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## THE MORPHOLOGY AND SUBSTRUCTURE OF BUTTERFLY MARTENSITE IN FERROUS ALLOYS

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**Abstract.**— A transmission electron microscopy and diffraction study of butterfly martensite in Fe-Ni-Cr-C alloys was carried out with particular attention to details of the martensite substructure. It was confirmed that a butterfly martensite is consisted with two plates with  $(252)_f$  and  $(252)_f$  habit plane variants having the junction plane near  $(100)_f$ .  $\{112\}_b$  twins, lengthy dislocations and  $\{101\}_b$  planar defects were observed as substructures of butterfly martensite. Observed  $\{112\}_b$  twins were not shaped as parallelograms, and twin edges inside a martensite plate were not parallel to the twinning shear direction  $[\bar{1}\bar{1}1]_b$  in contrast to those in Fe-Ni lenticular martensite. The majority of the lengthy dislocations were seen parallel to  $[\bar{1}\bar{1}\bar{1}]_b$  which is close to the shape strain direction of the  $(252)_f$  variant.  $(011)_b$  planar defects considered to be produced by the coalescence of martensite platelets were often observed. In the surrounding austenite slip on  $(111)_f$  planes probably produced by the accommodation of the transformation shape strain were observed. In general, although butterfly martensite exhibits a unique paired morphology, its substructures were found to be quite similar to those observed in other morphology of martensite with the same  $\{225\}_f$  habit.

## I. Introduction

In ferrous alloys at least four different morphologies of bcc(bct) martensites have been recognized, i.e. lath[1], butterfly[2], lenticular[1] and thin plate[4] martensites. In spite of many previous works on the morphology and substructures of ferrous martensites, little is known about butterfly martensite[2,4-6] probably because it forms above room temperature in most of the alloys. Our previous investigation[7] revealed that a butterfly martensite consisted with special pair of variants such as  $(252)_f$  and  $(\bar{2}52)_f$ . The optical microscope observation showed that there are two types of butterfly martensites; type A is characterized by thin wings, smooth and straight austenite-martensite interfaces and without a mid-rib while type B is characterized by thicker wings and an existence of a mid-rib. In this paper, recent observation made with transmission electron microscopy on the morphology and substructure of butterfly martensite in Fe-Ni-Cr-C alloys are presented.

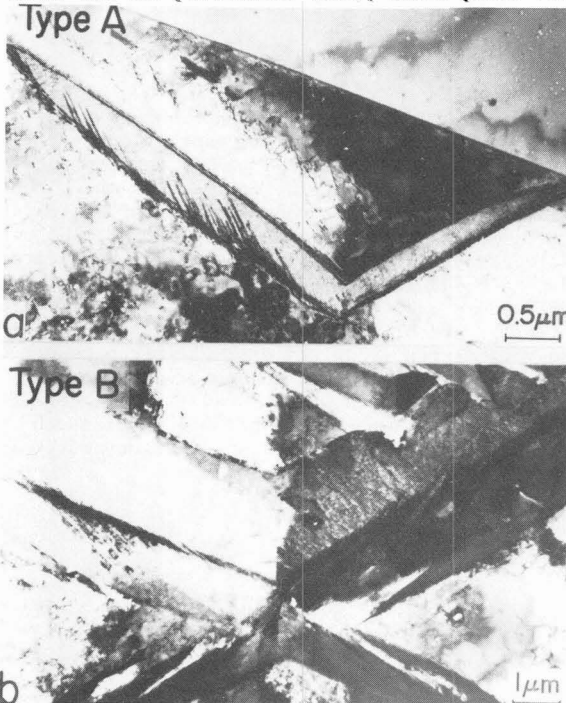
## II. Experimental Procedure

Fe-18.3Ni-1.0Cr-0.50C(wt%) ( $M_s=243K$ ), Fe-27.4Ni-1.3Cr-0.08C ( $M_s=230K$ ) and Fe-32.2Ni ( $M_s=193K$ ) alloys used were prepared by vacuum induction melting. Two Fe-Ni-Cr-C alloys exhibited butterfly martensite and Fe-Ni alloy showed lenticular martensite. The ingots were hot-forged at 1373K to produce sheets about 10mm in thickness, and then homogenized in vacuum at 1473K for 20h. After being homogenized, they were cold-rolled down to 0.5mm thick. Specimens were austenitized in vacuum at 1473 or 1273K for 1h and air-cooled to room temperature. Foils for transmission electron microscopy were prepared by chemical and electro polishing, and examined in JEM-200CX and 100CX microscopes.

## III. Results and Discussion

## (1) General Features of Butterfly Martensite

Photographs 1(a) and (b) show the typical examples of transmission electron micrographs of type A and type B butterfly martensites, respectively. It was reconfirmed from diffraction and trace analysis that a butterfly martensite is composed of two plates with  $(252)_f$  and  $(252)_f$  habit plane variants and the junction plane of these plates is near  $(100)_f$ . As is seen the austenite-martensite interfaces are relatively smooth but the junction plane of two plates is irregular and not a simple flat plane. The dark parallel bands seen in each plate are  $\{112\}_b$  transformation twins and the particular  $(252)_f$  habit plane variant is associated with the  $(112)_b$



twins. In type A butterfly martensite  $\{112\}_b$  transformation twins were observed only at the outer surface and they appear to extend upwards. Thus the outer surface of the type A butterfly martensite is considered to correspond to the nucleation side (mid-rib) and martensite plate grow only to one-side. In type B butterfly martensite a mid-rib is observed around the center of each plate along the longitudinal direction. It was noted that such mid-ribs in the two plates are continuous at the junction plane. The  $\{112\}_b$  transformation twins are localized at the center mid-rib region of the each plate and appear to extend towards both interfaces from a mid-rib region. Photo.2 shows a butterfly martensite which exhibits both features of type A and B. As is seen the plate in the left hand side shows twins only at the outer surface while the plate in the right hand side exhibits a mid-rib along the length of plate. The existence of such a butterfly martensite indicates that type A and B butterfly martensite forms under the same formation condition. Thus, the differ-

Photo.1 Electron micrographs showing typical butterfly martensites formed in Fe-18Ni-1Cr-0.50C cooled to 233K: (a) type A; (b) type B.

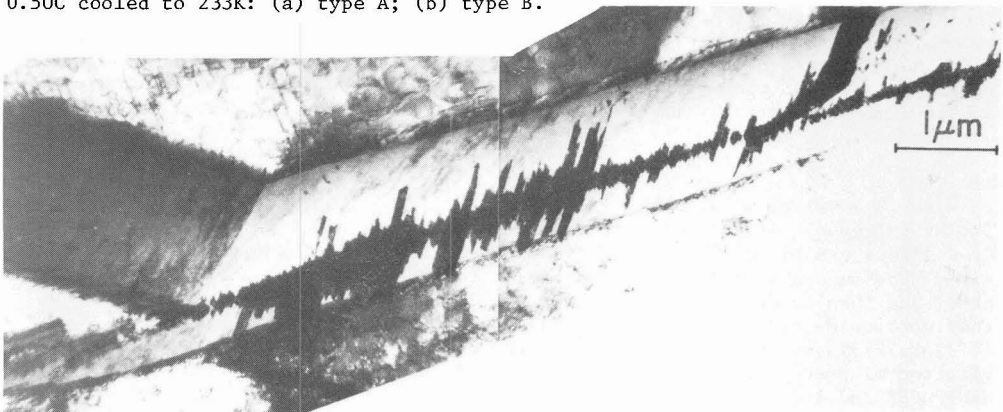


Photo.2 Electron micrograph showing a butterfly martensite exhibits both features of type A and B. Fe-18Ni-1Cr-0.50C cooled to 233K.

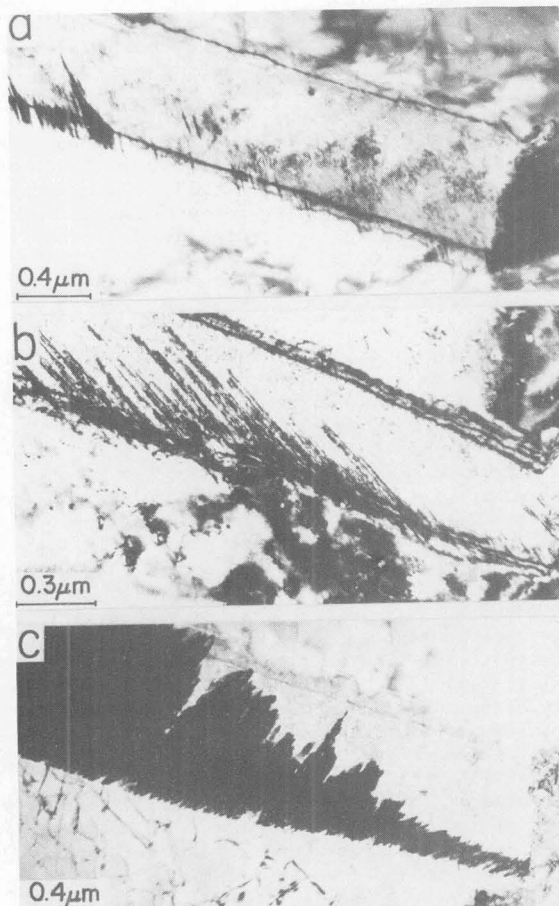


Photo.3 Electron micrographs showing the variation of the extension of  $\{112\}_b$  twins. Fe-18Ni-1Cr-0.5C cooled to 233K.

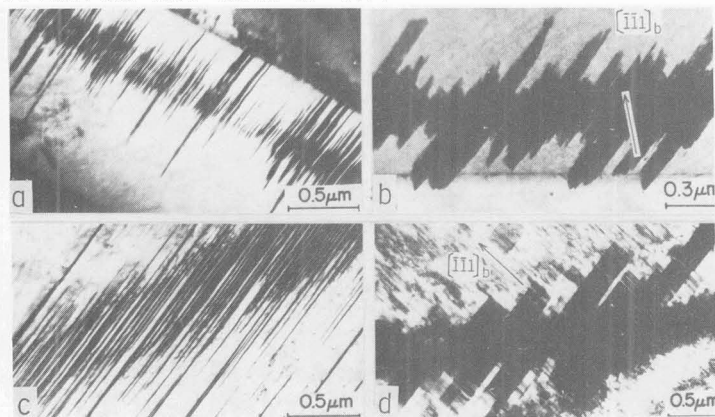


Photo.4 Comparison of the  $\{112\}_b$  transformation twins: (a)&(b) butterfly martensite in Fe-18Ni-1Cr-0.5C; (c)&(d) lenticular martensite in Fe-32Ni.

ence in the morphology between type A and B is considered to be produced just by the difference in the growth mechanism; whether one sided (type A) or growth on both sides (type B) from a mid-rib. In the present observation any further difference in substructures was not observed between these two types.

## (2) $\{112\}_b$ Transformation Twins

Although the  $\{112\}_b$  transformation twins were observed in every butterfly martensite plate formed by subzero cooling, the density and extension of twins in butterfly martensite varies extensively from plate to plate. Photo.3 shows three butterfly martensites of type A formed at different areas of the same specimen. In each micrograph the junction plane is located near the right edge. In (a) sparsely distributed twins are seen only near the outer surface, in (b) a somewhat higher density of twins is observed and some twins are extended to about the half width of the plate and in (c) a high density of twins is observed and some are extended completely from interface to interface.

The features of  $\{112\}_b$  twins in butterfly martensite is to be distinguished from those in Fe-Ni lenticular martensite. Photo.4 shows the difference observed in the thickness and shapes of the twins. Here (a) and (c) respectively show the  $\{112\}_b$  twins in butterfly and lenticular martensites when those are perpendicular to the foil surface. It is seen that in lenticular martensite density and thickness of twins are almost uniform throughout the plate but this is not the case for butterfly martensite (a). In butterfly martensite the thickness of twins varies from several nm to several tens of nm. It is interesting to note that in butterfly martensite twins are curved at the mid-rib region. Photo. 4(b) and (d) respectively show the case for butterfly and lenticular martensite where twin edges are easily to observe.

In lenticular martensite the twin edges are parallel to each other and to the twinning shear direction  $[\bar{1}\bar{1}\bar{1}]_b[8]$  as is seen in (d). For the martensite with  $\{225\}_f$  habit the intersection of the  $(112)_b$  twin plane with the  $(252)_f$  habit plane corresponds to the twinning shear direction  $[\bar{1}\bar{1}\bar{1}]_b$ . However, as is seen in (b) twin edges inside the martensite plate are rather irregular and not parallel to  $[\bar{1}\bar{1}\bar{1}]_b$  nor parallel to each other. It is noted that the features of  $(112)_b$  twins in butterfly martensite shown in Photo.4(a) and (b) are similar to those observed for twins of  $\{225\}_f$  martensite formed in Fe-Cr-C[9] or Fe-Mn-Cr-C[10] alloys although the martensite morphology is different. Thus it can be concluded that the features of  $\{112\}_b$  transformation twins depends mostly on the crystallographic orientation of the habit plane, that is whether it is  $\{225\}_f$  or  $\{259\}_f$  or  $\{3,10,15\}$ .

### (3) Other Internal Defects

Photo.5 shows a butterfly martensite plate exhibiting several internal defects. A diffraction pattern taken from the martensite is given at the upper left corner and showed that the electron beam is parallel to  $[\bar{1}01]_b$ . The pattern was indexed so that the habit plane of the martensite is  $(252)_f$  which is  $(\bar{3}74)_b$  according to the Bain correspondence. From this specific orientation, traces of the habit plane and internal defects were analyzed. The transformation twins marked A are consistent with  $(112)_b$ . In untwinned region of plate, lengthy dislocation lines are seen in three directions. From trace analysis direction B where the majority of lengthy dislocations are seen is parallel to  $[\bar{1}\bar{1}\bar{1}]_b$ . This direction corresponds to  $[011]_f$  according to the Bain correspondence and is approximately parallel to the shape strain direction of the  $(252)_f$  habit. Direction C and D coincide with  $[010]_b$  and  $[111]_b$ , respectively. Since  $[\bar{1}\bar{1}\bar{1}]_b$ ,  $[010]_b$  and  $[111]_b$  directions are respectively the traces of  $(011)_b$ ,  $(101)_b$  and  $(011)_b$  planes on the specimen surface, these dislocations are considered to lie in these  $\{110\}_b$  planes. The direction of dislocations in each  $\{110\}_b$  plane is supposed to be  $[\bar{1}\bar{1}\bar{1}]_b$ ,  $[\bar{1}\bar{1}\bar{1}]_b$  and  $[111]_b$ . Since  $\langle 111 \rangle_b$  is one of the possible Burgers vector of  $\{110\}_b$  slip, these dislocations might be pure screw.

Photo.6 shows further examples of internal defects in a butterfly martensite plate. From diffraction pattern the foil plane was indexed as  $(\bar{3}\bar{1}3)_b$  so that the habit plane of the martensite plate is  $(252)_f$ . In this case the planar defects marked A and B are consistent with the traces of  $(101)_b$  and  $(011)_b$  planes, respectively. The direction C where a high density of lengthy dislocations is seen corresponds to the projection of the  $[\bar{1}\bar{1}\bar{1}]_b$  direction on the specimen surface. However, the direction parallel to the sparsely distributed dislocations marked D does not correspond to any  $\langle 111 \rangle_b$  type direction but is nearly parallel to the projection of the  $[213]_b$  direction on the specimen surface.

Photo.7 is a further example of  $(011)_b$  planar defects. This micrograph was taken from the martensite plate shown in Photo.5 at a slightly different diffracting

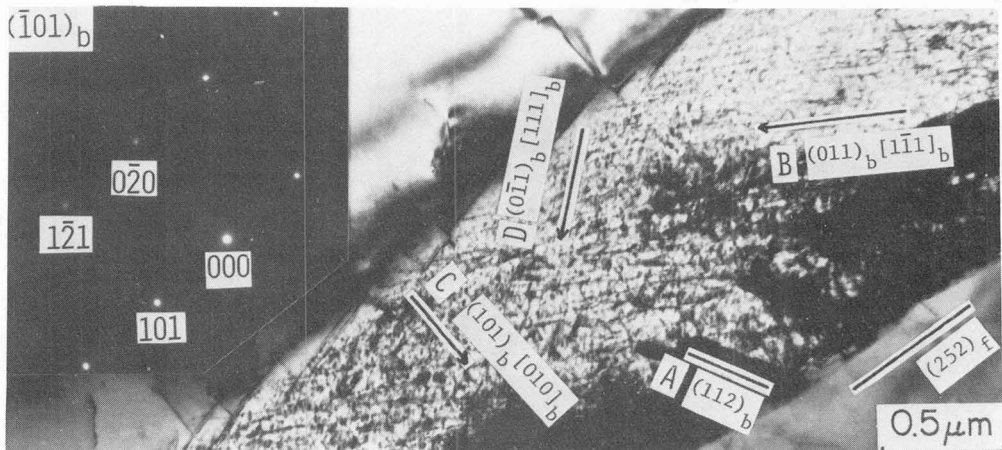


Photo.5 Electron micrograph showing  $(112)_b$  twins and lengthy dislocations parallel to three directions. Fe-27Ni-1.3Cr-0.08C cooled to 193K.

condition. From trace analysis trace A is nearly parallel to  $(011)_b$ . It is seen that the distribution of the  $(011)_b$  planar defects along the length of the plate is erratic and planes are somewhat curved. The martensite-austenite interfaces are often serrated associated with  $(011)_b$  planar defects. Similar  $(011)_b$  defects have been observed in  $\{225\}_f$  martensite formed in Fe-Cr-C[9] and Fe-Ni-Mn[11] alloys. Shimizu et al[9] suggested that these defects are  $(011)_b$  twins. In tetragonal martensite it is possible to form  $(011)_b$  twins. However,  $(011)_b$  defects other than twins must exist since similar  $(011)_b$  defects were observed in the cubic martensite formed in an Fe-Ni-Mn alloy. Kajiwara[11] suggested that these  $(011)_b$  defects in the martensite have been formed as a result of the coalescence of martensite platelets.

In the surrounding austenite a high density of dislocations was observed especially around tips of martensite plates. An example of such dislocations are shown in Photo.8. The foil plane is  $(001)_f$ . From trace analysis the two habits and junction planes were consistent with  $(252)_f$ ,  $(\bar{2}52)_f$  and  $(100)_f$  as indicated in the picture. It is seen that the  $(252)_f$  habit is associated with slip on  $(111)_f$  and the

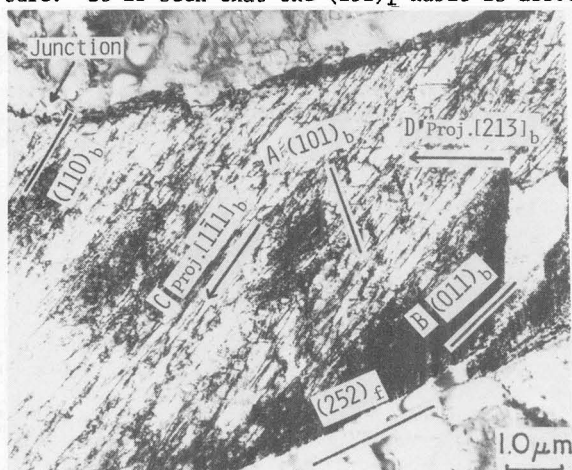


Photo.6 Electron micrograph showing  $\{110\}_b$  planar defects and lengthy dislocations. Fe-18Ni-1Cr-0.5C cooled to 228K.

Photo.9 demonstrates the possibility of coalescence of martensite platelets along  $(111)_f$  which corresponds to  $(011)_b$  according to the Bain correspondence. The

$(\bar{2}52)_f$  habit is associated with slip on  $(111)_f$ .

As previously proposed by Shimizu et al[12], the associated  $\{111\}_f$  austenite slips might be caused by an accommodation effect. For the particular  $(252)_f$  habit plane variant the nearest shear plane of the austenite is  $(111)_f$ , which makes an angle of  $25^\circ$  with the  $(252)_f$  variant. The shape strain direction of the commonly observed  $(252)_f$  variant is near  $[01\bar{1}]_f$ [10,13,14], which lie in  $(111)_f$ . Therefore, the shape strain of the martensite plate will be most effectively accommodated in the austenite if the slip on  $(111)_f$  is activated. However, it should be noted in Photo. 8 that dislocations in the surrounding austenite are not distributed uniformly along the length of plate but confined to the  $\{111\}_f$  planes around the tips of martensite plates.

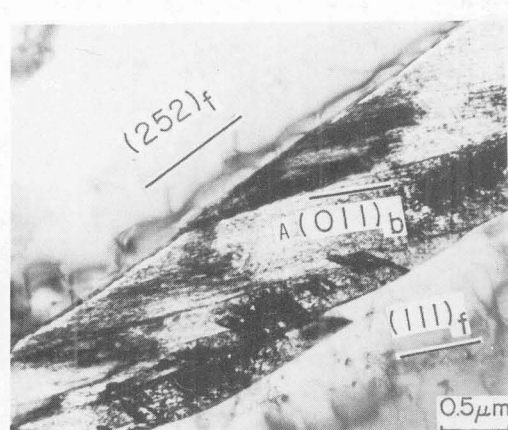


Photo.7 Electron micrograph showing  $(011)_b$  planar defects. Micrograph was taken from the same area with Photo.5.

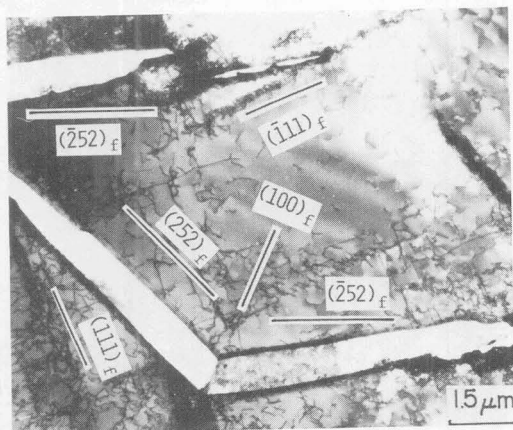


Photo.8 Electron micrograph showing associated slips. Fe-27Ni-1.3Cr-0.08C cooled to 193K.

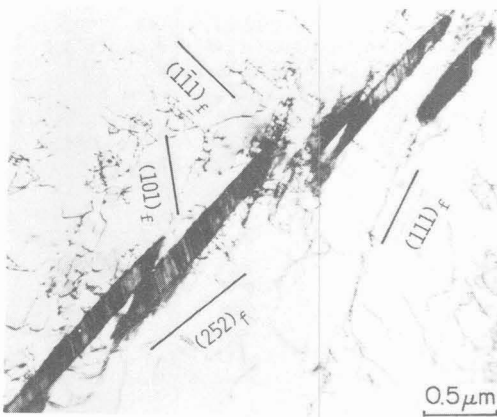


Photo.9 Electron micrograph showing segmented martensite platelets which are associated with austenite slip. Fe-18Ni-1Cr-0.5C cooled to 243K.

pair with the plate of particular  $(252)_f$  variant is not fully understood. In the present observation small martensite platelets in the near-nucleation stage whose thickness is less than  $0.2\mu\text{m}$  are often observed as single plates (not paired). This suggests that the second variant must be nucleated during the growth of the first plate. It is known [10,13,14] that the shape strain direction  $d_1$  for the martensite plates of  $(252)_f$  and  $(\bar{2}52)_f$  habit plane variants are close to each other and those are near  $[01\bar{1}]_f$ . Therefore plates of  $(252)_f$  and  $(\bar{2}52)_f$  habit plane variants could not form a self-accommodating pair. That is, the second plate would not be induced by the shape strain of the first plate. It is known that for the martensite of thin plate morphology, a 'kink' type morphology is often observed. This morphology is consisted with a pair of  $(3,15,10)_f$  and  $(\bar{3},15,10)_f$  variants and the junction plane is  $(100)_f$  [15]. Considering the morphological and crystallographic similarities between the 'kink' type and butterfly morphologies, it would be expected that there is an common formation mechanism operating these morphologies.

In summary, butterfly martensite plates of the particular  $(252)_f$  habit plane variants are associated with  $(112)_b$  transformation twins, lengthy dislocations mostly parallel to the shape strain direction  $[\bar{1}\bar{1}\bar{1}]_b$  and austenite slip on  $(111)_f$  plane. Moreover  $(011)_b$  planar defects probably formed by the coalescence of the martensite plates are often observed. In general, the substructures of butterfly martensite have many similarities to those of non-paired  $\{225\}_f$  martensite formed in other ferrous alloys either athermally [9,10,13] or isothermally [11].

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foil plane is  $(\bar{1}01)_f$ . In the picture several martensite platelets of  $(252)_f$  habit plane variants are seen and those are associated with the austenite slip on  $(111)_f$  planes. It appears that the dislocations on the  $(111)_f$  plane constrain the growth of martensite platelets on one side and also nucleates another martensite plate on another side. Thus these structures are considered to be formed by an autocatalytic nucleation, that is, an initially transformed plate generates  $(111)_f$  slip which in turn nucleates second plate of the same variant, etc. The growth of these platelets produces boundaries along the  $(111)_f$  which is parallel to  $(011)_b$ . It should be noted that  $(111)_f$  and  $(011)_b$  planes are parallel close-packed planes of the two structures according to the K-S orientation relationship.

The reason why the plate of a particular  $(252)_f$  habit plane variant forms a