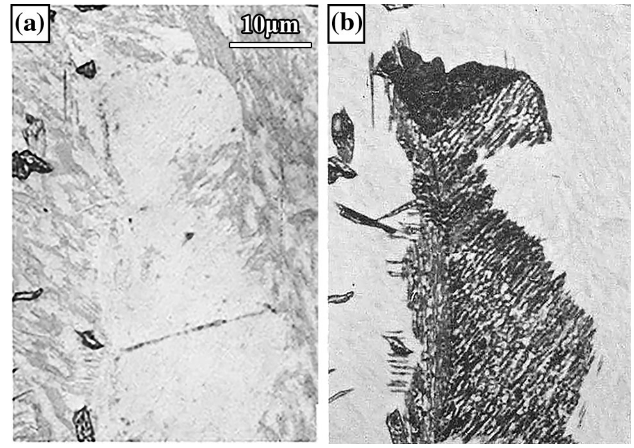

Fig. 5—Bainite in two grains and pearlite in the third. Formed under 6 seconds at 716 K (443 °C) in steel with 0.6 mass pct C. (*a*) is etched in nital, (*b*) is etched in picral. All three are parts of the same crystal of ferrite. Reprinted from Ref. [5].

rather seems that ferrite plates in Fe-C alloys can develop facets with a considerable degree of freedom.

With case (b2) in Figure 1, Aaronson illustrated Widmanstätten plates that are separated from the grain boundary by an allotriomorph. He called them secondary sideplates and suggested that they are outgrowths from the allotriomorph, *i.e.*, part of the same crystal. He also proposed that a new crystal can form by sympathetic nucleation and develop as a secondary sideplate on the periphery of the allotriomorph and of the same crystalline orientation as the allotriomorph. This shape was not included by Hillert in Figure 2.

On the other hand, Hillert[5] observed that the ferritic constituent of bainite can have the same orientation in two neighboring grains of austenite, which presumably implies that a grain boundary nucleated particles of ferrite can develop as plates into both grains, Figure 5. The specimen was etched in nital, Figure 5(a), and it is known that the attack on $(100)_\alpha$ faces is much weaker than on other faces. It is evident in Figure 5(a) that the ferritic constituent of bainite on two sides of a grain boundary was close to that orientation and this also holds for the ferritic constituent of pearlite in the third grain. Particles that have actually developed as plates in both grains were observed after low degree of transformation, Figure 6.[23] Hillert included this shape as case (b) in Figure 2. It is now proposed that such a particle will be called chevron.

Figure 6 also includes rather equiaxed particles bounded by facets. Aaronson described them as Widmanstätten sawteeth and included them as fairly regular triangles in case (c1) in Figure 1 with the third side of the triangle coinciding with the grain boundary. However, Hillert with case (c) in Figure 2 illustrated that such a particle can develop two facets into both grains. In addition, Aaronson included equiaxed particles that he called idiomorphs although they had no facets.

It should finally be mentioned that Goodenow and Hehemann[25] suggested that a plate of bainitic ferrite

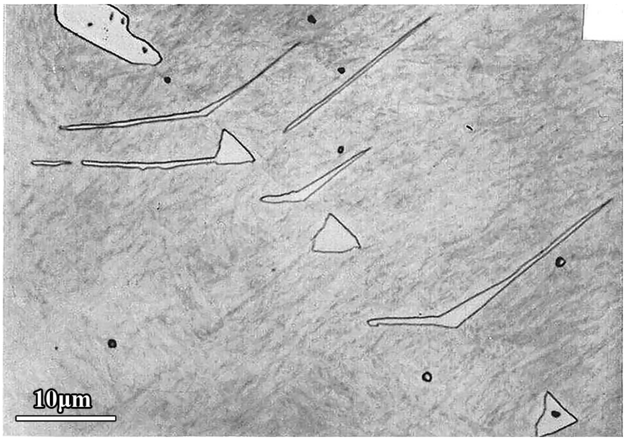

Fig. 6—Ferrite particles formed at a low-energy grain boundary after a short isothermal heat treatment of a hypoeutectoid steel. Both sawteeth and chevrons have formed. Reprinted from Ref. [23].

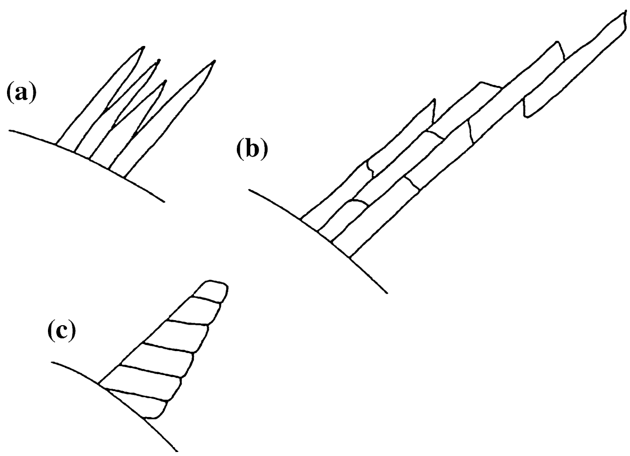

Fig. 7—Shapes of ferrite crystals according to Oblak and Hehemann.[26] (*a*) Widmanstätten plates, (*b*) subgrains in upper bainite, (*c*) subunits in lower bainite. Reprinted from Ref. [26].

only grows to a limited length but then stimulates the nucleation of a new parallel plate that carries the growth further, so-called subunits. Oblak and Hehemann[26] illustrated this with case (b) in a series of sketches for three temperature levels. It is here reproduced as Figure 7 and the role of subunits is illustrated in Figure 7(b).

III. EXPERIMENTAL

To avoid complications that could be caused by special effects of alloying elements, it was first decided to study the morphology of proeutectoid ferrite in a Fe-C alloy. To have access to a large range of temperature, one should limit the competition from pearlite by selecting a low carbon content, which increases the growth rate of ferrite. On the other hand, to limit the competition from martensite one should decrease the M_S temperature by selecting a high carbon content. As a compromise, it was decided to use 0.3 mass pct carbon. In addition, it was then decided to add 0.5 mass pct silicon in order to extend the study of undisturbed development of ferrite by delaying the formation of cementite. Silicon is a ferrite stabilizer and it was not expected to have much effect on the formation of ferrite. The composition and characteristic temperatures of the alloy are given in Table I. The A_3 temperatures for full equilibrium and for para-equilibrium[27] were calculated using the Thermo-Calc software with the TCFE7 database.[28] A single micrograph was included from a similar alloy with a further addition of 0.5 mass pct Mn. Specimens with a thickness of 2 mm and a size of 15 × 8 mm were austenitized at 1473 K (1200 °C) for 2 hours with protective argon atmosphere and manually transferred to a Bi-Sn melt at temperatures ranging from 1023 K to 473 K (750 °C to 200 °C) and finally quenched in iced brine. All specimens were mechanically polished with 0.05 μm alumina suspension in the final step. They were etched in 2 pct picral for light optical microscopy, LOM, which was the main method at 973 K (700 °C) in order to make direct comparisons with published micrographs from the classical works on morphology easier. Nital and Vilella's reagents were used for SEM studies, which were carried out at lower temperatures with a field emission gun-scanning electron microscope (FEG-SEM) JEOL JSM-7800F (Japan Electron Optics Laboratory Ltd., Tokyo, Japan), operated at 15 kV and with a working distance of approximately 7 mm.

In preliminary experiments with isothermal transformation, it was found that the rapid transformations in the present alloys caused difficulties. For the highest holding temperatures, it was difficult to avoid that some transformation also occurred during the quench because the rate of transformation was increasing at lower temperatures. This effect may also be noticed in some of Aaronson's micrographs[3] and was even taken advantage of by Hillert.[5] For lower holding temperatures, the rate of transformation may be higher during the cooling down to the holding temperature and the transformation started before the holding temperature was reached.

The formation of ferrite was increasingly rapid below the eutectoid temperature, 1000 K (727 °C), and with the shortest possible holding time of about 1 second it was just possible to catch early shapes of ferrite particles at 973 K (700 °C) but not below. The study of small particles was thus performed at that temperature. It was limited to shapes of particles formed in contact with grain boundaries because at short times there was no intragranular ferrite until much lower temperatures. With two exceptions, all the micrographs were taken on the alloy described in Table I. The exceptions will be mentioned in the figure captions.

IV. MORPHOLOGICAL OBSERVATIONS

A. *Grain Boundary Films*

Aaronson[3] described the first particle in Figure 1 as grain boundary allotriomorph, which seems adequate

Table I. Chemical Composition (Mass Percent) of Alloy and Calculated A_3 for Full Equilibrium and Para-Equilibrium by Thermo-Calc with TCFE7 Database[28]

Fe	C	Si	Mn	A_3, full equilibrium	A_3, para-equilibrium
99.10	0.28	0.52	0.06	1108 K (835 °C)	1102 K (829 °C)

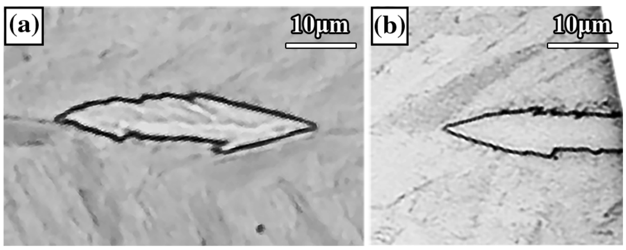

Fig. 8—Grain boundary allotriomorph after 2 s at 973 K (700 °C).

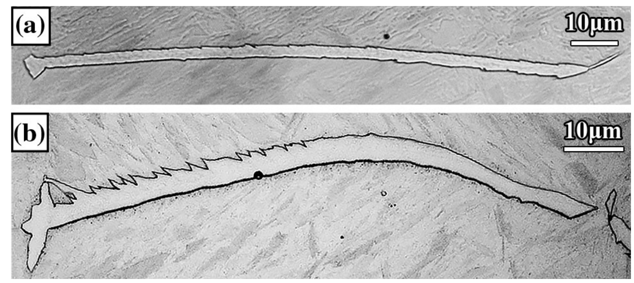

Fig. 9—Grain boundary films of ferrite at 973 K (700 °C), (*a*) after 1.5 s, (*b*) after 2 s. (a) is classified as a grain boundary allotriomorph. The nature of (b) is less certain but it is proposed that spikes could not develop on the right-hand part because they would be parallel to the grain boundary.

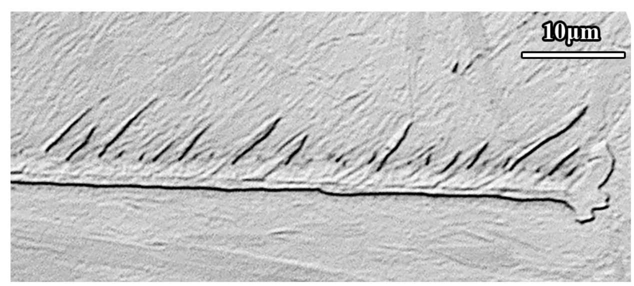

Fig. 10—Grain boundary film formed after 2 s at 973 K (700 °C). It shows a ghost line indicating the position of the prior grain boundary. The plates have started from the grain boundary and part of their interspaces was later transformed by thickening of the plates. The thin layer below the ghost line formed by sideways growth.

because and with that name its shape should not be affected by any anisotropic surface properties of its own. The particle should not have any special orientation relation to the austenite grains. It should thus be symmetric with respect to the grain boundary and it was depicted with two spherical caps as interfaces, probably by inspiration from the equilibrium shape of grain boundary particles with incoherent interfaces to the parent phase. The symmetric particle in Figure 8(a) was observed in the present study and it is elongated due to growth along the grain boundary. Evidently, as soon as an allotriomorph has started to grow along the grain boundary, it could not be expected to show spherical caps. Instead, the symmetric shape was taken as an indication that a particle has no special orientation relationship to any of the two austenite grains and it was thus identified as a grain boundary allotriomorph although it should ideally have had smoother interfaces. Figure 8(b) shows the end of a similar but longer particle. On further growth, these particles may be expected to form grain boundary films extending over the whole grain boundary as illustrated by the film in Figure 9(a) which was identified as a grain boundary allotriomorph on the two criteria that the broad faces were comparatively smooth and there was a ghost line indicating that the prior grain boundary (not visible in the reproduced micrograph) is situated close to the middle of the film. It is also interesting that one of the ends of the film in Figure 9(a) has the same shape as the ends of the particles shown in Figure 8. It should be emphasized that this film, extending over the whole length of a grain boundary, indicates that the growth rate along the grain boundary is more than an order of magnitude higher than for thickening.

On the other hand, the grain boundary film in Figure 9(b), which looks uniform for a considerable length, changed behavior when the growth direction changed for the left-hand part, due to the changed direction of the grain boundary. Then many small spikes developed roughly parallel to the initial growth direction, which may explain why they did not develop in the first part of the film. There seems to be some special orientation relationship to the upper austenite grain but the nature of this grain boundary film could not be decided.

Figure 10 shows a similar grain boundary film but here the spikes are more well developed and make a larger angle to the grain boundary. In addition, there is a long ghost line that might indicate the position of the prior grain boundary. In this case, the grain boundary has thickened into both grains but most on the side of spikes. Due to an internal structure, the origin of some spikes can be traced back to the ghost line indicating that they started to form on or very close to the prior grain boundary and that may then hold for all the spikes. It thus seems likely that the spikes nucleated in contact with the grain boundary and primarily it may not have been a grain boundary film but closely spaced spikes. Smithiomorphs are easier to identify, especially when they appear as neighbors as in Figure 11, which shows three typical smithiomorphs.

Spanos and Hall[29] have discussed possible mechanisms for the formation of secondary sideplates of

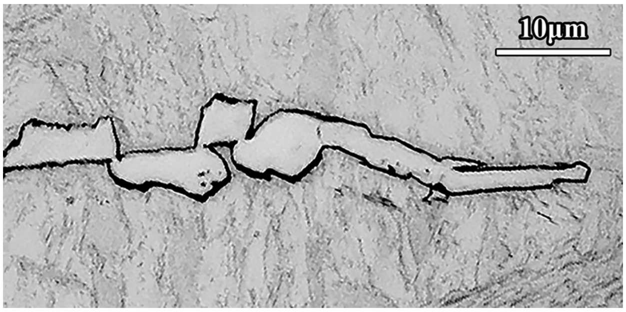

Fig. 11—Some small smithiomorphs formed after 2 s at 973 K (700 °C).

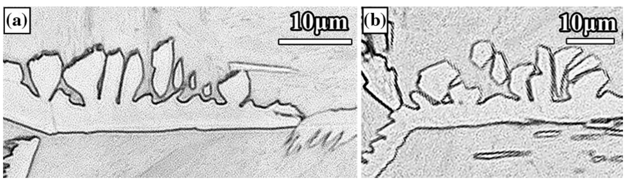

Fig. 12—Rare shape found after 2 s at 973 K (700 °C), probably the beginning of dendritic growth into a grain boundary situated just outside the plane of polish.

ferrite. Their first case was based on instability-driven formation from an allotriomorph. They presented a sketch and also a TEM micrograph, which was "the only one example ever found" in hundreds of fields of view. Figures 12(a) and (b) show similar cases but much coarser, which may be due to a higher temperature, 973 instead of 823 K (700 instead of 550 °C). As an alternative explanation, it is now proposed that the micrographs illustrate the beginning of two-dimensional dendritic growth along a grain boundary situated just below or above the plane of polish. However, it should be mentioned that Kral[4] in a review stated that ferrite does not grow in a dendritic fashion along austenite grain boundaries, whereas cementite does.

B. *Grain Boundary Nucleated Particles*

In striking contrast to long grain boundary films, there are grain boundaries with many ferrite particles isolated from each other. The sawteeth in (c1) of Figure 1 with two facets and an angle of about 60 deg illustrate an extreme case. Transitions to Aaronson's primary sideplates with a sharper top in (b1) were also observed in the present study, Figures 13 and 14. Figure 14(c) illustrates that the sawteeth can be far from perpendicular to the grain boundary. One can ask whether the base line of a sawtooth, which coincides with the grain boundary, is actually yet another facet in a crystallographic sense, similar to the facets of the smithiomorphs in Figure 4, which could deviate with a small angle from the direction of the prior grain boundary. This is confirmed by several micrographs, in particular by Figure 14(a), which demonstrates that the base lines of neighboring sawteeth are parallel to each other but not exactly coinciding with the grain boundary. It is thus accepted that they are crystallographic facets. At least in most cases, the sawteeth thus have at least three facets, at least two to one grain and at least one to the other. It may be noted that the sawtooth in Hillert's sketch in Figure 2(c) had even two facets to the lower austenite grain.

When the base line deviates more from the grain boundary, it often happens that it is elongated and develops a spike into the lower grain as in Figures 15 and 16. The spike is thicker when the angle is larger and the spike then develops into a sawtooth as in Figure 17. It will no longer be possible to regard the upper sawtooth as more special than the lower one. Figure 18 represents two almost symmetric particles. In all these cases, the particles show four facets, two to each grain, but possibly move in three dimensions.

Figure 19 illustrates that even sawteeth, which are so thin that they could as well be classified as plates, can develop spikes into the other grain. Figure 20 shows a symmetric case, identical to the chevrons in Figure 6. It is interesting that the sawteeth and chevrons, which appeared to be two completely different kinds of particles, have thus been found to be the two limiting cases of a continuous series of shapes. It is concluded that all particles in this series are formed with the same mechanism and in each austenite grain they show two facets.

Figure 21 summarizes the variation of shapes and arranges them according to the number of assumed orientation relationships to austenite grains. Class 0 contains the allotriomorphs which have no facets and is assumed to be related to no grain. Class 1 contains the smithiomorphs which have one facet and is assumed to be related to one grain. Class 2 is related to the particles which have facets to two grains and are assumed to be related to both. This class is divided into two series: class 2A is based on the sawteeth and plates while class 2B on the chevrons. The lower case letters refer to the relative sizes of the two parts with a for 0 to e for 1. It is implied that any number of intermediate cases between the two series may exist and the sawtooth, plate, and chevron are just three limiting cases in a whole field of shapes. It is a different question how one would like to describe intermediate cases. A possible way is indicated below the sketches. It should be emphasized that this classification concerns the shape of particles in a two-dimensional section. This is evident already from the terms sawtooth and chevron. The three-dimensional shapes can be studied by deep etching, as demonstrated by Kral and Spanos,[30] or by serial sectioning, as used by Kral and Spanos[8] to show that a sawtooth particle can be shaped as a wedge or spear. To study the three-dimensional shapes of the large variety of particle shapes, illustrated by Figure 21, was not possible within the scope of the present work.

Usually, all particles on a grain boundary have the same general shape and when they have grown large enough and are many enough, they may impinge and start to merge into a large common crystal. Eventually, they may form a complete layer and with some particle shapes it becomes increasingly difficult to recognize the individual shapes. Figure 22 illustrates two cases. As the individual particles grow with time, the edges may

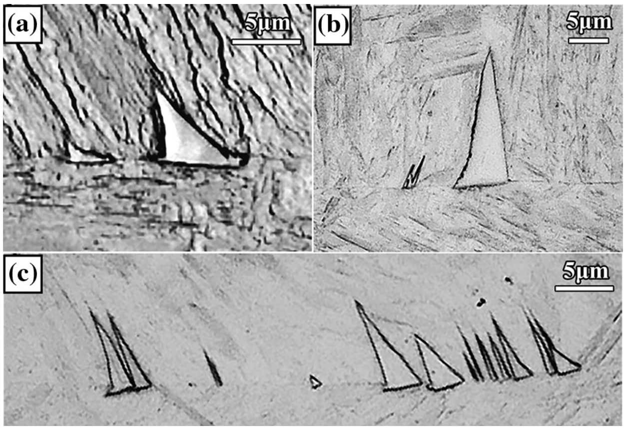

Fig. 13—Sawteeth formed at 973 K (700 °C) after 1.5 s for (*a*) and (*b*), after 2 s for (*c*).

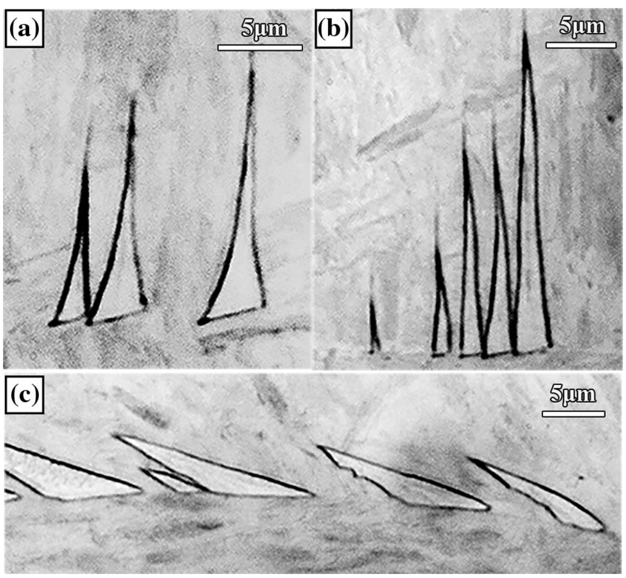

Fig. 14—Sawteeth or plates formed at 973 K (700 °C) after 2 s for (*a*) and (*b*), after 1.5 s for (*c*). Those in (a) probably started as sawteeth and later developed a plate-like outgrowths.

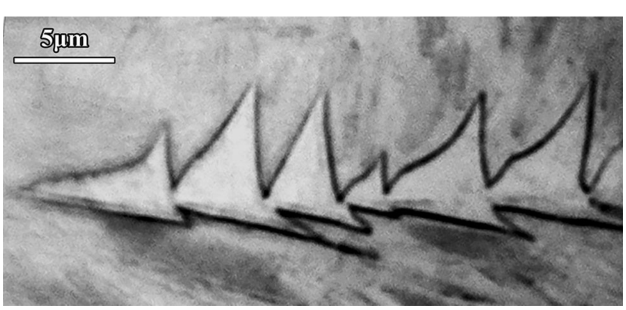

Fig. 15—Sawteeth formed after 1.5 s at 973 K (700 °C). They have also developed as sawteeth in the lower grain.

become more pronounced and develop into plates. This has started in Figure 23 where the particles initially were sawteeth. For a long chain of particles, formed by merging, there will be many such plates and, due to

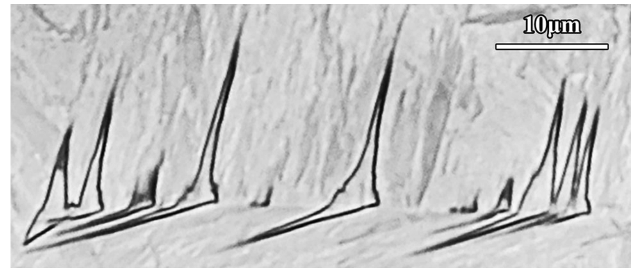

Fig. 16—Particles developed as plates into both grains, classified as chevrons. Formed after 1.5 s at 973 K (700 °C).

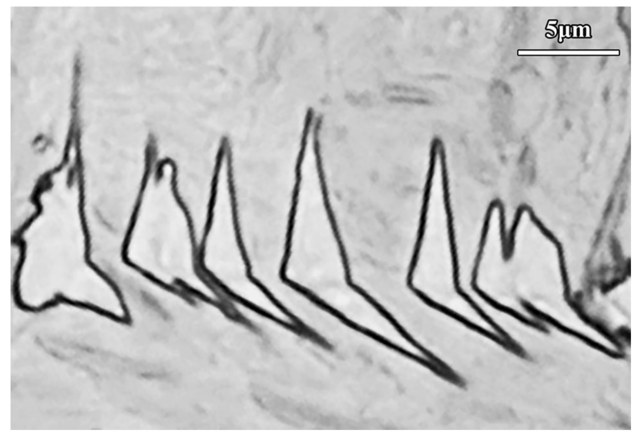

Fig. 17—Particles developed as sawteeth into both grains, classified as chevrons. Formed after 2 s at 973 K (700 °C).

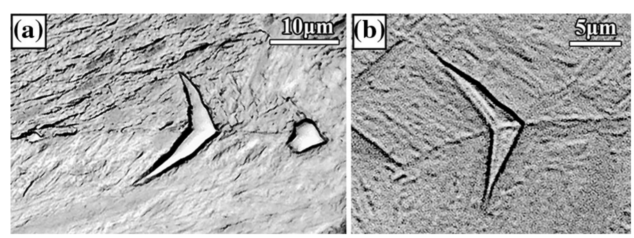

Fig. 18—Particles from 973 K (700 °C), developed as plates into both grains, classified as chevrons, (*a*) formed after 1.5 s, (*b*) formed after 2 s. Ghost lines in three directions.

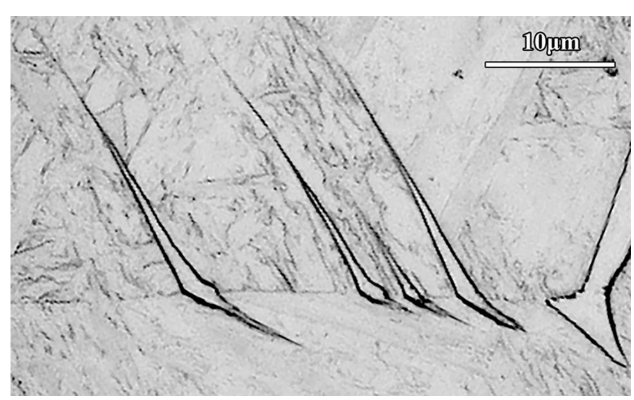

Fig. 19—Particles developed well as plates into one grain and barely into the other. Formed after 1.5 s at 973 K (700 °C). Long, thin outgrowths formed during the quench.

Fig. 20—Chevrons formed after 1.5 s at 973 K (700 °C). The inner corners are in the process of being filled.

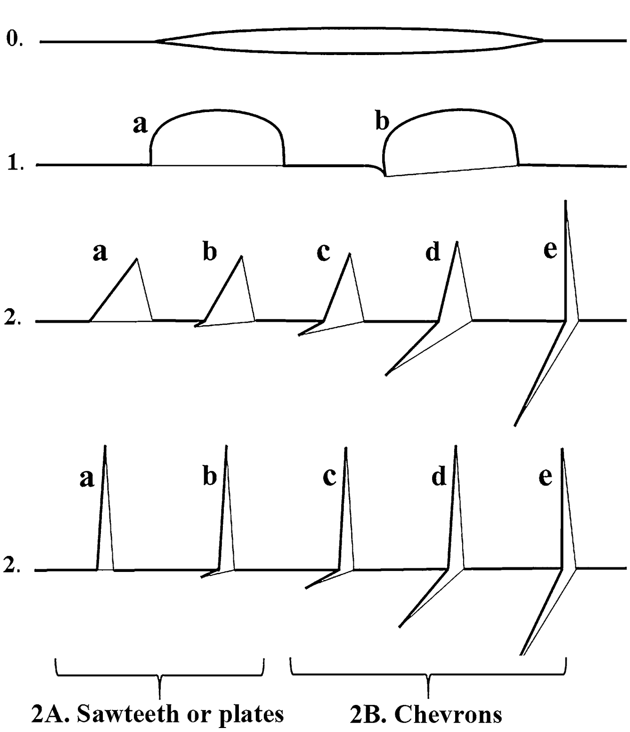

Fig. 21—Morphological classification of sectioned ferrite particles based on orientation relationships to austenite grains as indicated by facets. Thin lines represent facets with suggested low energy and possibly high degree of coherency.

uniform crystalline orientation, they will generally be parallel in each grain. An initial stage of that development from a chain of chevrons is illustrated in Figure 24. Figures 25 through 27 illustrate later stages for various forms of the initial particles. As seen on the right-hand part of Figure 25, the particles consisted of plates on the upper side of the grain boundary and on the lower side there was a tendency to form short plates with an angle of about 45 deg. However, it should be realized that, if a group of plates appear short in a section, they may be longer in their main growth direction far away from the plane of polish. To the left in Figure 25, there are no visible extensions of plates into the lower grain, probably because the grain boundary now has a similar direction as the plates would have had.

In Figure 26, the particles have developed as sawteeth into the lower grain but it should again be stressed that they may have a longer extension in a direction outside the plane of polish. In Figure 27, there are well-developed plates in both grains and there is a well-developed chevron on the right-hand side, which has only started to merge with neighbors.

In Figures 28 through 30, there are plates in one of the grains only. In Figure 28, one may trace all the plates back to the prior grain boundary and it seems that they have all nucleated in contact with the grain boundary but then widened and merged and have now formed a complete grain boundary film with a rather smooth interface to the lower grain. This could have been a later stage of Figure 10. Figure 29 illustrates that individual but closely packed plates can form in contact with a grain boundary without yet extending into the lower grain and without yet having merged into a continuous grain boundary film. This micrograph may represent an earlier stage of Figures 10 and 28.

Figure 30 is an example from 923 K (650 °C) and demonstrates that SEM can also yield some information on the internal structure of ferrite similar to that obtained with LOM through Figures 10 and 28. It thus indicates that the plates were nucleated individually in contact with the grain boundary and also that a continuous film then developed along the grain boundary. Figures 28 through 30 thus represent cases that may later develop as grain boundary nucleated bainite into one of the grains only.

C. *Feathers*

Upper bainite can form in an arrangement called feathery bainite by Mehl,[17] containing a large group of parallel plates of ferrite that originate from a grain boundary. The term is most adequate when there is bainite on both sides of a grain boundary. An example was presented already in Figure 5. Mehl applied the term also to a case with bainite on only one side. His definition of the term feathery will be accepted here. It will be applied independent of a presence of cementite between the ferrite plates. About 10 pct of the grain boundaries were covered by feathers in fully transformed specimens from 973 K (700 °C) and it increased to about 90 pct at 673 K (400 °C).

The microstructures in all of Figures 25 through 30 will thus be regarded as feathery. The term will also include all micrographs in Figure 31, which compares

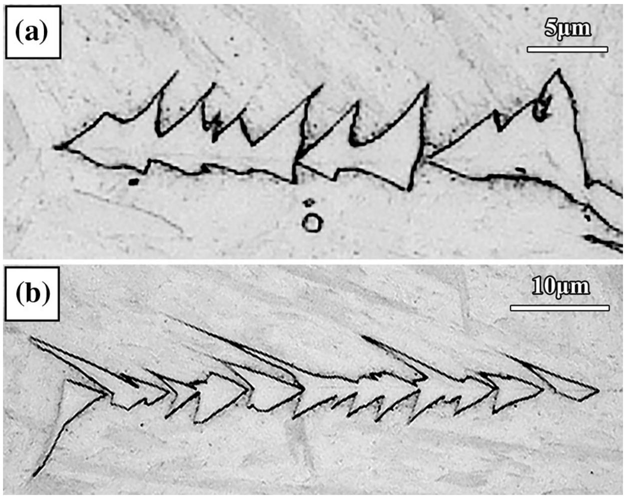

Fig. 22—Chevrons of the sawtooth variety, starting to merge after 2 s at 973 K (700 °C). Very thin outgrowths in (*a*) formed during the quench. Outgrowths as normal plates in (*b*) formed mainly before the quench.

Fig. 23—Sawteeth after 1.5 s at 973 K (700 °C) starting to merge. Plate-like outgrowths formed mainly before the quench.

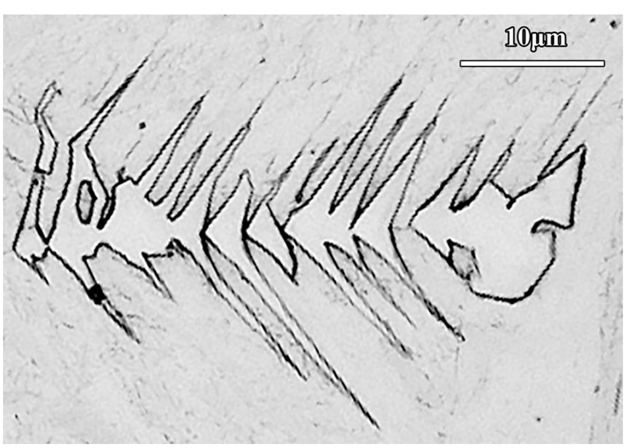

Fig. 24—Chevrons not yet completely merged after second at 973 K (700 °C).

feathers from the whole temperature range. They are all presented at the same magnification and, with one exception, they show no general difference except for the

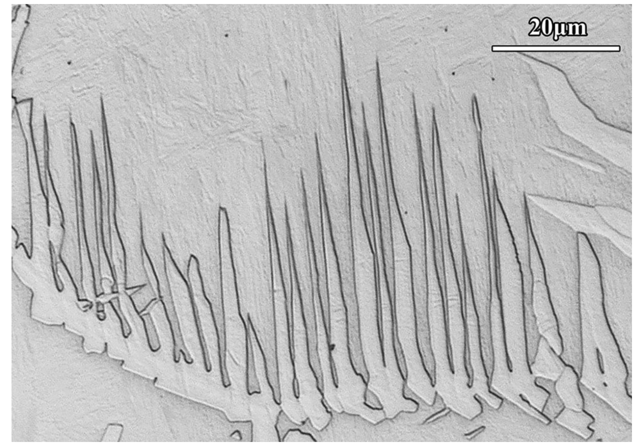

Fig. 25—Wide group of parallel plates formed from grain boundary after 10 s at 973 K (700 °C). Individual nucleation is evident from the right-hand part where some outgrowth can be seen in the lower grain. This is not evident in the left-hand part but it is suggested that the outgrowths in the lower grain are there parallel to the grain boundary and cannot be discerned.

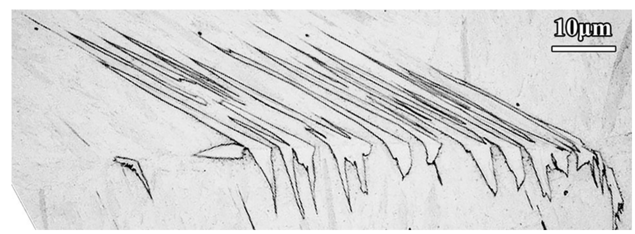

Fig. 26—Wide group of parallel plates formed from grain boundary after 2 s at 973 K (700 °C). The nuclei have developed as sawteeth in the other grain, probably with their main growth direction at a large angle to the plane of polish.

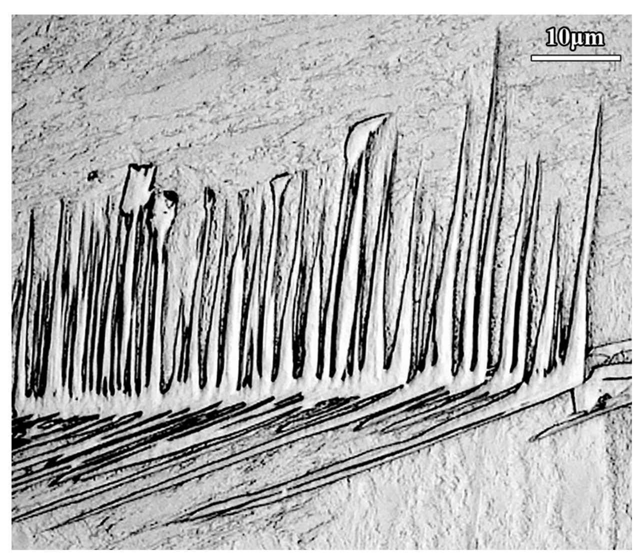

Fig. 27—Wide groups of parallel plates formed into both grains from chevrons after 2 s at 923 K (650 °C).

expected decrease of coarseness and the increasing presence of cementite at lower temperatures. The exception is Figure 31(a) which has developed into one

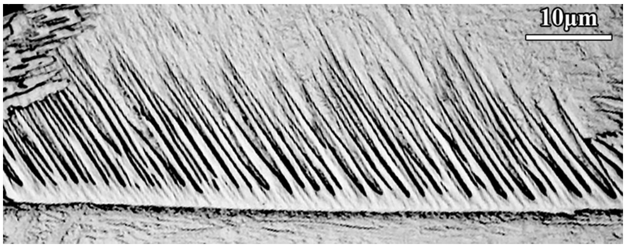

Fig. 28—Semifeather, a wide group of parallel plates on one side of a grain boundary and formed from individual nuclei, which have later merged to a seeming grain boundary film. From 923 K (650 °C) after 2 s.

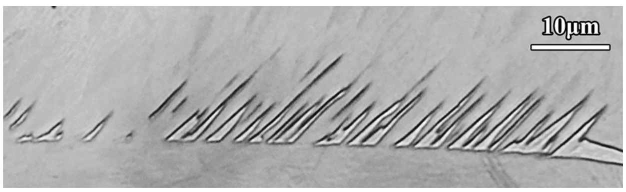

Fig. 29—Dense group of plates at a grain boundary that could later develop into a semifeather. From 973 K (700 °C) after 1.5 s.

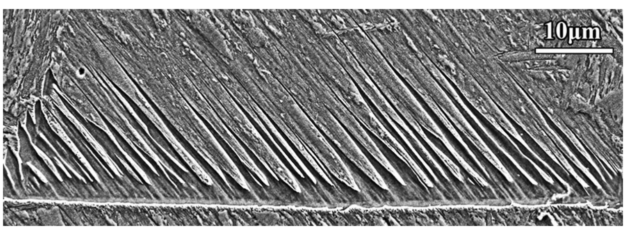

Fig. 30—SEM micrograph from same specimen as in Fig. 28 but with a different semifeather. It illustrates even better that the plates have nucleated at the prior grain boundary.

grain only. That can occur at the other temperatures as well and is not an effect of temperature. The internal structure is the same and such cases may be called semifeathers. It should be noted that for all feathers in Figure 31 it was possible to follow plates all the way from the grain boundary to the growth front without any sign of separation into a series of subunits.

Figure 32 from 723 K (450 °C) is a rare case of upper bainite without a continuous layer of ferrite along the prior grain boundary. Short pieces of the prior grain boundary may thus remain in contrast to the general behavior of grain boundary nucleated particles of ferrite to thicken in contact with the grain boundary and finally merge with their neighbors. Figure 33 is an example of thickening along the grain boundary but in only one direction. The particles in Figure 29 from 973 K (700 °C) are also separated but that is an early stage and they may thicken and merge later on.

D. *Sheaves*

Aaronson and Wells[18] proposed that intragranular sheaves or packets form by sympathetic nucleation of new plates in succession, starting from a primary crystal nucleated intragranularly by a different mechanism. This possible phenomenon could not be studied in the present alloy because intragranular precipitation of ferrite occurred very late compared to grain boundary precipitation. On the other hand, sheaves often originated from nuclei at grain boundaries. Figure 34 gives two examples from 923 K and 673 K (650 °C and 400 °C). In both cases, different pieces of the grain boundary give rise to sheaves on alternating sides. It seems that these grain boundaries can favor two kinds of nuclei and it may be a matter of chance which one will win in a particular position. An example of two different shapes of particles nucleated on the same grain boundary is already given in Figure 6.

Sheaves can also originate from ordinary feathery bainite as demonstrated by Figure 35. This feather has not been sectioned in the main growth direction and the short plates at the tops of the sheaves, which are magnified in the inset, are the upper parts of plates nucleated at the same grain boundary but on a different level. These sheaves are thus developing without sympathetic nucleation.

E. *Shape of Ferrite Plates*

In Figure 36 from 823 K (550 °C), the growth of a group of plates of ferrite has stopped due to the impingement of pearlite growing in an opposite direction. On the other hand, the growth of another group of plates further to the right has not stopped until the final quench of the specimen. The shapes of their tips differ dramatically from those of the first group. It is evident that the growth did not stop directly by the quench. Growth continued for some time while temperature was dropping and it then resulted in very thin tops. The true shape during isothermal growth is probably close to the shape shown by the first group of plates. Figure 37 shows a more dramatic change of coarseness by insufficient quench after 10 seconds at 973 K (700 °C). Similar but usually much shorter plates can be seen on many edges on various shapes presented earlier, *e.g.*, Figures 22(a) and 24.

Figure 38 shows a series of micrographs of growth fronts from 873 K to 673 K (600 °C to 400 °C) and most have thin tops formed during the quench. Except for that, many plates are well shaped and with a thickness slowly increasing for a considerable length behind the thin tip. For those plates, the two sides are often rather straight and with a curvature that can hardly be noticed. This is close to what may be regarded as the ideal shape of a Widmanstätten plate of ferrite. The temperature does not seem to have any effect on the shape.

There are three parallel plates close to the upper right corner in Figure 39 from 873 K (600 °C). At the arrow, the third one suddenly thickens in an asymmetric way and its upper side comes close to its neighbor. It is evident that the two broad faces of the plates have the same kinetic properties as long as they thicken in a symmetric way but here the upper side suddenly turned more mobile. The same happened to several of the other

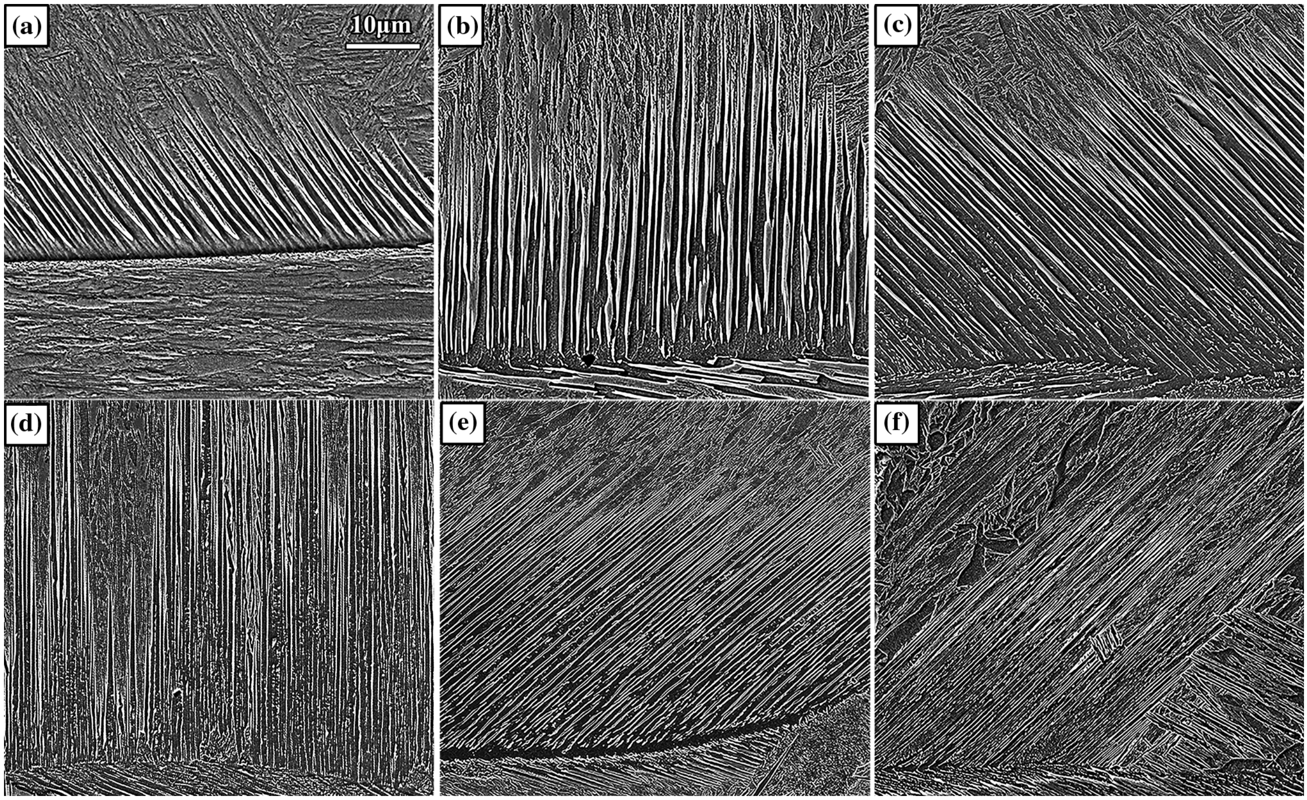

Fig. 31—(*a*) One semifeather from 923 K (650 °C), and (*b* to *f*) five feathers from 873 K, 823 K, 773 K, 723 K, and 673 K (600 °C, 550 °C, 500 °C, 450 °C, and 400 °C), respectively.

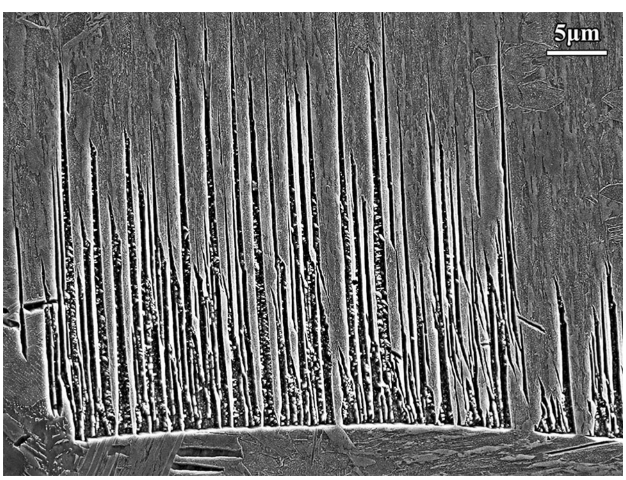

Fig. 32—Semifeather where the plates have not merged enough to cover the whole grain boundary. After 1 s at 723 K (450 °C).

plates in the micrograph and it may be significant that they thickened in the same direction.

In sections that are almost but not quite parallel to the main growth direction, the plane of polish will cut through some plates as in Figure 40 from 973 K (700 °C). All these plates are parallel and have probably nucleated on the extension of the grain boundary shown in the lower right part of the field of view. All the upper ends are sharp and may represent the advancing edges. The lower ends show the cuts through the plates. They are blunt and roughly perpendicular to the length

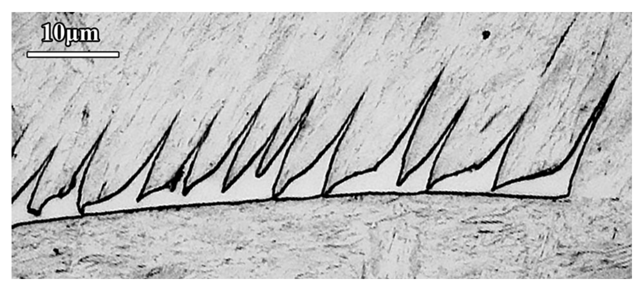

Fig. 33—Series of plates or sawteeth that have thickened in contact with the grain boundary but only in one direction. After 1.5 s at 973 K (700 °C).

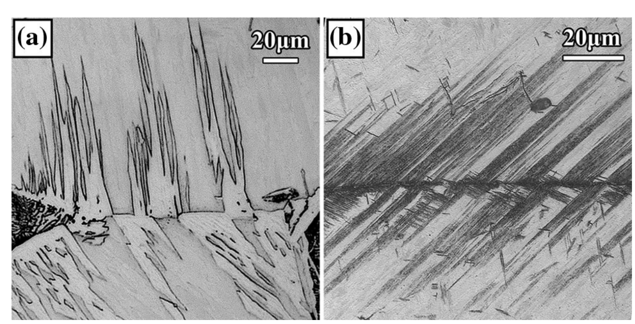

Fig. 34—Two examples of sheaves formed on both sides of a grain boundary due to two similar kinds of nuclei but with opposite direction. (*a*) 5 s at 923 K (650 °C), (*b*) Fe-0.48Mn-0.51Si-0.26C (in mass pct) alloy, 2 s at 673 K (400 °C).

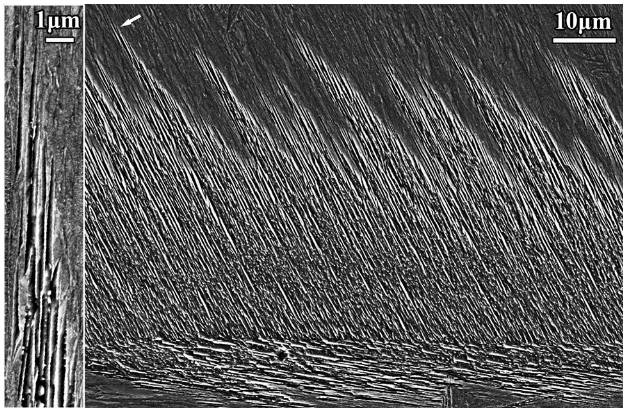

Fig. 35—Development of sheaves from a feather. The inset is a magnification of the top part of a sheaf, showing the arrangement of fine plates, sometimes regarded as subunits. After 2 s at 673 K (400 °C).

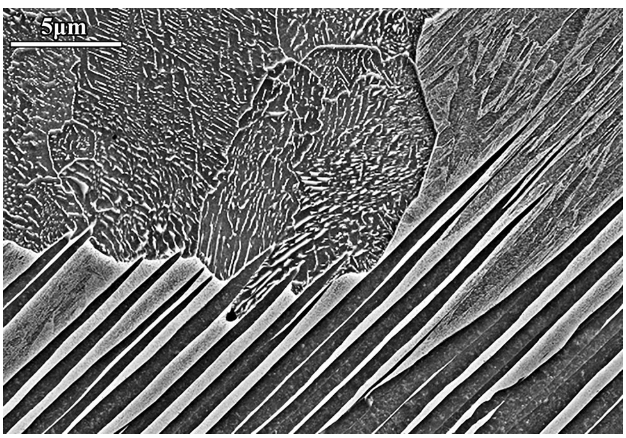

Fig. 36—Growth front of a feather is stopped by a growing pearlite colony to the left. To the very right, some plates have later stopped during gradual cooling. The tips look quite different. From 823 K (550 °C).

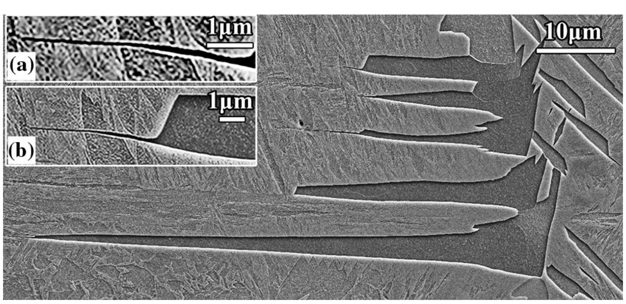

Fig. 37—Very coarse plates of ferrite after 10 s at 973 K (700 °C) are quenched but managed to continue growing as very thin plates during cooling, (*a*) and (*b*) are higher magnifications of the tip of the plate close to the top.

direction which demonstrates that the plates had a roughly rectangular cross section. The plates may thus be lath-like or rather wedge-like,[31] if one considers the advancing edge. The cross sections do not have sharp edges as a double-edged sword.

The plates in Figure 41 have been sectioned with a small angle from their main growth direction and the micrograph shows where the section cuts through their short side. The cut through the side would have been perpendicular to the length axis as in Figure 40 if the section had been perpendicular to the broad faces. Instead, the cut is now sloping. However, the slope is not the same for all the plates and some tips are thus longer than others. An explanation may be provided by Figure 42, showing a section through four sheaves. One shows very thin cross sections and that is probably close to the true thickness of the plates. Another one shows very thick units because it has been sectioned almost parallel to the broad faces but with a small angle to the length axis. It seems that the true cross section is roughly rectangular but Figure 42 reveals that there are protrusions on the short sides of the cross sections and they are different for different plates and may be described as spikes in the micrograph. However, in order to show up as they do in Figure 41 they must be ridges in 3D. Similar protrusions were reported by Watson and McDougall[32] who regarded them as tails.

Figure 43(a) shows four sectioned plates belonging to a sheaf that has invaded a feather sectioned almost along the main growth direction. Those plates are limited to a space between plates in the feather. The sketch in Figure 43(b) illustrates an attempt to define the initial shapes of the cross sections and to identify the protrusions. In all of Figures 41 through 43, there is a tendency of the protrusions or spikes to extend outside the broad faces of the plates. That tendency is very strong in Figure 44(a) from 723 K (450 °C) and it seems that a ridge or small plate is attached to the side of each plate and its broad faces have a slightly new direction. Figure 44(b) from 873 K (600 °C) illustrates that even short ridges in a new direction can give the morphology described as degenerate plates of ferrite by Aaronson.[3]

The ridges seem to be attached to the short side of the cross section or to a corner but to extend along the main direction of the plate. In a section in the main growth direction of the feather, the ridges would hardly be noticed but the effect may be very evident in an oblique section to the main growth direction, as illustrated by Figure 45. It looks as if new plates in a new direction have been nucleated but they do not seem to grow very long. At higher magnification in Figure 45(b), it is evident that each seeming new plate is actually directly attached to an ordinary plate and all normal plates have such attachments on both ends, which are visible due to the oblique sectioning. Inside the sheaf it is not so easy to distinguish between parallel plates because the intervening spaces have transformed to a eutectoid mixture. The similarity of Figure 45 to Figure 41 is striking and it is evident that the longest tips in Figure 41 are caused by well-developed protrusions.

F. *Effect of Twin Boundaries*

If a plate has some special orientation relationship to the parent austenite crystal, it is not expected to retain its shape when crossing a twin boundary. Nevertheless, it may be interesting to study how a plate reacts when it

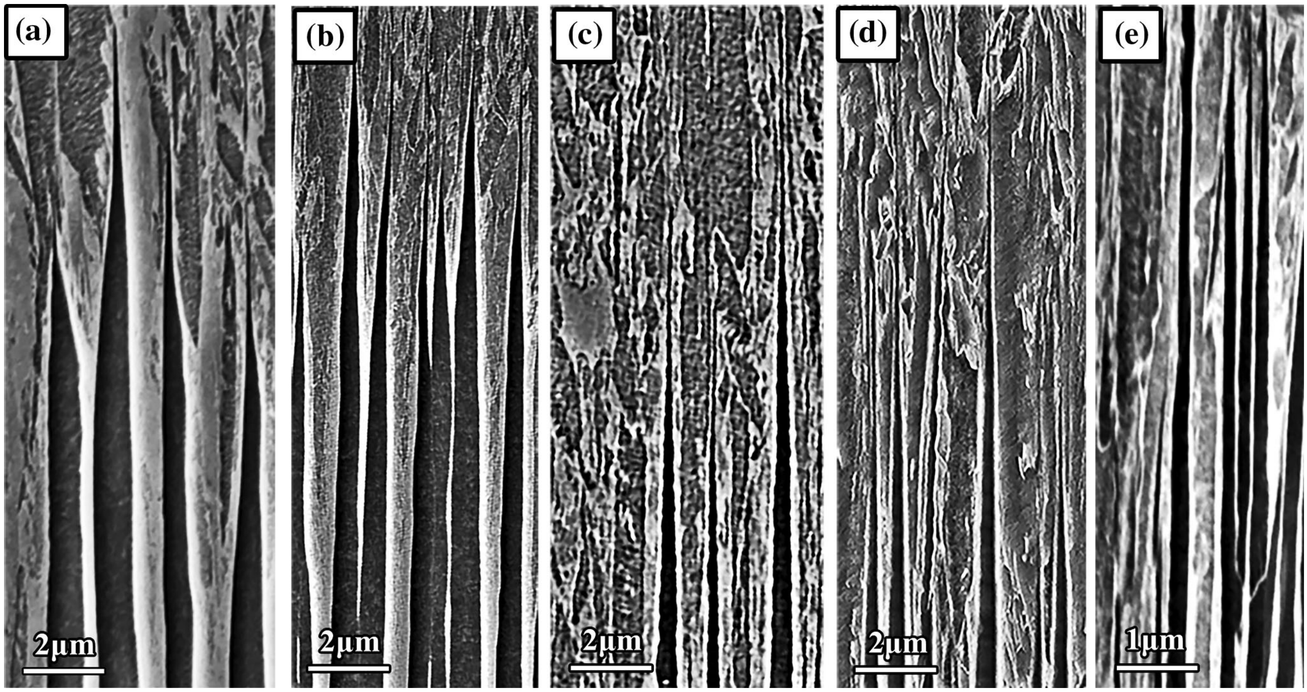

Fig. 38—Ferrite tips of quenched specimens from various temperatures, (*a* to *e*) are from 873 K, 823 K, 773 K, 723 K, and 673 K (600 °C, 550 °C, 500 °C, 450 °C, and 400 °C), respectively.

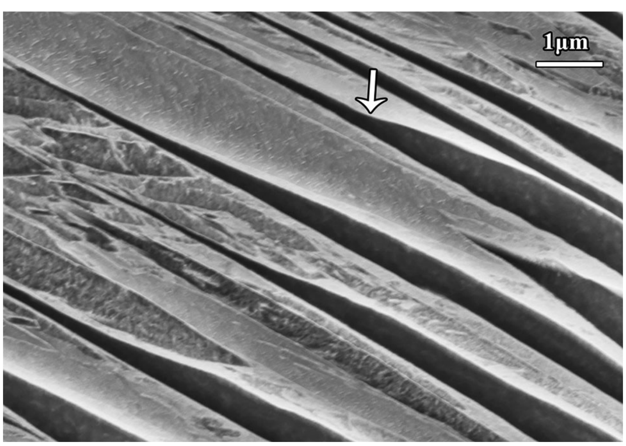

Fig. 39—Close to the growth front of a feather at 873 K (600 °C). The third plate from the top has suddenly started to thicken on one side, which indicates that this interface has turned more mobile.

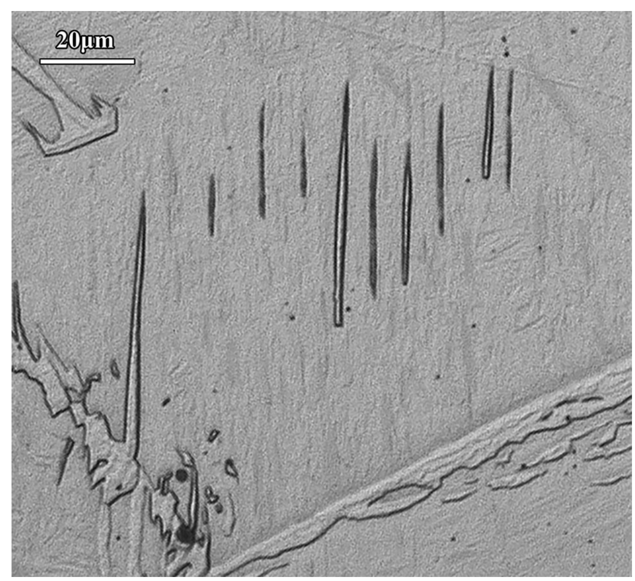

Fig. 40—Parallel Widmanstätten plates which must have had a common origin, probably the grain boundary which is seen at the lower left corner, but they have been sectioned by the plane of polish. The lower ends, shown in this plane, indicate that the cross sections are roughly rectangular and the plates do not have sharp sides.

encounters one. Figures 46(a) and (b) illustrate the effect with two cases from 973 K (700 °C). It is evident that the plate thickens more rapidly in contact with the twin boundary and the thickening is spreading backwards. Figure 46(c) from 923 K (650 °C) illustrates that the ferrite crystal can grow into the twin but only to form a cap that covers the width of the particle in the first grain. In Figure 47(a) from 823 K (550 °C) and Figure 47(b) from 673 K (400 °C), the plates have also thickened when stopped by a twin boundary. It is concluded that twin boundaries have the same effect on ferrite plates in the whole temperature range.

V. DISCUSSION

A. *Grain Boundary Films*

According to Smith's interpretation, the nucleation of a grain boundary allotriomorph could not have occurred on the grain boundary itself because there it should obtain an orientation relationship to one of the grains in order to decrease the activation energy for

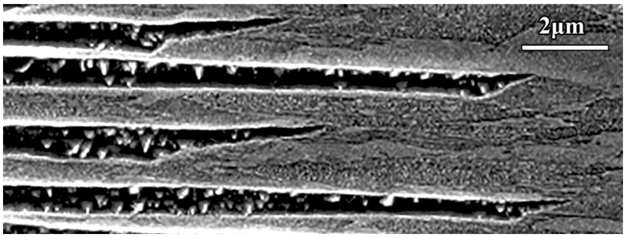

Fig. 41—Plates from 723 K (450 °C) with some white cementite particles. The tops have been cut off by the plane of polish. The ends are not blunt as in Fig. 40 and all do not look the same.

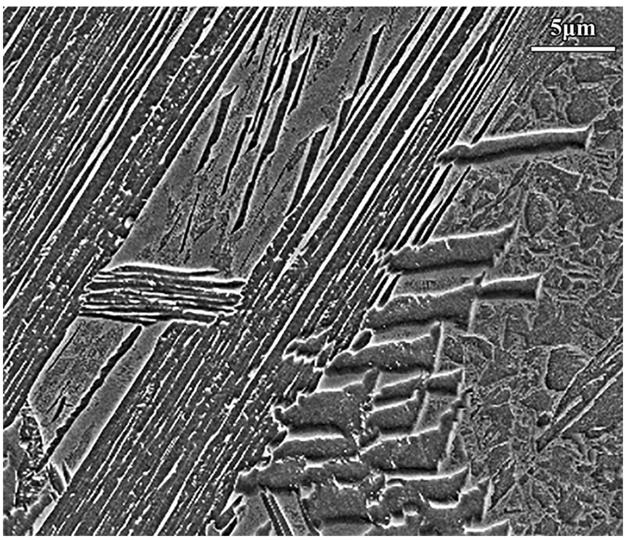

Fig. 42—Sections through group of plates from 773 K (500 °C) in a direction rather parallel to the main growth direction. The thickness of the cross section is thus much magnified. There are irregular protrusions at the ends.

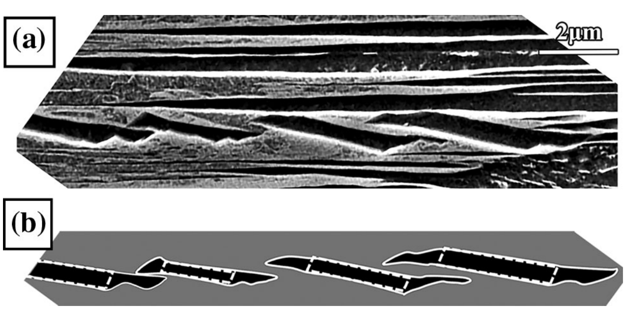

Fig. 43—(*a*) Cross sections of four plates from 773 K (500 °C). (*b*) Suggested initial cross sections and protrusions.

nucleation. Except for large supersaturations, the driving force for nucleation would not have been sufficient. It is now proposed that an allotriomorph instead nucleates with an orientation relationship to a third grain, *e.g.*, the grain to the left of the grain corner in Figure 9. It is even possible that it nucleated at a 3D corner where four grains meet. It has long been realized that such points are the most favorable nucleation sites[33] and it has been shown that this is where the nucleation starts in austenite of low supersaturation.[19]

At first sight, the nucleation of the three smithiomorphs in Figure 11 looks straight forward. However, Smith's suggestion requires that the atomic plane of one of the austenite grains along the grain boundary is favorable to the formation of a low-energy interface to ferrite but that should apply to both grains when there are smithiomorphs in both. That further emphasizes that this crystallographic condition cannot be very strict.

B. *Grain Boundary Nucleated Particles*

Closely spaced particles of ferrite have been observed on many grain boundaries. Their shape varies considerably but it is rather uniform for each grain boundary. It is evident that the shape of particles is in some way governed by the properties of the grain boundary and those properties depend on the orientation relationship between the two austenite grains but also on the direction of the grain boundary relative to the two lattices. The latter factor is of primary importance for the formation of smithiomorphs and sawteeth which have a facet more or less coinciding with the grain boundary.

It may be concluded that grain boundaries with faceted particles of a uniform shape have a characteristic structure. Because the particles do not seem to have much competition from grain boundary films of ferrite, one may speculate that such grain boundaries have low interfacial energy. Normally, grain boundary films would spread more efficiently along high-energy boundaries. It is suggested that these low-energy grain boundaries have unique atomic arrangements and act as preferred sites for nucleation of particles characteristic of the particular grain boundary.

Another possibility is that already the controlling factors, mentioned above, determine the crystalline orientation of the ferrite nucleus and give the same result independent of the properties of the preferred site. However, in Figure 6 the grain boundary has stimulated the formation of two different kinds of particles and this also applies to Figures 34(a) and (b). Supposedly, there are two kinds of preferred sites in these grain boundaries.

On the other hand, one may wonder how it is at all possible that a crystalline orientation of the ferrite nucleus can exist that can form facets to both grains of austenite. It seems that the conditions to form facets are not very strict. It may be mentioned that Strangwood[34] has referred to the observed occurrence of a number of closely related orientation relationships for Widmanstätten plates and suggested that there are a number of energy minima. It may now be suggested that facets can form in a considerable range of orientations of the planes of the two crystals at the interface and one may wonder whether a facet can be stable unless there is an energy cusp.

The conditions for chevrons may seem particularly severe. This is due to several reasons, firstly, the occurrence of facets to both grains implies that there should be special orientation relations to both grains. However, King and Bell[35] and Furuhara *et al.*[14] have shown that grain boundary ferrite can have such relationships to both grains and they studied the

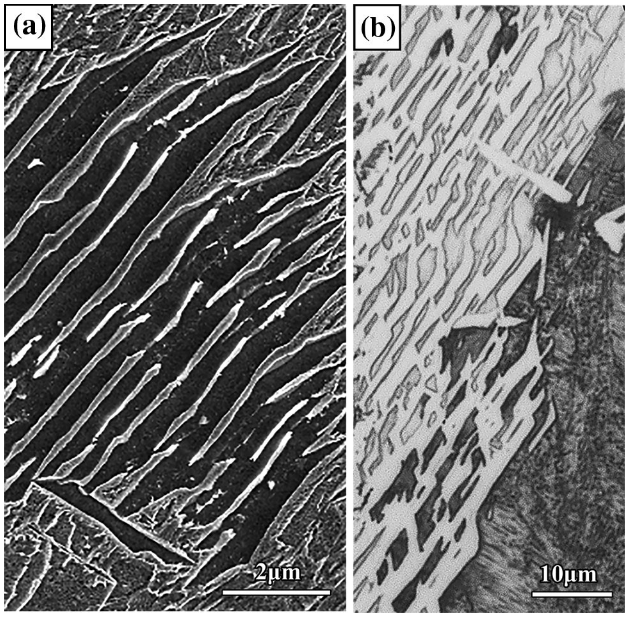

Fig. 44—(*a*) Plates with very large protrusions from 723 K (450 °C), and (*b*) microstructure of Fe-0.48Mn-0.51Si-0.26C (in mass pct) alloy after 5 s at 873 K (600 °C). Ferrite (white); Austenite, martensite (light gray); Pearlite (dark).

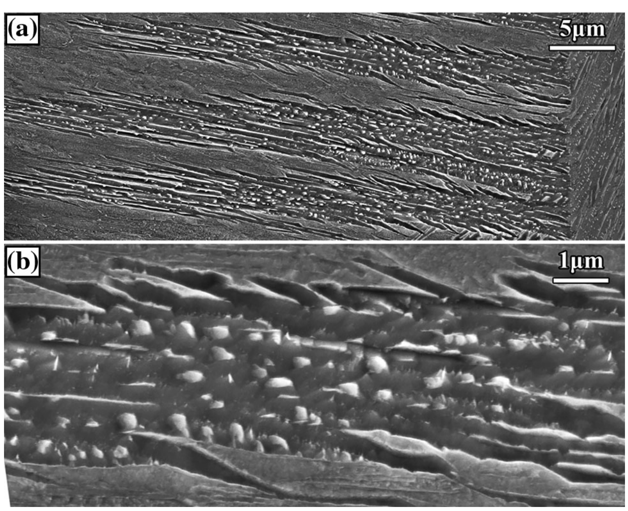

Fig. 45—(*a*) Groups of plates growing from grain boundary at 673 K (400 °C). They were sectioned at an angle and look as sheaves. (*b*) At higher magnification, the protrusions are shown on the sides of the sheaves and give the impression of newly formed new plates.

deviation from the ideal habit plane for Widmanstätten plates. Secondly, it is necessary that the two facets have such directions that their line of intersection falls on the grain boundary because all chevrons have been observed to have their outer corner on the grain boundary. Thirdly, the relationships should also allow a second facet to form in each grain, *i.e.*, those which define the inner sides of the chevron. For a chevron to form, it seems that the conditions for a facet to form cannot be very strict.

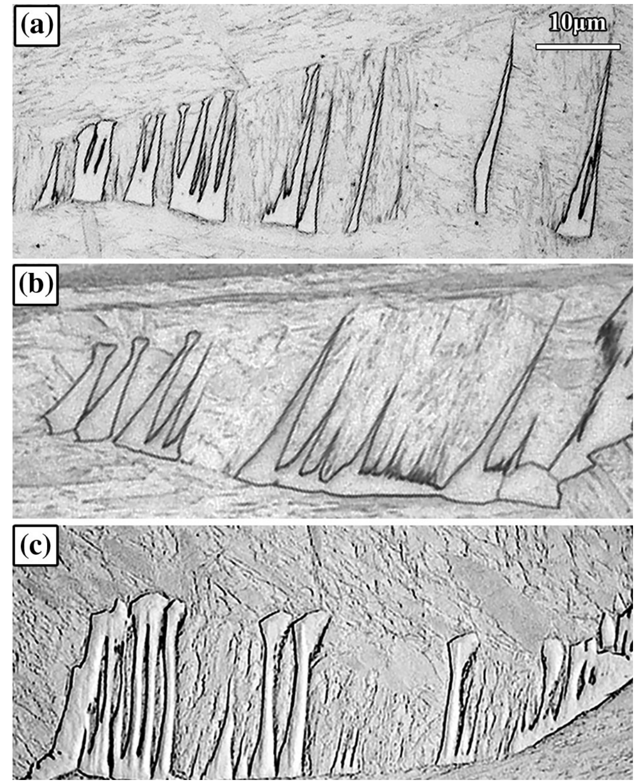

Fig. 46—Effect of twin boundaries on the growth of plates. (*a*) 1.5 s at 973 K (700 °C), (*b*) 1.5 s at 973 K (700 °C), (*c*) 2 s at 923 K (650 °C).

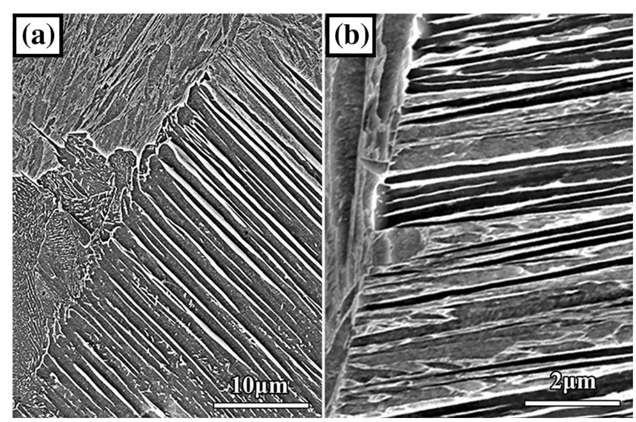

Fig. 47—Effect of twin boundaries on the growth of plates in feathers. (*a*) 1 s at 823 K (550 °C), (*b*) 2 s at 673 K (400 °C).

Facets are usually taken as an indication of anisotropic interface properties, often expressed as some kind of coherency. In the present case, it seems that facets could exist with a lower degree of coherency than one may normally expect. Maybe the probability that grain boundaries can form faceted particles may increase if many of them have obtained low energy due to an advantage during recrystallization and grain growth.

Furthermore, it is proposed that all facets in a chevron may not have the same degree of coherency. It may be imagined that the orientation of the critical nucleus is optimized to minimize the total interfacial energy and that state may define the four facets as low-energy interfaces but of different energy and degree of coherency. It is suggested that one facet to each grain is more coherent than the other. This alternative was introduced to Figure 21 by using thin lines to represent interfaces suggested to have lower energy, in comparison with those interfaces represented by thick lines. This choice has consequences on the expected behavior of the particles during growth, assuming that low energy implies low mobility. A possible example is given by Figure 33 where all the initial particles, which may have been sawteeth or plates, have later thickened along the grain boundary but in only one direction. It is suggested that this is because the right-hand side of the plates has an interface of lower mobility. Another possible example is Figure 20 with well-developed chevrons. The two interfaces that meet in an outer corner are straighter than those that meet in the inner corner, which is being filled in by the inner interfaces moving. On the other hand, that may simply be due to the automatic supply of ledges in any inner corner.

The high rate of transformation of the present alloys also provides evidence of a difference between two facets. In connection to Figures 36 and 37, the tendency of very fine plates to form on quenching was discussed. Fine plates were also formed from the tips of sawteeth in Figure 22(a) and they are all extensions of the same sides of the sawteeth. They can be recognized as Widmanstätten plates and they seem to indicate that one side of a sawteeth is closer to a habit plane of Widmanstätten plates than the other. It is tempting to accept this observation as support for the proposal that one of the two sides of a plate or sawtooth is more coherent than the other. There are many more examples of this kind among the micrographs but the tendency is not always as evident as in Figure 22(a) with its large angle between the two facets.

In this connection, it should also be emphasized that at 973 K (700 °C) the broad faces of Widmanstätten plates are often far from straight as in Figures 25 and 27. This indicates that there is a considerable flexibility. An interesting example is shown in Figure 37 and comes from 5 minutes at 973 K (700 °C). The main picture shows a long, well-developed plate but the others are more or less defect. The upper one is particularly interesting because its lower side started out in the same direction as the long plate but then it bent. See inset b. It is unexpected that the fine plate, which formed during the quench, inherited this direction but then gradually changed to the direction of the long plate.

Figure 48(a) is from a specimen held at 673 K (400 °C) but the thickest plate certainly started at a higher temperature. It soon starts to bend gradually and finally grows in the same direction as all the other plates, which started to form closer to the holding temperature. Without knowing if the crystalline lattice rotates and the crystalline plane of ferrite at the interface is constant or the lattice orientation remains and the crystalline plane of ferrite changes gradually, this is another example that the crystalline plane of austenite at the interface can vary.

Many of the speculations presented in Section V–B should be checked by crystallographic studies, *e.g.*, by EBSD. The overall issue is the relation between the facets and the structure of the grain boundary where the particle was nucleated. It would be necessary first to study the orientation relationships between the ferrite particle and the austenite matrix and then to apply serial sectioning to determine the orientation of the facet in three dimensions, relative to both crystals, ferrite and austenite. For most facetted particles, one would have to consider two facets. It would be more complicated for particles with facets to both austenite grains. One would then have to consider the structure of the grain boundary, as determined by the orientation of the grain boundary relative to the lattices of both austenite grains, which again requires serial sectioning. The final challenge would be to consider a facetted nucleus situated on the grain boundary in order to understand why the particular orientation of the particle was favored. Experimental studies along these lines were beyond the scope of the present work but the new classification scheme of the varieties of shapes in two dimensions may possibly be some value in future work.

C. *Feathers*

It is common to remark that Widmanstätten ferrite and ferrite in upper bainite look very similar and at the same time to mention some difference, *e.g.*, that one nucleates directly on the grain boundary and the other on a grain boundary allotriomorph.[36] However, in the present work Figures 25 through 27 illustrate that a feathery arrangement of ferrite plates seems to start from closely spaced chevron particles at 973 K (700 °C) and the series of micrographs from 923 to 673 K (650 to 400 °C) in Figure 31 confirmed that this is the case for the whole range of temperature. The plates in Figure 31 and the tops in Figure 38 confirmed that there is no evident effect of temperature on the shapes of the ferrite plates. There is no morphological indication of a transition from higher to lower temperature, except for the appearance of cementite in connection to acicular ferrite, which can be used as a definition of bainite. Furthermore, the effect of twin boundaries on ferrite plates was the same in the whole temperature range. It is thus concluded that there is no main difference in the growth mechanism of Widmanstätten ferrite at higher temperatures and ferrite plates in upper bainite, often called bainitic ferrite. Since it is accepted that Widmanstätten ferrite grows under diffusion of carbon, it should also be accepted that ferrite in upper bainite does.

D. *Subunits*

The discovery by Ko and Cottrell[37] that the formation of bainite has a surface relief effect, resulted in the displacive hypothesis. However, by combination with the prior idea that bainite is somehow related to martensite and the understanding that martensite grows

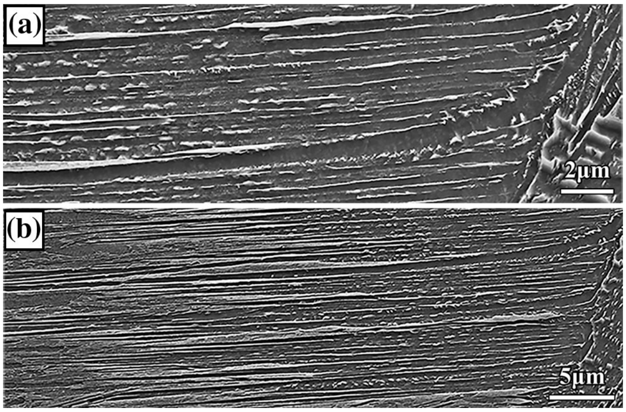

Fig. 48—(*a*) Part of feather from 673 K (400 °C) with one plate thicker than the others. It has started to form before the holding temperature was reached. Initially it bends strongly. (*b*) At lower magnification, one can see that this plate gradually grows thinner and approaches the normal thickness. It seems to have grown continuously without any abrupt changes.

with a displacive mechanism, it was at the same time assumed that the growth was rapid and without diffusion of carbon, *i.e.*, diffusionless. This combination has been generally accepted and it is often stated that the bainite formation is diffusionless because it is displacive or sometimes just taken for granted without being stated. This was unfortunate and unnecessary because already Ko[38] showed that also Widmanstätten ferrite has the same surface relief effect. That has been accepted and at the same time it was accepted that Widmanstätten ferrite also grows with a displacive mechanism. However, for Widmanstätten ferrite it was not connected to rapid growth without carbon diffusion.

From the beginning, it was realized that the diffusionless hypothesis had a problem with the experimental information on growth rates that were too slow to prevent carbon from escaping the growing ferrite in bainite formation. Goodenow and Hehemann[25] proposed a solution of this problem when they in bainite observed a microstructure with subunits of limited lengths. They concluded that "The growth rate of upper bainite appears to be determined by the rate of nucleation of the substructural units." This hypothesis has been widely accepted and it seems that no alternative explanation has been proposed by proponents of the diffusionless hypothesis. It thus appears that it completely depends on the proposed role of subunits. Oblak and Hehemann[26] then reported that the subunits were about 10 μm long and presented a sketch illustrating how they contribute to the lengthening of a sheaf, Figure 7.

The micrographs in Figure 31 were chosen because it was possible to trace plates from the growth front and all the way back to the neighborhood of the grain boundary. No morphological difference was found between Widmanstätten ferrite and bainitic ferrite. Ohmori *et al.*[36] reached the same conclusion but suggested a difference regarding the nucleation. Such a difference of nucleation was not found in the present work. With these micrographs, it was also possible to conclude that subunits play no role in the lengthening of upper bainite. It should be emphasized that ferrite plates are known to be lath-like and a feather has to be sectioned sufficiently close to its main growth direction to show its full length. As demonstrated in Figure 35, a more oblique section would jump from one plate to a neighboring one, *etc*. It would thus give the false impression of a series of subunits that nucleate in succession and contribute to the lengthening of a sheaf of plates.

Even though it has now been shown that the plates of ferrite can extend all the way from the grain boundary to the growth front without any sign of subunits, somebody may argue that the successive formation of subunits does not necessarily result in discontinuities in the shape of the composite plate. One may attempt to test the existence of subunits by crystallographic examination using TEM or EBSD but the result could be interpreted differently depending on what criteria about orientation difference are used for distinguishing between Hehemann's subunits and a substructure of a different origin. A more straight-forward test was here obtained by examining the shapes of plates formed under continuous cooling.

Such specimens were obtained unintentionally in two ways. First, the coarse plate of ferrite in Figure 48(a) has nucleated and started to grow during the cooling toward the holding temperature of 673 K (400 °C). That is why it is considerably coarser than the neighboring plates that started to form closer to the holding temperature. The lower magnification in Figure 48(b) shows that the coarseness decreased gradually during growth for at least 50 μm, evidently due to continuous growth during decreasing temperature. However, there is no sign of any discontinuous change of coarseness.

Secondly, the five plates in Figure 37 formed under 10 seconds at 973 K (700 °C) and some fine outgrowths formed during the final quench. This is shown for the upper plate in inset b and it is further magnified in inset a. It has gradually grown thinner during decreasing temperature. During this growth, there is no abrupt decrease of thickness as a memory of an intermission. It can thus be concluded that rapidly growing subunits play no role in the growth of ferrite plates.

In view of the above results, it is proposed that the assumption of rapid, diffusionless growth of ferrite plates in bainite is removed from the displacive hypothesis. The discussion whether the formation of Widmanstätten ferrite and bainitic ferrite differs by one being reconstructive and the other displacive could then focus on the properties of the interfaces.

It should finally be mentioned that it seems to become common to describe the individual fine, parallel plates in a sheaf as subunits. Of course, in that sense subunits may exist but they are not examples of Hehemann's subunits and they are not related to the overall lengthening rate. An example was presented in the inset of Figure 35 which gives a false impression of being formed in a succession but it is evident that they are part of feathery bainite and have thus started from close to the grain boundary. In other cases, it may be necessary to apply serial sectioning to reveal the true 3D structure of a sheaf.

VI. SUMMARY AND CONCLUSIONS

The main results were obtained from an Fe alloy with 0.3 C, 0.5 Si (mass pct). The study concentrated on early stages of precipitation on grain boundaries. Particles were classified according to the number of facets and they were accepted as signs of some special orientation relationship to the surrounding austenite grains.

Class 0 Allotriomorphs have no orientation relationship to the neighboring grains. They nucleate in contact with a third grain and are classified as allotriomorphs when they spread along a random grain boundary. They have no facet and no special orientation relationship to the neighboring grains.
Class 1. Smithiomorphs nucleate on a random grain boundary with one facet close to the grain boundary. They have a special orientation relationship to one grain but grow mainly into the other.
Class 2. These have special orientation relationships to both grains. The grain boundary may be non-random. This class includes sawteeth, plates, and chevrons and transitions between them.
Plates and sawteeth have two facets to one grain and one coinciding with the grain boundary. They differ only by the sharpness of the top angle. Chevrons have two facets to each grain and so have all transitions. Class 2 can thus be divided into two classes.

Class 2A This class is based on the plate or sawtooth and comprises the cases with a small plate in the second grain.
Class 2B This class is based on the chevron and comprises cases with decreasing size of one leg.

A. *Conclusions About Other Features*

Feathers are primarily composed of parallel plates of ferrite in both directions from a grain boundary. The plates may form from a long series of chevrons. They grow continuously until stopped by an obstacle. Growth by successive nucleation of subunits does not occur. The morphology of ferrite plates does not change with temperature, except for effects of cementite at later stages and lower temperatures. Morphologically there is no transition from Widmanstätten ferrite to bainitic ferrite.

Semifeathers form in the same way as feathers but grow only into one grain. They may form from a long series of plates or a grain boundary film with some orientation relationship to one grain.

Facets have some kind of coherency. When there are two facets to the same austenite grain, one is more coherent than the other.

Finally, it should be emphasized that, in the present classification of grain boundary nucleated ferrite particles, it was accepted that a facetted interface can be taken as a sign of some orientation relationship. Particles with two facets can have different shapes and their existence indicates that there is a range of such relationships. That possibility is emphasized by the existence of a wide variety of particles with facets to both austenite grains. An extensive EBSD work would be required for a study of these relationships. In particular, it should be an interesting challenge for future EBSD work to try to understand the role of the structure of the austenite/austenite grain boundary in the selection of the orientation of nuclei for the various varieties of ferrite particles.

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