Apparent Re-entrant Corner Effect due to Impurities in Ribbon-like Morphology of Hematite Twins

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Abstract

The origin of ribbon-like morphology of hematite crystals twinned by rotation around [0001] with composition plane (10 $\bar{1}$ 0) was accounted for as due to the accelerated growth at the twin junction by heterogeneous two-dimensional nucleation around the selectively precipitated crystallites of Mn–Ti rich phase, and not due to the simple presence of a re-entrant corner.

Introduction

It has been empirically known that twinned crystals of some minerals exhibit morphological characteristics which are markedly different from those of the co-existing single crystals. Becke (1911) and Chudoba (1927) summarized them in the following four points:

- 1) Twinned crystals are in general larger than the co-existing single crystals.
- 2) They take flattened or elongated morphology.
- 3) Less common faces which are not seen on single crystals often appear on twinned crystals.
- 4) On twinned crystals, kinds of crystal faces are less than those on single crystals.

The origin of these morphological characteristics of twinned crystals was at first explained in terms of preferential growth at twin re-entrant corners (Hartman, 1956). This explanation was later criticized theoretically by Kitamura et al. (1979), who proposed a concept of pseudo- or apparent re-entrant corner effect. According to their analysis, preferential growth at twin re-entrant corners can be expected only in perfect crystals containing no dislocations. For real crystals with dislocations, preferential growth can occur only when 1) screw dislocations active for growth converge along the trail of a twin junction, or 2) growth layers on the two sets of crystallographically equivalent faces meeting at the re-entrant twin junction and at the opposite twin junction where re-entrant corner is not present behave differently.

It has been proved by re-growth experiments (Sunagawa et al., 1979) and X-ray

topographic investigations (Yasuda and Sunagawa, 1982; Sunagawa and Yasuda, 1983) on Japanese twins of quartz crystals that the above two reasons were in fact responsible for the morphological characteristics of the twins. Since growth can be accelerated by other reasons than screw dislocations, it is to be expected that similar apparent re-entrant corner effect may occur due to other reasons than the above two. It is the purpose of this paper to report such an example observed on hematite crystals, in which impurities selectively precipitated at the twin junction play a role of growth accelerator, giving an apparent re-entrant corner effect.

Samples

Hematite crystals occur in network veinlets of cristobalite in a dacite lava at Sasazawa, Nagano Prefecture, Japan, and are assumed to have been crystallized through the chemical vapor transport process due to the post volcanic action of Kenashi volcano. Hematite crystals of similar mode of occurrence are found all over the world and they exclusively take thin platy habits which are different from the habits of hematite crystals occurring in hydrothermal veins or contact metamorphic deposits. The crystals from Sasazawa are also thin platy bounded by well developed $\{0001\}$, and narrow $\{10\bar{1}1\}$ and $\{11\bar{2}0\}$ faces.

The surface microtopographs of $\{0001\}$ faces of hematite crystals crystallized by natural chemical vapor transport process were extensively investigated by Sunagawa on the samples from all over the world (Sunagawa, 1960 a–d, 1961, 1962a, b). On their $\{0001\}$ faces, growth spirals with mono-molecular step heights are commonly observed, although their morphological characteristics are different from locality to locality. The crystals from Sasazawa show the following morphological characteristics which are different from those of other localities:

- 1) Twinned crystals with twin axis $[0001]$ and composition plane $(10\bar{1}0)$ occur more commonly than in other localities.
- 2) Twinned crystals take ribbon-like morphology elongated parallel to the trail of composition plane.
- 3) Growth layers on the $\{0001\}$ and $\{10\bar{1}1\}$ faces are less polygonized and very much undulated.

As to the origin of the undulated growth steps, it has been demonstrated that the crystallites of Mn–Ti rich phase epitaxially settled on the growing $\{0001\}$ surface were responsible, about which report will be made separately (Lu and Sunagawa, to be published). In this paper, we shall pay our main attention to the origin of morphological characteristics of twinned crystals. For this purpose, surface microtopographic characteristics of $\{0001\}$, $\{10\bar{1}1\}$ and $\{11\bar{2}0\}$ faces were investigated in connection with the twinning.

The observations were made by means of phase contrast and interference contrast microscopy, scanning electron microscopy, replica technique of electron microscopy and also by two-beam interferometry. In addition, chemical compositions of impurity crystallites selectively adsorbed along the twin boundary were analysed by means of an electronprobe microanalyzer (EPMA), and the strain distribution in the crystals was visualized by X-ray topography.

Observations

Morphology

Twinned crystals of hematite from Sasazawa are characterized by the ribbon-like morphology elongated parallel to $\langle 11\bar{2}0 \rangle$, with width, length and thickness sizes ranging from 0.2, 4.0, 0.1 mm to 3.0, 20.0, 1.5 mm, respectively, Fig. 1. The width: length ratios range from 1:25 to 1:5.

When crystals are simply twinned containing only one composition plane, they

FIG. 1. (a), (b) Two representative examples of ribbon-like morphology exhibited by simply twinned crystals of hematite from Sasazawa. Only one twin boundary, T.B., is seen on the (0001) face. Note the swallow-tails step pattern on the (0001) face in (b), (see text). Growth centers are indicated by arrows. (c) An example of multiply twinned crystals. Plural numbers of T.B. are seen on the (0001) face. Step pattern is also different from (a) and (b), and many growth centres (arrows) are seen over the whole (0001) surface.

exclusively take ribbon-like morphology with width: length ratio more than 1:20 (Fig. 1a), but they can take wider ribbon-like morphology (Fig. 1b) or even hexagonal platy habit (Fig. 1c) when twinning is more complicated. For narrower ribbon-like crystals, the twin boundary seen on the $\{0001\}$ face is straight and single (Fig. 1a), but for wider ribbon or hexagonal platy crystals the twin boundaries are plural (Fig. 1c), either parallel or inclined, and often show kinks and bents.

Surface microtopography of $\{0001\}$ and $\{10\bar{1}1\}$ faces

The step patterns on the $\{0001\}$ faces of hematite crystals, and particularly their relations to the twin boundaries were well documented by Sunagawa (1960b, c). He described in detail how growth layers on the $\{0001\}$ face behave when they advance across the twin boundaries. The present observations, together with his observations, on the surface microtopographs of $\{0001\}$ faces are summarized in the followings, and are schematically illustrated in Fig. 2.

- 1) When twinning is simple and contains only one or two parallel composition planes, growth centres on the $\{0001\}$ face usually situate close to the tip of the crystal, and the spiral growth layers with mono-molecular step height originating from them advance toward the tail (Figs. 1a, b, 2a, b and 3). They

FIG. 2. Schematically shows the interrelation among the external morphology, step patterns of $\{0001\}$ faces, and twinning. Twin boundaries, i.e. outcrops of composition plane on the $\{0001\}$ face, are indicated by a letter T.B.

advance with higher advance rates along the edges of the crystal. This results in a valley like step pattern with swallow tails extending along the elongation of the crystal, Fig. 1b, Fig. 2b.

- 2) When a (0001) face exhibits plural number of twin boundaries, parallel or inclined, and with kinks and bents, plural number of growth centres are observed over the whole surface and they are not localized close to the tip of the crystal (Figs. 1c, 2c). The (0001) face does not show swallow-tails step pattern.
- 3) The twin boundaries, i.e. the outcrops of composition planes on a (0001) face may be straight, bent, kinked or even curved, and occasionally twisted. There is a level difference on both sides of a twin boundary.
- 4) Bunched thick growth layers can advance across a twin boundary but create kinks there. Thin mono-molecular growth layers can not cross the boundary (Fig. 3). Although the original level difference on both sides of a twin boundary is too small to be detected even with highly sensitive microscopy, the twin boundary can be traced because the kinks on bunched thick layers align along it. Sunagawa (1960c) estimated that the original level difference was in

FIG. 3. A negative phase contrast photomicrograph showing the centres (arrows) of growth spirals close to the tip of a twinned crystal. T.B. indicates two parallel twin boundaries. Also note the behavior of thin and thick growth steps when they advance across a twin boundary.

the order of a fraction of a unit cell height.

- 5) Growth layers observed on the $\{0001\}$ face are undulated, which is a characteristic of the crystals from Sasazawa differing from those of other localities. The wavelengths of undulation become longer as the heights of growth layers increase.

Similarly as $\{0001\}$ faces, $\{10\bar{1}1\}$ faces parallel to the composition plane, i.e. to the elongation of a ribbon-like twin usually exhibit very flat surfaces on which growth spirals with mono-molecular step heights are seen. The growth spirals are more circular than those observed on the $\{0001\}$ faces, and are undulated with shorter wavelength (Fig. 4). Bunching of mono-molecular growth steps is less encountered on this face than on $\{0001\}$ face. In contrast to the extremely flat surface of the above $\{10\bar{1}1\}$ faces, crystallographically equivalent $\{10\bar{1}1\}$ faces which appear on the tip of an elongated crystal, i.e. those inclined to the composition plane, exclusively exhibit typical hopper surfaces. There is a deep depression at the centre of a face, surrounded by flat surface along the periphery of the face. Since the $\{10\bar{1}1\}$ faces meeting at a

FIG. 4. An example of growth spirals observed on flat $\{10\bar{1}1\}$ face, whose growth is not perturbed by twinning. The spiral steps are decorated by other phases after the cessation of growth. This increases their visibility. In the white areas, spiral steps which are not decorated are seen faintly on the original.

re-entrant twin junction are usually very small, it was not possible to observe their surface microtopography in detail.

Surface microtopography of $\{11\bar{2}0\}$ faces

Since the twin composition plane is $(10\bar{1}0)$, one set of $\{11\bar{2}0\}$ faces is perpendicular to the composition plane, whereas other two sets are inclined at 150° . Thus on the former surface, the composition planes outcrop, whereas on the latter they usually do not. The two types of $\{11\bar{2}0\}$ faces exhibit different surface microtopographs. The $\{11\bar{2}0\}$ faces containing no twin boundaries are characterized by a hopper nature, with flat surface around the periphery of the face and deep central depression, whereas the $\{11\bar{2}0\}$ faces containing twin boundaries are flat. The difference is seen in Figs. 5a, b, and 6a, b. Figs. 5a, b are negative phase contrast photomicrographs, and Figs. 6a, b, two-beam interferograms. On the flat area of $\{11\bar{2}0\}$ face containing no twin boundaries (Figs. 5b, 6b) straight steps parallel to the edges with $\{0001\}$ faces develop in a downward stepwise manner from both edges. Their step heights are in the order of 10 Å. Much shorter and thicker elongated steps with the same direction also originate from the edges with the neighbouring $\{10\bar{1}1\}$ faces. The step heights are 50 Å. The depth of the central depression is in the order of microns.

FIG. 5. Negative phase contrast photomicrographs of $\{11\bar{2}0\}$ faces containing two twin boundaries (T.B) (a) and without twin boundaries (b) on the same crystal. Note the flat surface in (a) and hoppered surface in (b).

On the surface of $\{11\bar{2}0\}$ face perpendicular to the twin composition plane, out-crops of twin boundaries running perpendicularly to and growth steps elongating parallel to the edges with $\{0001\}$ are seen on the extremely flat surface. The flatness of this surface may be judged from the interferogram (Fig. 6a), on which fringes run almost straight and in parallel. On both sides of a twin boundary, there is a level difference of the order of 400–500 Å (Figs. 7a, b). The surfaces of both sides of a twin boundary exhibit different characteristics of step patterns (Fig. 8). On the higher side (Fig. 8a left side of the twin boundary; also see Fig. 5a, left side of the twin boundary), growth steps parallel to the edge with $\{0001\}$ originate principally from both upper and lower edges and advance inward. Thus the surface has a profile, stepwisely going down from the edges with $\{0001\}$ toward the middle portion of the surface, although this stepwise profile is too faint to be detected even on the interferogram (Fig. 6a).

On the lower side of the twin boundary (Fig. 8a, right side of the twin boundary), a large number of heavily undulated steps are seen to originate from the bottom of the cliff created by the twin boundary and advance for a short distance, ca. 30 μm , parallel to the twin boundary (within the zones indicated by arrows in Fig. 8a). The steps parallel to the twin boundary are not continuous steps but consist of a series of coalesced rounded steps. Further away from the twin boundary, the steps become elon-

FIG. 6a, b. Two-beam interferograms corresponding to Figs. 5a and b.

FIG. 7. High magnification interferogram (a) and the corresponding profile of the twin boundaries on $(11\bar{2}0)$ face (b).

gated perpendicular to the twin boundary, i.e. parallel to the edges with $\{0001\}$ (Fig. 5a, right side of the twin boundary; also Fig. 8b, at a higher magnification). Although these steps developing on the lower side of the twin boundary appear similarly in their elongations as the steps developing on the higher side, their natures are different in two points. In contrast to the stepwise profile observed on the higher side of the twin boundary, the profile of the lower side surface is a valley and hill type. In contrast to the straight steps observed on the higher side, the steps on the lower side are undulated (Fig. 8b). Interferometric investigations have demonstrated that the heights of elongated growth steps on both sides of a twin boundary and also those appearing near the cliff of a twin boundary are in the order of $10 \text{ \AA}$. Thus the whole surface produces a

FIG. 8. Enlarged negative phase-contrast photomicrograph to show the difference of step patterns of $(\bar{1}2\bar{1}0)A, B$ faces on the higher (left side of T.B in (a)) and lower (right side of T.B in (a), and (b)) sides of a twin boundary.

FIG. 9. Etch hillocks appearing selectively along the twin boundaries outcropped on ($\bar{1}210$) (a) and (0001) (b) faces.

set of very smooth, straight and parallel interference fringes (Fig. 6a), demonstrating the extremely flat surface of $\{11\bar{2}0\}$ faces.

Concentration of impurities along the twin boundaries

When etching is applied to the $\{11\bar{2}0\}$ (Fig. 9a) and $\{0001\}$ (Fig. 9b) faces containing twin boundaries, arrays of etch hillocks, not etch pits, appear along the twin boundaries. As will be reported separately (Lu and Sunagawa, to be published), etch hillocks are formed because impurity crystallites of Mn–Ti rich phase play a role of resistance against etching. This was proved because such crystallites were seen at the summits of etch hillocks. The observation thus demonstrates that the crystallites of Mn–Ti rich phase concentrate along the twin composition plane. EPMA analyses of the vicinity of a twin boundary and the portion apart from the boundary have demonstrated that the contents of Mn and Ti are definitely higher in the former (Table 1).

TABLE 1. Comparison of EPMA data between the areas with and without twin boundaries.

	FeO	MnO	TiO ₂	Total
with twin boundary	84.40	1.38	0.35	86.13
without twin boundary	93.00	0	0	93.00

X-ray topography

An example of X-ray topographs of twinned crystals taken by the Lang method is shown in Fig. 10a, together with the corresponding surface microtopograph of the (0001) face, Fig. 10b. The X-ray topograph was taken with the diffraction vector $11\bar{2}0$ with Ag target for 6 hours. X-ray topographs with other diffraction vectors were also taken.

The hopper nature of the $\{10\bar{1}1\}$ faces at the tip of the elongated crystal (those inclined at an angle of 60° to the trail of the twin boundary) in Fig. 10a is immediately noticed because deep, oval shape voids are present in the corresponding growth sectors. The growth sectors of $\{10\bar{1}1\}$ and $\{11\bar{2}0\}$ faces meeting at the twin junction do not show hopper nature and appear to form the main bone of the crystal. Also, the growth sectors of $\{10\bar{1}1\}$ faces parallel to the elongation of the crystal do not exhibit contrast images of hopper nature.

On the X-ray topograph, both the twin boundary and the surface step pattern of the (0001) face are recorded as contrast images. Judging from the appearance and disappearance of contrast images under different diffraction images, it was clarified that the observed contrast images represent the strain fields accompanied to the precipitation of crystallites of Mn–Ti rich phase. Detail of this correspondence will be reported separately.

FIG. 10. An example of X-ray topographs of hematite twins from Sasazawa (a) and the corresponding surface microtopograph of the (0001) face (b) g vector is $11\bar{2}0$. By courtesy of K. Maiwa.

Discussion

The ribbon-like morphology of hematite twins is clearly due to the accelerated growth at the tips of elongation. The accelerated growth takes place on the $\{10\bar{1}1\}$ and $\{11\bar{2}0\}$ faces appearing at the tips of twinned crystals. For the sake of explanation, we shall denote these faces as indicated in Fig. 11. Accelerated growth takes place on $(\bar{1}011)_A$, B, $(\bar{1}2\bar{1}0)_A$, B, $(01\bar{1}1)_A$, B and $(11\bar{2}0)_A$, B of individual bodies A and B. Clearly, the growth of the faces parallel to the composition plane, $(10\bar{1}1)_A$, B is not accelerated.

On single hematite crystals from Sasazawa, $\{0001\}$ faces develop the largest, followed by $\{10\bar{1}1\}$ and then $\{11\bar{2}0\}$ faces. Their normal growth rates are $R_{0001} \ll R_{10\bar{1}1} < R_{11\bar{2}0}$ when the crystal is single. The difference is represented on the surface microtopographic characteristics of respective faces on single crystals. Growth spirals of monomolecular step heights are observed on both $\{0001\}$ and $\{10\bar{1}1\}$ faces, but not on $\{11\bar{2}0\}$ face, which shows only parallel step systems and hopped surfaces. The spirals observed on $\{10\bar{1}1\}$ faces are more circular and have narrower step separations than those on $\{0001\}$ faces. Therefore, the $\{0001\}$ interface was the most smooth, followed by $\{10\bar{1}1\}$, and the $\{11\bar{2}0\}$ interface was the least smooth (Sunagawa, 1981, 1982) when the growth was not accelerated by the introduction of twinning.

In contrast to these characteristics observed on single crystals, the corresponding faces appearing at the tips of twinned crystals show markedly different surface microtopographs. The $(\bar{1}2\bar{1}0)_A$, B faces exhibit flat surface on twinned crystals, in contrast to the hopper surface on single crystals. The $(01\bar{1}1)_A$, B faces take on hopped surface on twinned crystals, in contrast to the smooth surface on single crystals. These characteristics are indicative of that accelerated growth took place at the tips of twinned crystals. Also noted are marked differences between the faces directly related to the twin junction and those having no direct relation.

Although $(\bar{1}011)_A$, B and $(01\bar{1}1)_A$, B, and $(\bar{1}2\bar{1}0)_A$, B and $(11\bar{2}0)_A$, B faces are crystallographically equivalent, respectively, their surface microtopographs and X-ray topographs are distinctly different. Both $(\bar{1}011)_A$, B and $(\bar{1}2\bar{1}0)_A$, B, which have a

FIG. 11. Indexing individual faces on an elongated ribbon-like twin crystal for the sake of explanation in the text.

direct relation with the twin junction, exhibit flat surfaces and solid growth sectors. In contrast, both $(01\bar{1}1)_A$, B and $(11\bar{2}0)_A$, B faces exhibit hopper surfaces and contain voids in their growth sectors. The growth modes are different between the two groups of faces. These observations indicate that the growth of $(\bar{1}011)_A$, B and $(\bar{1}2\bar{1}0)_A$, B faces leads the growth of a ribbon-like twinned crystal. The backbone of the crystal is constructed initially by the accelerated growth on these faces, and the growth of $(01\bar{1}1)_A$, B and $(11\bar{2}0)_A$, B faces follows later. This is analogous to the growth of main branch, followed by the appearance of secondary branches, in dendritic crystals. The growth of $(10\bar{1}1)_A$, B faces is not affected at all by the introduction of twinning.

Now the problem is to clarify the origin for the accelerated growth. As possible causes, we may nominate 1) twin re-entrant corner, 2) concentrated dislocations of screw type, and 3) selective adsorption of impurities along twin boundaries. Suppose that the growth of $(\bar{1}011)_A$ and $(\bar{1}011)_B$ faces meeting at the twin re-entrant junction, is accelerated and increased larger than R $(\bar{1}2\bar{1}0)_A$, B faces, because of the introduction of a re-entrant corner by twinning. The two $(\bar{1}011)_A$, B faces will soon disappear and be replaced by the $(\bar{1}2\bar{1}0)_A$, B faces (Fig. 12b). Since $(\bar{1}2\bar{1}0)_A$, B faces are perpendicular to the composition plane, there is no more re-entrant corner present at the twin junction. By geometry, the $(\bar{1}2\bar{1}0)_A$, B faces will be replaced by $(01\bar{1}1)_A$, B faces, which will meet with each other at the twin junction with a protruding angle of 120° , Fig. 12b. The resultant morphology of a twinned crystal is thus a slightly elongated hexagonal plate, and not a ribbon-like morphology, if we assume that the presence of a re-entrant corner is the unique cause to accelerate the growth. We therefore exclude the simple presence of a re-entrant corner as a possible origin for the accelerated

FIG. 12. Schematic illustration of expected morphology of hematite twin, projected along the c-axis when only re-entrant corner effect is operative. (a) shows the twin relation, (b) shows the expected morphology when the re-entrant corner is the unique cause for the accelerated growth. Dotted lines represent the traces of outline of a growing crystal.

growth.

The observations on the surface microtopographs of $(\bar{1}2\bar{1}0)A$, B faces containing twin boundaries have demonstrated that

- 1) there is a level difference of about 500 Å on both sides of a twin boundary,
- 2) surface microtopographs are different between the higher and the lower sides of a twin boundary.

EPMA analysis coupled with these observations has also demonstrated that

- 3) crystallites of Mn–Ti rich phase concentrate along the twin boundary,
- 4) the difference in step patterns between the higher and the lower sides of a twin boundary, i.e. between $(\bar{1}2\bar{1}0)A$ and $(\bar{1}2\bar{1}0)B$ faces is related to the presence of these crystallites, and
- 5) due to their presence, growth layers are more frequently nucleated on the lower side, but not on the higher side. Namely, heterogeneous two dimensional nucleation is accelerated.

X-ray topography has also indicated the concentration of strain field along the twin composition plane, which is related to the presence of the crystallites.

It follows from these observations that the growth of $(\bar{1}2\bar{1}0)A$, $(\bar{1}2\bar{1}0)B$ faces meeting perpendicularly to the composition plane is accelerated because crystallites of Mn–Ti rich phase selectively precipitated along the lower side of a twin boundary, and they acted as the sites for heterogeneous two-dimensional nucleation. Since no spiral pattern is observed on these surfaces, the growth acceleration is not due to the self-perpetuating screw dislocations exposed on their surfaces, but due to the heterogeneous two-dimensional nucleation around the crystallites of Mn–Ti rich phase.

Possible sites for the selective precipitation of foreign phase to take place are either re-entrant corner or level difference at a twin junction. Their permanent presence throughout the whole growth history has to be assumed for both sites to obtain an elongated ribbon-like morphology.

If two individual bodies are different in size when they join together in twin orientation, a level difference is expected when the $(\bar{1}2\bar{1}0)A$ and $(\bar{1}2\bar{1}0)B$ faces on two individual bodies meet at a twin junction either directly or via a narrow ditch of a survived re-entrant corner. The level difference of this type is also self-perpetuating throughout the growth, since the growth front of the accelerated side will advance beyond the other side, which produces a cliff of opposite sign. This will occur alternatively, and thus the cliff remains permanently although the signs change alternatively.

The size of crystallites of Mn–Ti rich phase is around 0.3 μm as determined by the replica technique of electron microscopy. If the width of re-entrant corner on a twinned crystal become smaller than this value, the corner will be encapsulated by the crystallites, and the re-entrant corner will cease its role as a possible preferential

site for the precipitation of crystallites. Therefore, the initial size of hematite crystals when they were coalesced in twin orientation should have been larger than this value, $0.3\text{ }\mu\text{m}$, so that the re-entrant corner can survive.

From the preceding discussions, we may conclude that almost unceased accelerated growth at the twin junction, which is the reason for the ribbon-like morphology, is not simply due to the presence of re-entrant corner, neither due to the concentration of screw type dislocations along the twin boundaries, but due to the heterogeneous two-dimensional nucleation around crystallites of Mn–Ti rich phase, which are selectively precipitated along the twin junction. The selective precipitation occurs because of the presence of twin re-entrant corner formed by $(\bar{1}011)\text{A}$, B faces and of a cliff along the twin junction on the $(\bar{1}2\bar{1}0)\text{A}$, B faces.

On the interferograms of $(\bar{1}2\bar{1}0)\text{A}$, $(\bar{1}2\bar{1}0)\text{B}$ faces containing twin boundaries (Fig. 7a), a ditch with a depth of around $200\text{ }\text{\AA}$ and a width around $30\text{ }\mu\text{m}$ is seen parallel to the twin boundaries. Although the detail of the profile of the ditch is not discernible, this ditch should correspond to the survived re-entrant corner where $(\bar{1}011)\text{A}$, and $(\bar{1}011)\text{B}$ faces meet. Then the width should correspond to the original width of the re-entrant corner, at the beginning of twin formation.

Since this twinning is a rotation twin around the $[0001]$ with composition plane $(10\bar{1}0)$, two equivalent re-entrant corners appear at the twin junction on both ends (Fig. 12a). If the crystal grows in an open space, both ends may behave similarly, but if it grows standing on the vein wall, growth occurs only at one end. In reality, the latter is the case in most crystals, and accelerated growth occurs only at one end. This is the reason for the appearance of swallow-tails step patterns on the (0001) surface (Figs. 1b, 2b). The so-called Berg effect (Berg, 1938) is also partly responsible for the formation of swallow-tails step patterns.

When a crystal is multiply twinned, there are several preferential sites for growth. This is the reason for a wide ribbon or hexagonal platy habit exhibited by multiply twinned crystals, and the surface microtopographic characteristics of their $\{0001\}$ faces, such as seen in Figs. 1c, 2c.

Yasuda and Sunagawa (1982) and Sunagawa and Yasuda (1983) have recently demonstrated that the flattened morphology of quartz twins after Japanese law (contact twin, with the c axes being inclined at $84^\circ 33'$, and composition plane $(11\bar{2}2)$) is not due to the presence of re-entrant corner itself, but due to the concentration of screw dislocations along the composition plane. They have also shown that so far as $\{10\bar{1}1\}$ faces meet at the twin junction, accelerated growth can continue and the twinned crystal is flattened and elongated along the twin junction, but once $\{10\bar{1}0\}$ faces appear at the twin junction, the accelerated growth is ceased to operate, and the morphology changes from an elongated fan-like form to V form. They explained this transformation from fan-like to V form in terms of difference of screw dislocations as

active growth centers on the two types of faces. Dislocations run perpendicularly to $(10\bar{1}1)$ and are active as growth sites on this face, whereas they are inclined to $(10\bar{1}0)$ and thus become less active.

In the case of hematite, neither the proof for the outcrops of screw type dislocations nor the evidence to support their role in accelerating growth have been obtained on the $(\bar{1}2\bar{1}0)A, B$ faces meeting at the twin junction. It appears that crystallites of Mn–Ti rich phase took over the role of screw dislocations seen in quartz twins after Japanese law. Although the causes for accelerated growth are different between quartz and hematite, it is common in both cases that the simple presence of a twin re-entrant corner cannot provide the observed accelerated growth at twin junction. The concentration of either dislocations or impurities along the twin junction is the principal cause to accelerate the growth. It is also commonly observed in both cases that twinned crystals can take elongated morphology only when the causes for accelerated growth present at the twin junction throughout the growth history.

Conclusion

The origin of ribbon-like morphology exhibited by hematite crystals twinned by the rotation around $[0001]$ with composition plane $(10\bar{1}0)$ can be accounted for in terms of accelerated growth on both $\{10\bar{1}1\}$ and $\{11\bar{2}0\}$ faces meeting at the twin junction. The growth on these faces is accelerated because the rate of heterogeneous two dimensional nucleation, which act as a source for new growth layers, increases around the crystallites of Mn–Ti rich phase selectively precipitation along the composition plane. The selective precipitation occurs because the re-entrant corner formed by $\{10\bar{1}1\}$ faces of two individual bodies is survived and the cliff appeared on the $\{11\bar{2}0\}$ faces containing twin boundaries is self-perpetuating.

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References

- BECKE, F. (1911) *Forsch. Mineral. Kristallogr. Petrogy*, **1**, 68-85.
- BERG, W. F. (1938) *Proc. Roy. Soc. (London)*, **A614**, 79-95.
- CHUDoba, K. (1927) *Zeits. Kristallogr.*, **65**, 722-728.
- HARTMAN, P. (1956) *Zeits. Kristallogr.*, **107**, 225-237.
- KITAMURA, M., HOSOYA, S. & SUNAGAWA, I. (1979) *Journ. Crystal Growth*, **47**, 93-99.

- SUNAGAWA, I. (1960a) *Amer. Miner.*, **45**, 566-575.
SUNAGAWA, I. (1960b) *Mineral. Journ.*, **3**, 59-89.
SUNAGAWA, I. (1960c) *Lucas Mallada.*, **7**, 45-57.
SUNAGAWA, I. (1960d) *Serv. Geol. Portugal Mem.*, **6**, 44 p.
SUNAGAWA, I. (1961) *Amer. Miner.*, **46**, 1216-1226.
SUNAGAWA, I. (1962a) *Amer. Miner.*, **47**, 1139-1155.
SUNAGAWA, I. (1962b) *Amer. Miner.*, **47**, 1332-1335.
SUNAGAWA, I. (1981) *Bull. Mineral. (France)*, **104**, 81-87.
SUNAGAWA, I. (1982) *Estudios Geologicos*, **38**, 127-134.
SUNAGAWA, I., TAKAHASHI, T., AONUMA, K. & TAKAHASHI, M. (1979) *Phys. Chem. Minerals*, **5**, 53-63.
SUNAGAWA, I. & YASUDA, T. (1983) *Journ. Crystal Growth*, **65**, 43-49.
YASUDA, T. & SUNAGAWA, I. (1982) *Phys. Chem. Minerals*, **8**, 121-127.

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