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Ferromagnetic Domain Patterns on Nickel Crystals. II
Domain Patterns on General Surfaces of Unmagnetized Crystals*

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Synopsis

Ferromagnetic domain patterns were observed, with the magnetic colloid technique, on the hemispherical surfaces of unmagnetized nickel crystals. The complicated domain patterns observed on general crystal surfaces were interpreted thoroughly by comparing them with one another, starting from the previously clarified domain patterns on the (110) and (211) surfaces.

I. Introduction

In a previous paper(1), we presented and considered fully ferromagnetic domain patterns of various types observed on the (110) surface of unmagnetized nickel crystals and clarified the general character of the domain structure in a cubic crystal with the directions of easy magnetization along <111> directions. We also discussed in some detail domain patterns characteristic to the (211), (100) and (111) surfaces; the pattern on the (211) surfaces was found to be easily interpretable, while the details of complicated patterns on (100) and (111) surfaces remained unexplained. Domain patterns on nickel crystals are expected to be generally complicated as compared with those on iron crystals, since nickel has more directions of easy magnetization, lower wall energy(2), and higher magnetostrictive energy associated with flux-closure domains(3). It is one of aims of the present investigation to interpret the (100) and (111) domain patterns of unmagnetized nickel crystals by taking into consideration these various factors.

On the other hand, exact informations regarding domain patterns on crystal surfaces of higher crystallographic indices are required in most problems such as the problem of domain structures as dependent on the over-all magnetization in a crystal of the rectangular-rod form, in which the structure and energy of flux-closure domains formed on its side surfaces play an important rôle(4), and the problem of the function of grain boundaries in the magnetization process of a

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* The 843rd report of the Research Institute for Iron, Steel and Other Metals.

(1) M. Yamamoto and T. Iwata, Sci. Rep. RITU, **A5** (1953), 433, which will be referred to as [I] in this paper.

(2) B. A. Lilley, Phil. Mag., **41** (1950), 792.

(3) C. Kittel, Rev. Mod. Phys., **21** (1949), 541.

(4) For example, in an iron single crystal of the rectangular-rod form, surrounded by (100) and (011) surfaces, domain structures appearing on the side surfaces (011) play an important rôle in the magnetization process. Cf. L. Néel, J. de phys., [8] **5** (1944), 265; L. F. Bates and C. D. Mee, Proc. Phys. Soc., **A65** (1952), 129; E. W. Lee, Proc. Phys. Soc., **A66** (1953), 623.

polycrystal. The interpretation of complicated domain patterns formed on general surfaces of unmagnetized nickel crystals is another aim of the present study.

To achieve these aims, we first scanned the domain patterns on the hemispherical surface of unmagnetized nickel crystals, of which the radii are far larger than the width of domains, and constructed a "pole figure" of domain patterns. Then, we examined all parts of the "pole figure" successively, starting from the previously clarified (110) and (211) parts by comparing them with one another and by pursuing the development and extinction of domains of the given types in them.

Finally, it must be noted that in the present part we have changed notations for non-180° domain walls and employed the notations used for a theoretical convenience for instance by Lilley(2) instead of the notations used by Bozorth *et al*(5). So the 109° and 71° walls in the present part correspond to the 71° and 109° walls in [I], respectively.

II. Crystal specimens and experimental procedure

The methods of preparation and of electropolishing of nickel single crystals used as specimens are the same as in [I]. Microscopic domain-pattern observations were made on hemispherical surfaces, about 1.5 cm in diameter, of single crystals, which were flattened by electropolishing (without any mechanical polishing), wet with magnetic colloid, and covered with a thin glass plate made convex (by heating) to fit the crystal surface.

If we proceed by 0.4 mm along a great circle on a spherical surface, of which the diameter is about 1.5 cm, the surface becomes inclined about 3° to the surface at the starting point, so that the domain pattern on this surface may be fairly different from the initial one. During this displacement (the corresponding distance in all the photographs shown later is about 4.8 cm), however, the domain pattern characteristic to a certain crystallographic surface appears several times repeatedly, though a progressive alteration in detailed points may be accompanied. Thus, even if dimensions of basic domains are determined by the size of the crystal, the size of our specimen crystals never alters essentially the general view of domain patterns on any crystal surface and thus the observed domain patterns serve as the basis of the general discussions.

It is sufficient, from symmetry, to examine the domain patterns on an area surrounded by the three great circles connecting two of neighbouring (100), (110) and (111) poles of a spherical crystal surface(Fig. 1). But, actually, the specimen crystals had many defects such as small holes and fine crystal grains of different orientations so that the complete examination of a specified (100)-(110)-(111) area was impossible. Consequently, photographs of domain patterns taken on several areas were selected and arranged to construct a polar pattern of a (100)-(110)-(111) area, paying a special attention to the fact that the main feature of domain pattern often varies according to the method of demagnetization and other inevitable causes,

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(5) R. M. Bozorth and J. G. Walker, Phys. Rev., **79** (1950), 888.

as pointed out in [I]. It is to be noted, therefore, that domain patterns in which certain parts are exaggerated or erased as compared with those shown hereafter may also be possible in practice (cf. Section IV).

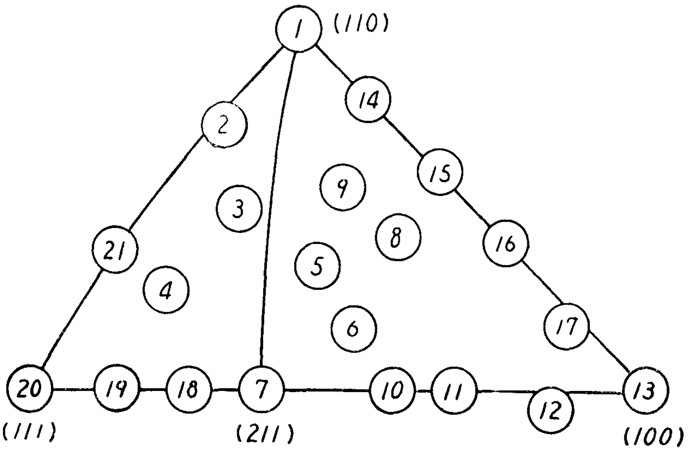

Fig. 1. Stereographic representation of positions on the hemispherical surface of nickel crystals where domain patterns were photographed. A circle represents approximately the area covered by a photograph.

Photographs of domain patterns, which were taken with weak magnetic field applied normally to the crystal surface for the sake of contrast, are reproduced in 120 magnification. Rough positions on a (100)-(110)-(111) area of the spherical crystal surface where the photographs were taken are shown stereographically in Fig. 1. A circle enclosing the number of a photograph represents approximately the area covered by the photograph.

III. Domain patterns on crystal surfaces ranging from the (110) plane to the (211) plane along the [$\bar{1}11$] zone and on nearby surfaces

The domain pattern observed on the (110) surface (Photo. 1) is essentially a modified parallelogram-net pattern, consisting of domains *K* and *L* magnetized, respectively, in the [$\bar{1}11$] and in the [$1\bar{1}1$] directions(6). The pattern also contains

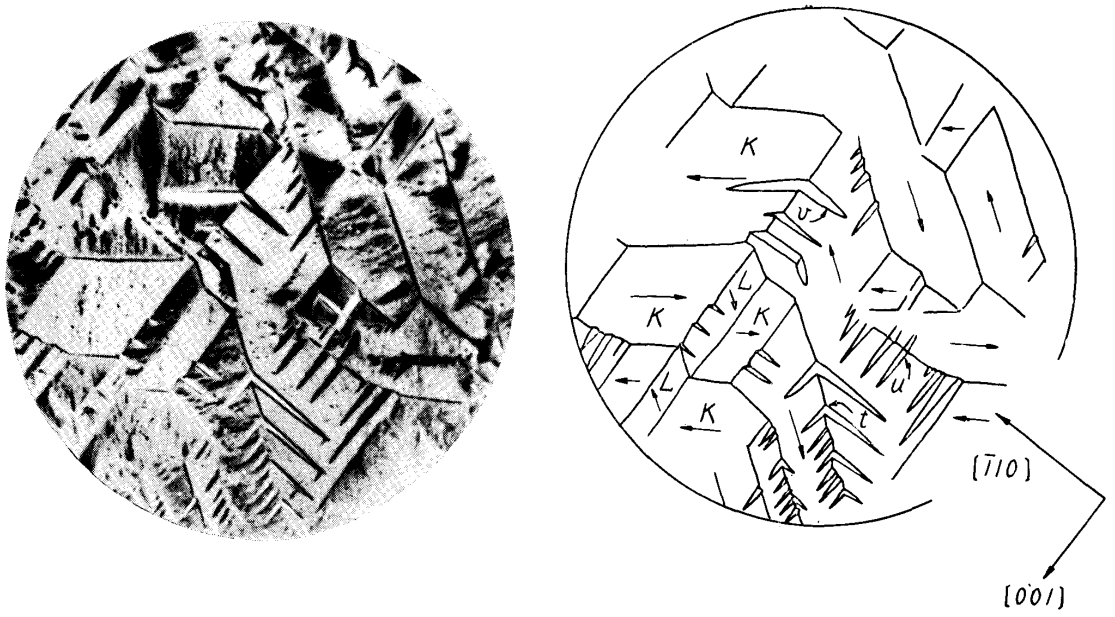

Photo. 1. Modified parallelogram-net pattern on the (110) surface composed of *K* and *L* domains, as containing tree patterns of three kinds. *t*, *u* and *v* are the tree patterns of the first, second and third kind, respectively.

three kinds of tree patterns composed of superficial branch domains, *t*, *u* and *v*, which are due to the over-all curvature and local unevenness of the crystal surface; *t*, *u* and *v* constitute tree patterns of the first, second, and third kind, respectively(7).

As we proceed from the (110) surface toward the (211) surface along the [$\bar{1}$11] zone, the *L* domains magnetized in [1$\bar{1}$1] direction degenerate progressively in consequence of an increase of the magnetostatic energy, since their magnetization vectors cut the surface with an increasing angle. These circumstances are seen in Photo. 2, which shows the domain pattern on a crystal surface near the (110) surface approximately in the [$\bar{1}$10] zone (cf. Fig. 1). The *K* and *L* domains carrying superficial *v* domains which constitute branches of the third-kind tree pattern occupy approximately the same area in the upper left part. And, as we proceed to the lower right part of the photograph, the *K* domains develop and the *L* domains degenerate gradually, accompanied with the diminution of fine superficial *v* domains on them and the basic domain structure comes to be composed only of plate-like *K'* domains which transformed from the *K* domains. The *L'* domain modified from the *L* domain comes to have the character of a branch domain of tree pattern in its appearance as well as in its function and it eventually degenerates into a branch domain such as *u'* or *l*. It is to be noted that these branch domains are of the lancet type which was interpreted previously in [I]. Further, Photo. 2 suggests that a slight deviation from parallelism of the two sides of the *L* domain running nearly along the [001] direction has a meaning similar to the narrowing of the joint (to the trunk or the basic domain wall) of the lancet-form branch domain.

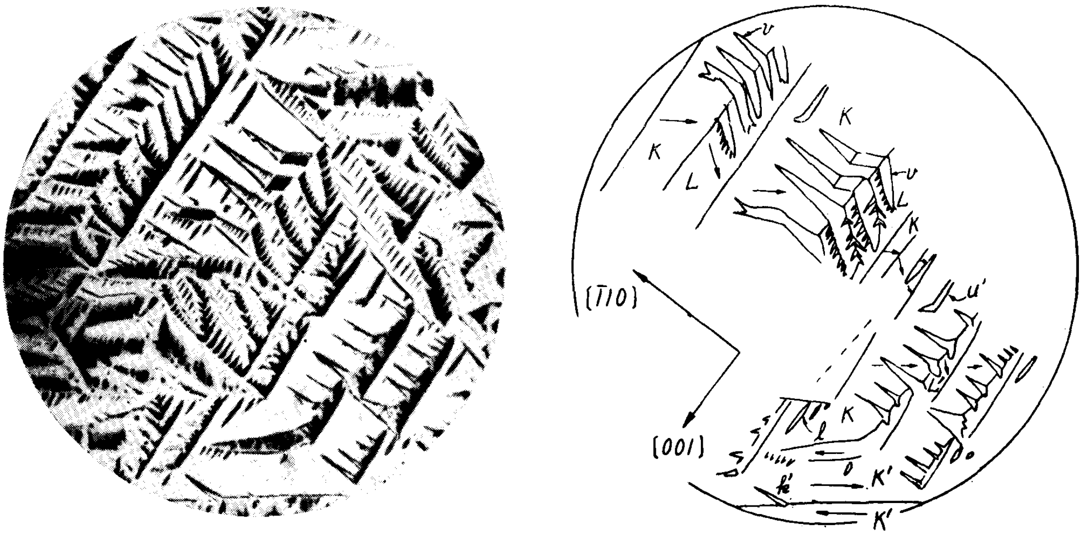

Photo. 2. Domain pattern on a surface near the (110) surface approximately in the [$\bar{1}$10] zone, showing the transition of the domain pattern from a modified parallelogram-net pattern (upper left portion) to a plate pattern (lowest portion).

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(6) Cf. Fig. 23 of [I]. The parallelogram-net pattern composed of 180° and 71° walls (109° walls in [I], see the end of Section I) was observed more frequently than that composed of 180° and 109° walls (71° walls in [I]), and this may be due to the fact that the energy of the 71° wall is lower than that of the 109° wall.

(7) Cf. Sections V, VII, and VIII of [I].

As we leave further from the (110) surface along a path in the (110)-(111)-(211) triangle (Fig. 1), the L' domain transforms further into a complicated branch domain l in Photos. 3 and 4. In Photo. 3 the branch domain l is radiated only from one side of a trunk or a 180° wall separating the K' domains. The left-side wall of the l branch domain radiates secondary branch domains Q' which may be regarded as an modification of the Q-type branch domain of the third-kind tree pattern(8). On crystal surfaces located near the [$\bar{1}$11] zone in the (110)-(211)-(100) triangle (Fig. 1), we observed another type of domain patterns roughly symmetric to those of Photo. 3, as might be expected (Photos. 5, 6, and 6a). These domain patterns will be considered later in Section IV.

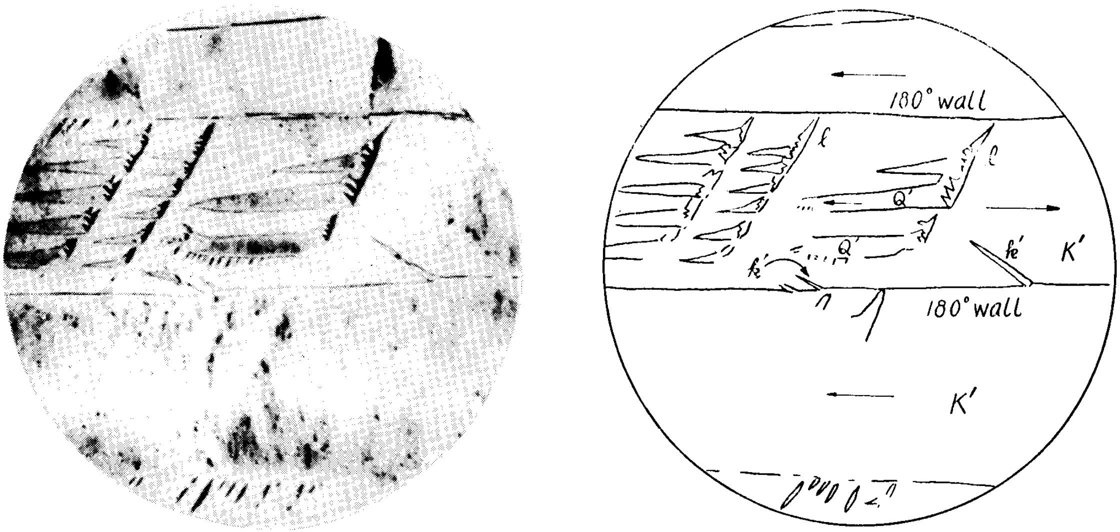

Photo. 3. One-side branch domains l radiated from the 180° wall separating K' domains, with secondary branch domains Q' magnetized antiparallel to the magnetization vector of the underlying K' domains.

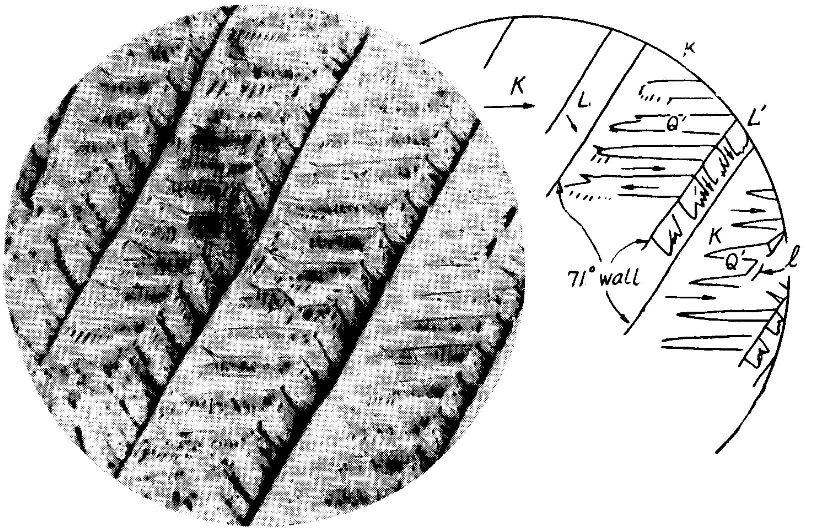

Photo. 4. Further development of complicated branch domains on the basic K and L domains on the crystal surface midway among the (110), (111) and (211) surfaces.

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(8) Cf. Section VIII of [I].

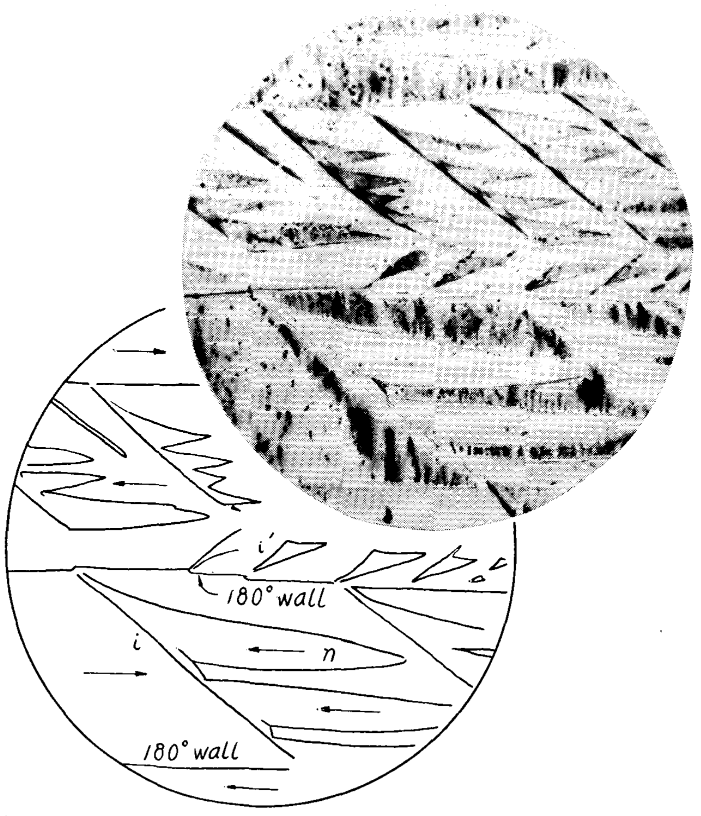

Photo. 5. Complicated tree pattern on the crystal surface inclined from the (211) plane towards the (100) and (110) planes. *i*, *n*, etc. are the same in Fig. 3.

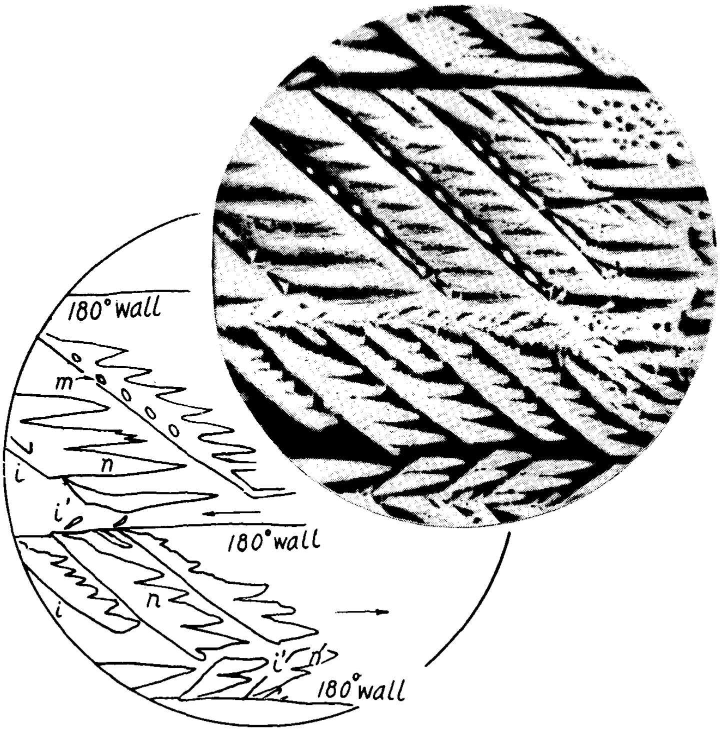

Photo. 6. Complicated tree pattern on the crystal surface slightly inclined from the (211) plane towards the (100) and (110) planes. *i*, *m*, *n*, etc. are the same as those in Fig. 3.

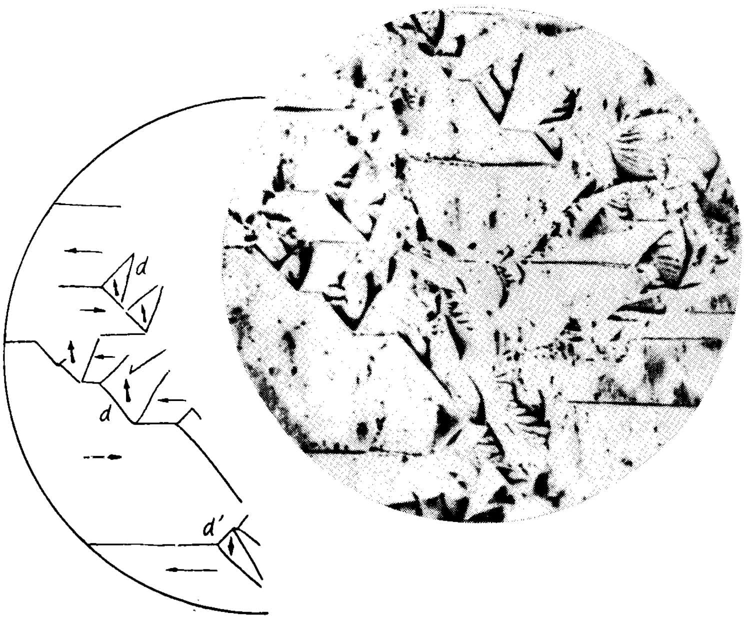

Photo. 6a. Domain pattern which often replaces those in Photos. 5 and 6.

In this way, the crystal surface gradually comes to be made up only by the K' domains, and thus the final form on the (211) surface is the plate pattern separated by 180° walls running along the [$\bar{1}$11] direction (Photo. 7).

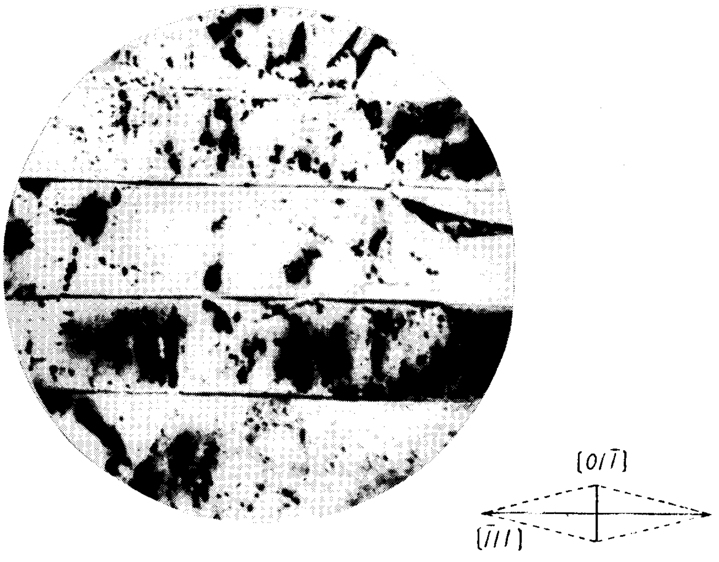

Photo. 7. Domain pattern on the (211) surface consisting of plate domains separated by 180° walls parallel to the [$\bar{1}$11] direction.

IV. Domain patterns on crystal surfaces ranging from the (211) plane to the (100) plane along the [0$\bar{1}$1] zone and on nearby crystal surfaces

Now we shall consider tree patterns which may appear on the crystal surface as it rotates gradually and slightly from the (211) plane towards the (100) plane

(Fig. 2(a)). Tentatively, we suppose that the shape of a branch domain is a prolonged ellipsoid cut by the crystal surface. The major axis of the ellipsoid, then, should be along one of bisectors of angles between magnetization vectors in the branch domain and in the underlying domain so as to reduce the energy of the demagnetizing field of the ellipsoid.

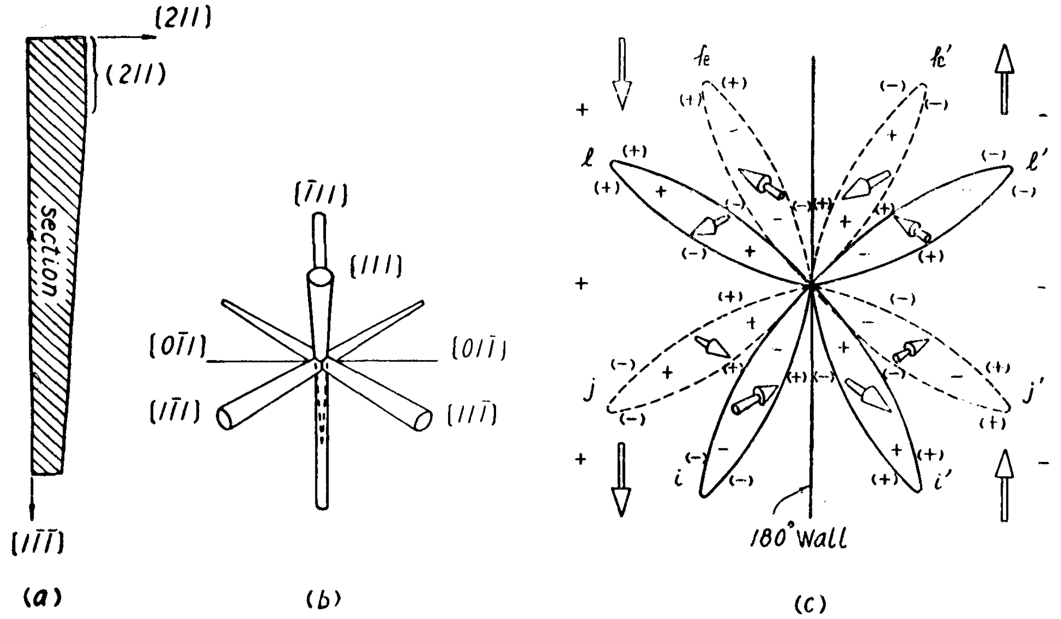

Fig. 2. Illustration for the formation of branch domains on the crystal surface slightly rotated from the (211) plane towards the (100) plane.

Possible branch domains are those whose magnetization vectors are, respectively, along the [111], $[1\bar{1}1]$ and $[11\bar{1}]$ directions, as shown in Fig. 2(b)(9), the latter two directions being inclined to the crystal surface concerned symmetrically with respect to the $[01\bar{1}]$ plane. These branch domains will be called, for simplicity, the [111], $[1\bar{1}1]$ and $[11\bar{1}]$ branch domains hereafter. It may readily be seen that the [111] branch domain need not be considered since it may be unstable because the angle of inclination of its magnetization vector to the crystal surface is much larger than those of magnetization vectors of the $[1\bar{1}1]$ and $[11\bar{1}]$ branch domains(10).

Let us consider, in the first place, the $[1\bar{1}1]$ and $[11\bar{1}]$ branch domains which will be radiated from the trunk (180° wall) on the $[0\bar{1}1]$ side, where the underlying domain has the magnetization vector pointing to the $[1\bar{1}\bar{1}]$ direction, and accordingly, it has positive free poles on the crystal surface (Fig. 2(c)). Since the $[1\bar{1}1]$ and $[11\bar{1}]$ directions cut the crystal surface at a fairly large angle, it may be considered that these branch domains, if they occur, reduce the energy of superficial free poles of underlying domains mainly by free poles appearing on

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(9) Crystallographic directions and magnetization vectors (arrows) are shown perspectively.

(10) The angle of inclination of the [111] direction is 70°32′ and that of the $[1\bar{1}1]$ and $[11\bar{1}]$ directions is 28°08′ when the crystal surface coincides with the (211) plane. As the crystal surface rotates toward the (100) plane, the former angle decreases and the latter increases, up to 35°16′.

their sections cut by the crystal surface and the effect of free poles on the wall enclosing the branch domains may be negligible(11). The directions of the magnetization vectors and of the major axes of *possible* $[1\bar{1}1]$ and $[11\bar{1}]$ branch domains as shown in Fig. 2(c) and the sign of free poles appearing on their sections cut by the crystal surface are given in the following table.

Branch domain	Direction of the magnetization vector	Direction of the major axis	Free poles on the section of the branch domain
l	$[1\bar{1}1]$	$[001]$	positive
i	$[\bar{1}1\bar{1}]$	$[1\bar{1}0]$	negative
j	$[11\bar{1}]$	$[0\bar{1}0]$	positive
k	$[\bar{1}\bar{1}1]$	$[\bar{1}01]$	negative

This table shows that *j* and *l* branch domains will create free poles of the same sign as those on the underlying domain on their sections cut by the crystal surface and so they may not be formed. On the contrary, *i* and *k* branch domains will create superficial free poles of the sign opposite to those on the underlying domain. But, if the *k* branch domain exists, its extreme part will be buried under the crystal surface owing to its geometrical nature, the area of the crystal surface cut by this branch domain being smaller, and consequently its formation is not so effective in reducing the magnetostatic energy of the underlying domain. Thus, after all, it may be concluded that only the *i* branch domains, magnetized in the $[\bar{1}1\bar{1}]$ direction and pointing to the "downhill" direction, will occur.

Now, an *i* branch domain has to extend into the sky so as to reduce the magnetostatic energy of the sky. Its extension may be more or less similar to that of the lancet-type branch domain discussed previously(12). In the present case, however, owing to the larger inclination of the major axis of the ellipsoid to the crystal surface(13), the slender extension of the branch domain has to be accompanied with the deviations of the direction of its major axis and of its shape from that of the originally supposed ellipsoid; the major axis of the *actual* branch domain does not lie in the $[1\bar{1}0]$ direction but coincides with an intersection of the (001) plane with the crystal surface, and the branch domain may become thin in width and become deeper, as shown in Fig. 3(b), as a result of the large density of free poles appearing along the bottom part of the branch (*r* in Fig. 3(b)). Further, as the magnetization vector in the *i* branch domain cuts the crystal surface with a fairly large angle, this branch domain may not be so favourable energetically. Therefore, the unstability of the *i* branch domain may be compensated by the occurrence of small secondary branch domains *m* in its interior,

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(11) The sign of free poles appearing on the domain wall enclosing possible branch domains are shown by plus or minus sign in the bracket in Fig. 2(c).

(12) Cf. Section VI of [I].

(13) This angle is 16°47′ when the crystal surface coincides with the (211) plane and increases up to 45° as the crystal surface rotates towards the (100) plane.

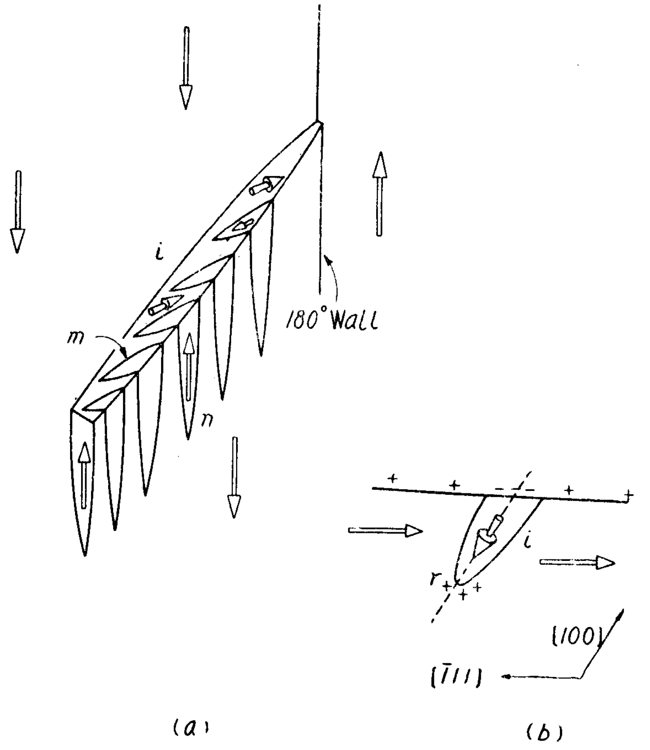

Fig. 3. Interpretation of the tree pattern observed on the crystal surface inclined slightly from the (211) plane towards the (100) plane. (b) shows a section of the *i* branch domain cut by the $(0\bar{1}1)$ plane.

and at the same time it may radiates, on the down-hill side, the secondary branch domains *n* which are magnetized antiparallel to the magnetization vector in the underlying domain and enclosed by the 180° wall, as illustrated in Fig. 3(a). It is to be noted, finally, that, since the direction· of the primary *i* branch domain is an intersection line of the (001) plane with the crystal surface, its inclination to the trunk is 39°15′ when the crystal surface coincides with the (211) plane, and it increases up to 45° as the crystal surface approaches to the (100) plane.

The domain patterns on another side of the trunk, namely, on the $[01\bar{1}]$ side, where the underlying domain has the magnetization vector pointing to the $[\bar{1}11]$ direction and accordingly has negative free poles on the crystal surface, can be interpreted similarly. The primary branch domains with the magnetization vector pointing to the $[11\bar{1}]$ direction (*i*′ in Fig. 2(c)) may be radiated at an angle of 39°15′ from the trunk. They are also accompanied with fringe domains whose magnetization vectors lie antiparallel to that of the underlying domain. Thus, the tree pattern on the crystal surface slightly inclined from the (211) plane towards the (100) plane may be symmetric on both sides of the trunk. Examples of this kind of tree patterns are actually seen in the lower part of Photo. 6.

As the crystal surface already inclined slightly from the (211) plane towards the (100) plane is further rotated towards the (110) plane, it cuts the magnetization vector along the $[\bar{1}1\bar{1}]$ direction at a decreasing angle and cuts the magnetization vector along the $[11\bar{1}]$ direction at an increasing angle, and thus the *i* branch domains on the $[0\bar{1}1]$ side of the trunk may become more stable while the *i*′ branch domains on the $[01\bar{1}]$ side of the trunk may become more unstable, as is evidenced by Photos. 6 and 5. Then, unstable *i*′ branch domains may gradually be replaced by new branch domains *j*′ as seen in Photo. 8, which are magnetized to the $[\bar{1}1\bar{1}]$ direction similarly to the *j*′ branch domains in Fig. 2(c). The effect of this new branch domain is mainly carried by free poles on their wall surface. Angles which the *i* and *j*′ branch domains make with the direction of the trunk ($[\bar{1}1\bar{1}]$ direction) change from 39°14′ and 58°31′ to 35°16′ and 54°44′, respectively, as the crystal surface rotates from the (211) plane to the (110) plane. Thus, the newly formed tree pattern is asymmetric on both sides of the trunk, and becomes a tree pattern of the first kind on a nearly (110) surface.

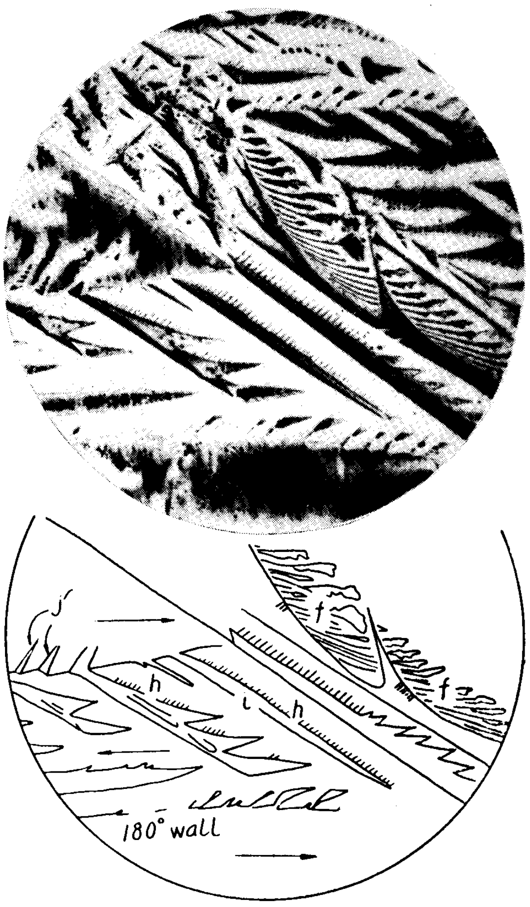

Photo. 8. Domain patterns on the crystal surface midway in the (100)-(110)-(211) triangle.

It is to be noted here that slender *i* branch domains on the lower side of the trunk in the central part of Photo. 8 have many fine hair-like secondary branch domains radiating nearly at the right angle to them (indicated by *h*). These secondary branch domains may have the same nature as the tree pattern of the type transient from the first kind to the second kind discussed in Section VI of [I]. Further, it may be seen that the j' branch domains on the upper side of the trunk in Photo. 8 have an internal structure due certainly to an increase of inclination of their magnetization vectors to the crystal surface. Such internal structure of the j' branch domains also appears in a magnified form in triangular patterns *D* in Photo. 9, in which the trunk (180° wall)

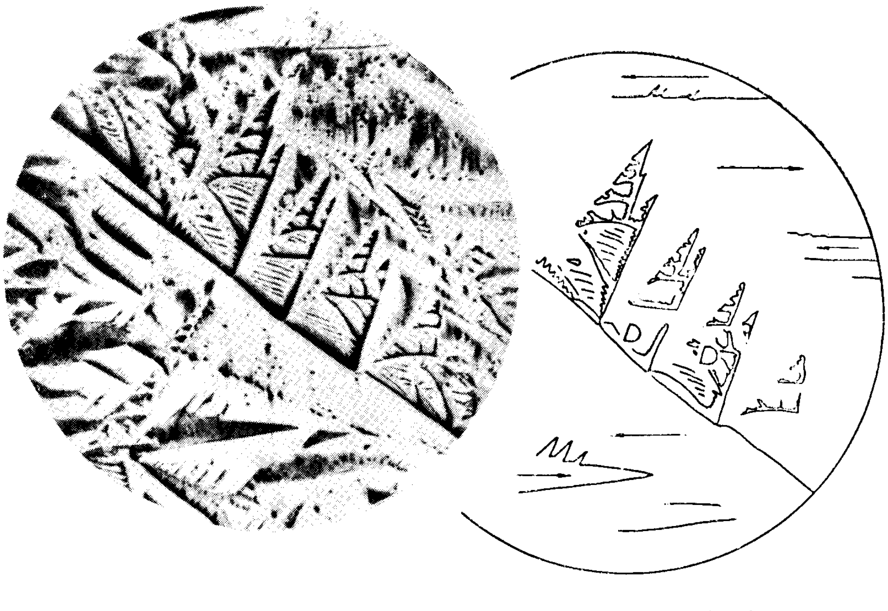

Photo. 9. Domain patterns on the crystal surface closer to the (110) plane than in Photo. 8.

is so broken that it nearly becomes a 109° wall(14) and the triangular patterns may be regarded as the *P*-type branches of the second-kind tree pattern(15).

Finally, we approach the (100) surface along the $[0\bar{1}1]$ zone. On one hand, tree patterns are developed with an increasing complexity, since basic domains magnetized in the $[1\bar{1}\bar{1}]$ direction become unfavourable. On the other hand, domains magnetized in the $[\bar{1}\bar{1}\bar{1}]$ direction become free from their disadvantage and

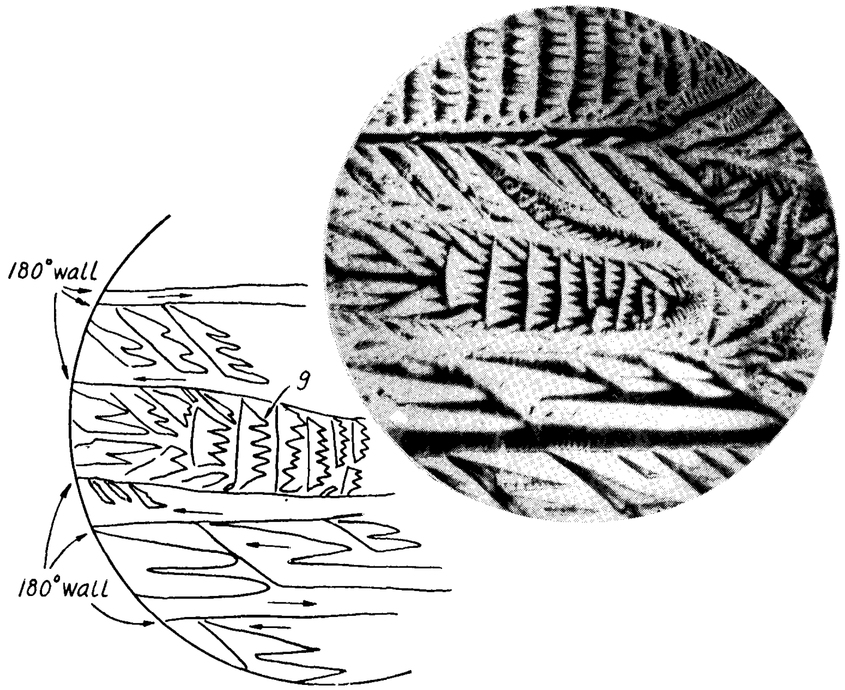

Photo. 10. Domain pattern on the crystal surface inclined from the (211) plane towards the (100) plane.

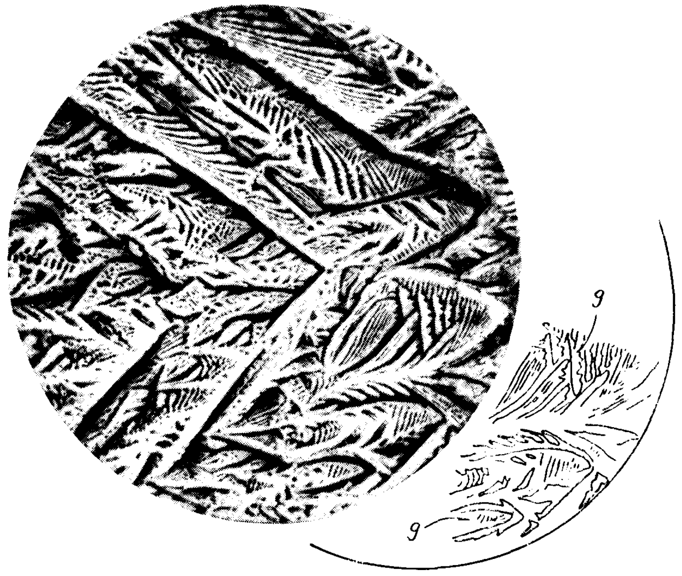

Photo. 11. Domain pattern on the crystal surface inclined further than in Photo. 10.

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(14) 71° wall in [I]. See the end of Section I.

(15) Cf. Section VII of [I].

get a chance for their occurence. For these reasons a domain pattern goes to an extreme of complexity. Not only domains magnetized in the $[1\bar{1}\bar{1}]$ directions but also those magnetized in the $[\bar{1}\bar{1}\bar{1}]$ directions may be contained in the pattern *g* in Photos. 10, 11 and 12. These *g* patterns grow up to large patterns *G* in Photo. 12, and finally they coexist with patterns *F* composed of basic domains magnetized in $[\bar{1}1\bar{1}]$ and $[11\bar{1}]$ directions (Photo. 13).

It must be added that the domain pattern suchs as in Photos. 5 and 6 are often replaced, for circumstances cited in Section II, by the pattern in Photo. 6a, in which the triangular domain *d* is naturally similar to the *D* pattern in Photo. 9 and the other triangular domain *d'* is a symmetric partner of *d* with respect to the 180° wall.

Photo. 12. Domain pattern on the crystal surface slightly inclined from the (100) plane towards the (211) plane.

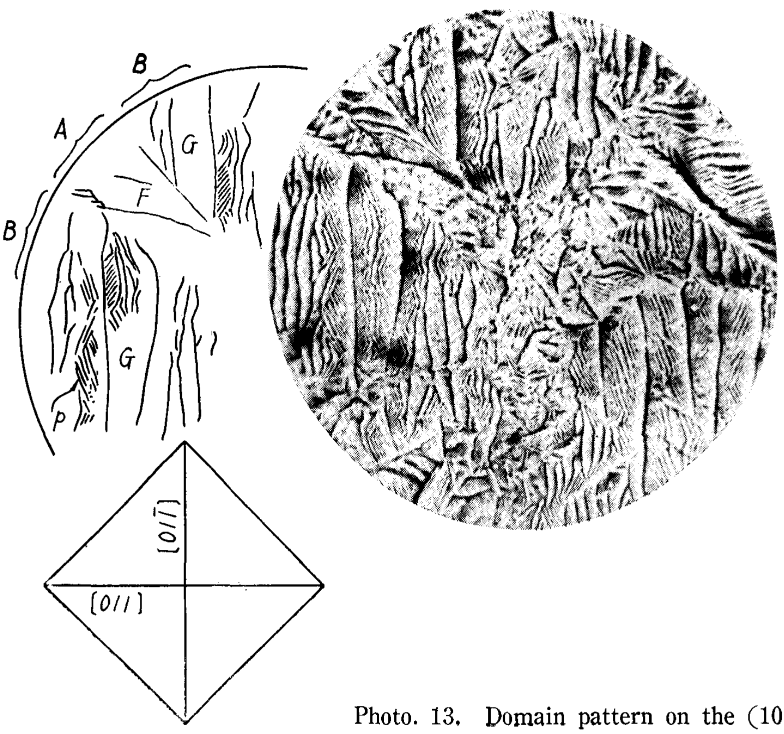

Photo. 13. Domain pattern on the (100) surface.

Photo. 13a. Domain pattern on the (100) surface in the remanent state after the specimen was saturated in the $[01\bar{1}]$ direction ↑.

V. Domain patterns on crystal surfaces ranging from the (110) plane to the (100) plane along the [001] zone

As we proceed from the (110) surface towards the (100) surface, the second-kind tree pattern changes gradually from the *P* type (*u* in Photo. 1) to the *Q* type (Photos. 14 and 15)(16). 180° walls enclosing the *Q*-type branch domains radiate many secondary branch domains, which may be regarded as branch domains of the first-kind tree pattern, as seen from Fig. 4.

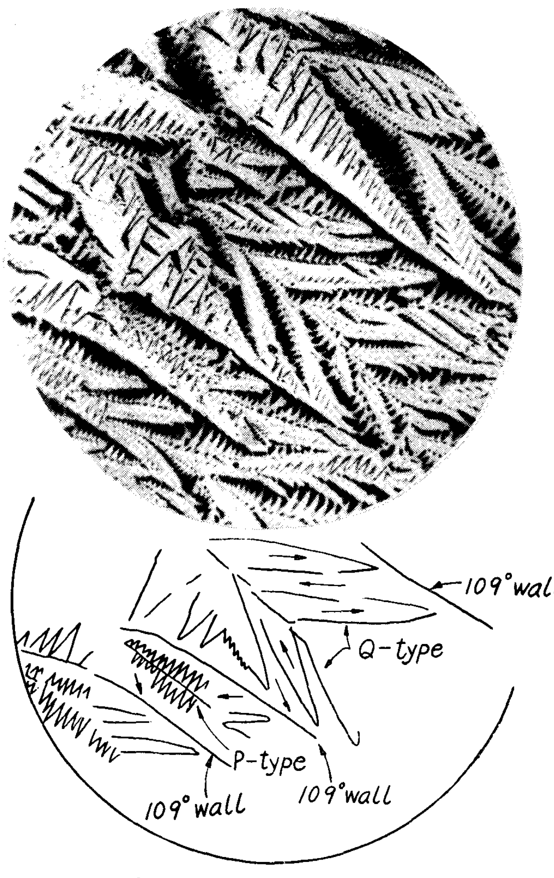

Photo. 14. Complicated second-kind tree pattern, mainly, of the *Q* type observed on the crystal surface inclined slightly from the (110) plane towards the (100) plane.

Photo. 15. More complicated second-kind tree pattern observed on the crystal surface inclined further than in Photo. 14.

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(16) Cf. Section VII of [I].

On crystal surfaces nearer to the (100) surface, superficial domains magnetized in the $[\bar{1}\bar{1}\bar{1}]$ and in the $[11\bar{1}]$ directions appear newly. Patterns *f* in Photo. 16 are composed of domains magnetized in the $[11\bar{1}]$ and in the $[\bar{1}1\bar{1}]$ directions, while patterns *g* in Photo. 17 are composed of domains magnetized in the $[\bar{1}\bar{1}\bar{1}]$ and in the $[\bar{1}\bar{1}1]$ directions. The *f* and *g* patterns develop, respectively, into the *F* and *G* patterns in the (100) domain

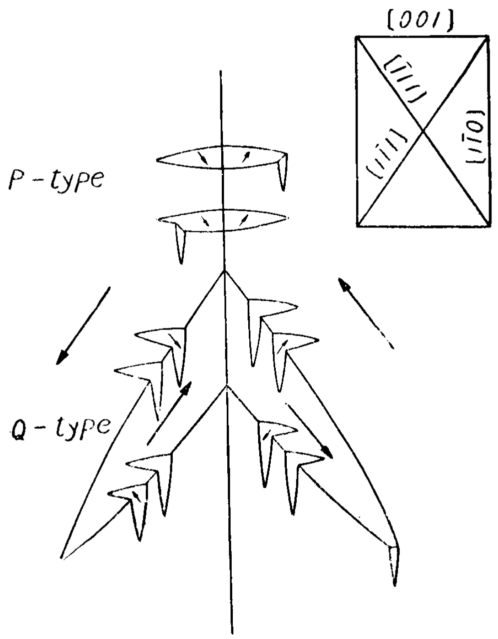

Fig. 4. Interpretation of the second-kind tree pattern observed on the crystal surface inclined from the (110) plane towards the (100) plane.

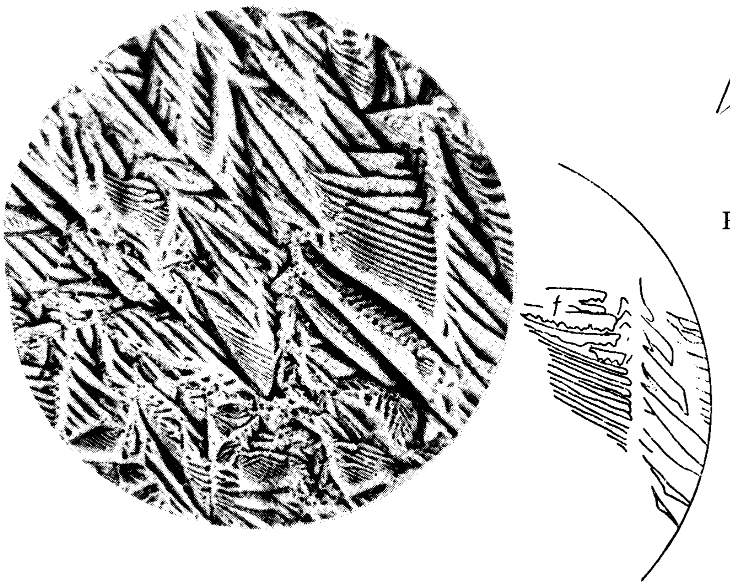

Photo. 16. Domain pattern on the crystal surface intermediate between the (110) and (100) surfaces.

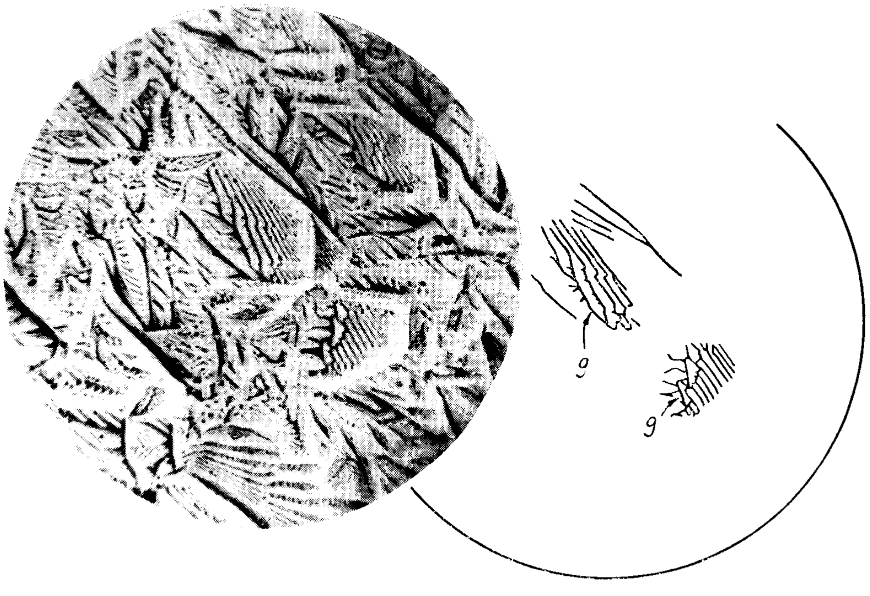

Photo. 17. Domain pattern on the crystal surface inclined slightly from the (100) plane towards the (110) plane.

pattern (Photo. 13). It is to be added that the *f* patterns have already appeared in the modified *Q*-type branches of the second-kind tree pattern in Photo. 8 and that the *g* patterns in Photo. 17 and in Photos. 10~12 are the same in nature.

VI. Domain patterns on the (100) surface

The domain pattern on the (100) surface (Photo. 13)(17) is composed of two regions *A* and *B*, which are packed by *F* and *G* patterns, respectively. As may be seen from the description of the last section, basic domains in the *A* region are magnetized along the $[11\bar{1}]$ or along the $[\bar{1}1\bar{1}]$ direction and those in another region *B* are magnetized along the $[\bar{1}\bar{1}\bar{1}]$ or along the $[1\bar{1}\bar{1}]$ direction, as shown in Fig. 5. Thick lines running roughly along the <110> directions, therefore, indicate the positions of 71° walls(18) dividing piled domains. When a magnetic field is applied in the $[01\bar{1}]$ direction, first a magnetization process consisting of the wall displacement, which is indicated by the growth of *A* regions and the degeneracy of *B* regions, proceeds until the whole crystal surface is completely covered by *A* regions, and then the magnetization process consisting of the rotation of magnetization vectors follows. The fact that domain patterns in the early stage of the rotation process of magnetization vectors and in the remanent state (Photo. 13a) are similar to those of the *A* or *B* regions supports the domain structure in the *A* region presented in Fig. 5.

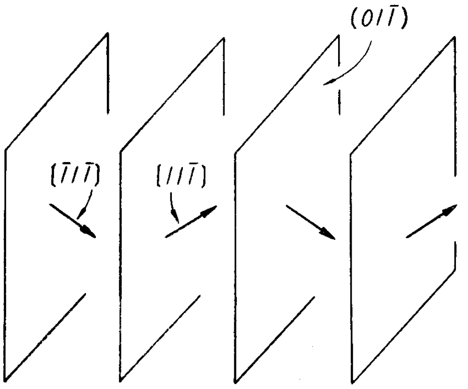

Fig. 5. Basic domain structure of the A region in the (100) domain pattern.

A fine structure composed of thin lines in the *F* and *G* patterns (*p* in Photo. 13) indicates minute flux-closure domains seemingly arranging themselves with some sort of regularity. As seen from Photo. 13, these superficial closure domains do not completely cover basic domains and thus basic domains appear on the crystal surface along domain walls separating them. These exposed areas collect colloidal particles, appearing as thick lines roughly parallel to the <110> directions. Accordingly, a thick <110> line does not at once indicate a domain wall, which is really located at the boundary between the thick line and its neighbouring blank area. By a close examination of the contrast of <110> thick lines under applied weak vertical field, it was observed that adjacent <110> lines have the associated blank area on the same side. This fact leads to the conclusion that each of the *F* (or *G*) patterns consists of two adjacent basic domains.

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(17) The domain pattern has some similarity in its appearance to that observed on the (111) surface of a silicon-iron crystal. Cf. R. M. Bozorth, J. de phys., [8] **12** (1951), 308.

(18) 109° wall in [I]. See the end of Section I.

VII. Domain patterns on crystal surfaces ranging from the (211) plane to the (111) plane along the $[01\bar{1}]$ zone and on nearby crystal surfaces

Tree patterns occurring on crystal surfaces inclined slightly from the (211) plane towards the (111) plane (Photo. 18) can be interpreted by considerations analogous to those described in Section IV. A trunk or 180° wall separating basic domains magnetized respectively parallel and antiparallel to the $[\bar{1}11]$ direction radiates, on the $[0\bar{1}1]$ side, branch domains magnetized in the $[1\bar{1}1]$ direction (corresponding to l in Fig. 2(c)(19)) and, on the $[01\bar{1}]$ side, branch domains magnetized in the $[\bar{1}\bar{1}1]$ direction (corresponding to l' in Fig. 2(c)). Angles between these branch domains and the trunk are equal to 58°31′ when the crystal surface coincides with the (211) plane and they increase up to 60° as the crystal surface approaches the (111) plane. It is also similar to the case considered in Section IV that secondary branch domains enclosed by 180° walls are radiated from the primary branch domains. Domain patterns in Photos. 18~20 can thus be interpreted satisfactorily.

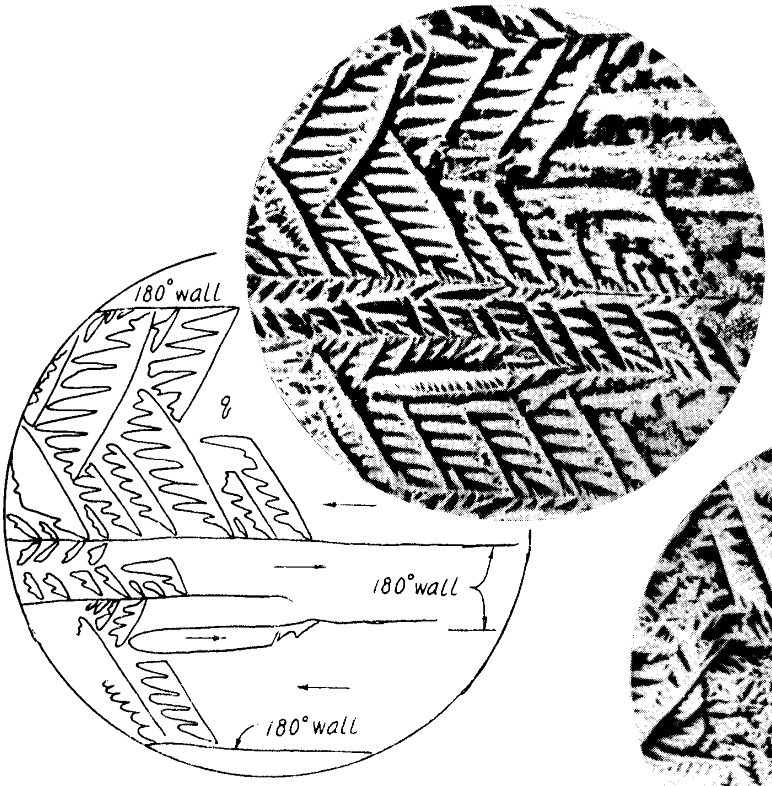

Photo. 18. Complicated tree pattern on the crystal surface slightly inclined from the (211) plane towards the (111) plane.

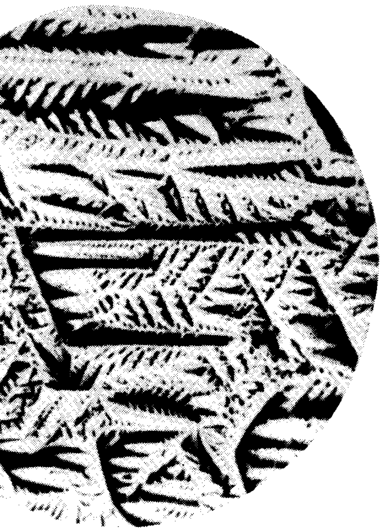

Photo. 19. Domain pattern on the crystal surface inclined slightly from the (111) plane towards the (211) plane.

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(19) Signs of free poles on the sky (basic domains) in Fig. 2(c) must be inverted in the present case.

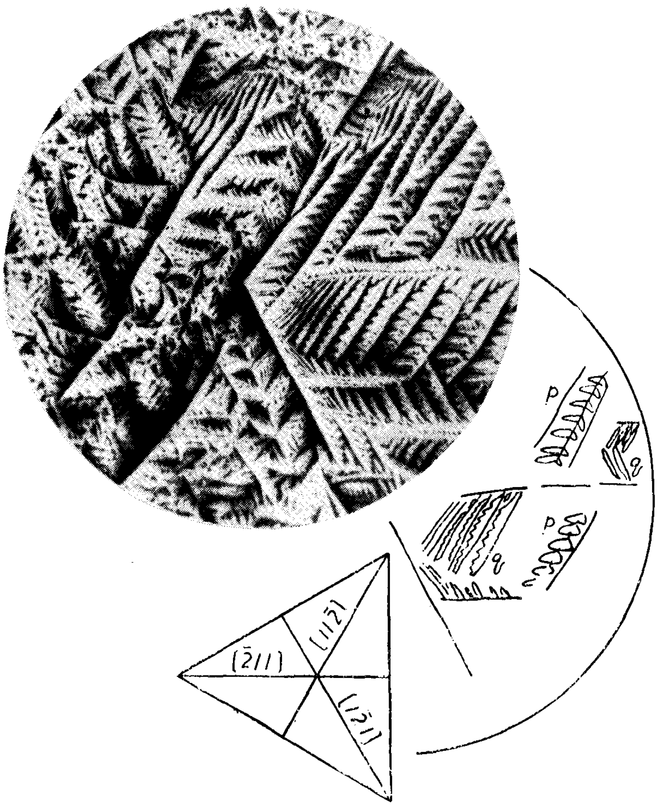

Photo. 20. Domain pattern on the (111) surface.

As the crystal surface already inclined slightly from the (211) plane towards the (111) plane is rotated further towards the (110) plane, the abovementioned primary branch domains of the tree pattern radiating on the $[01\bar{1}]$ side of the trunk degenerate and are replaced by new branch domains magnetzied in the $[1\bar{1}1]$ direction (corresponding to k' in Fig. 2(c)) (k' in Photo. 3). These new branch domains make an angle of 39°15′ with the trunk when the crystal surface coincides with the (211) plane and, as the crystal surface approaches the (110) plane, this angle decreases down to 35°16′ and the tree pattern as a whole comes to be of the first kind, as may be seen from Photos. 3 and 2.

Finally, as we approach the (111) surface along the $[01\bar{1}]$ zone, domains magnetized in the [111] direction become more and more unfavourable energetically, contrary to the case considered above in which we approached the (100) surface,

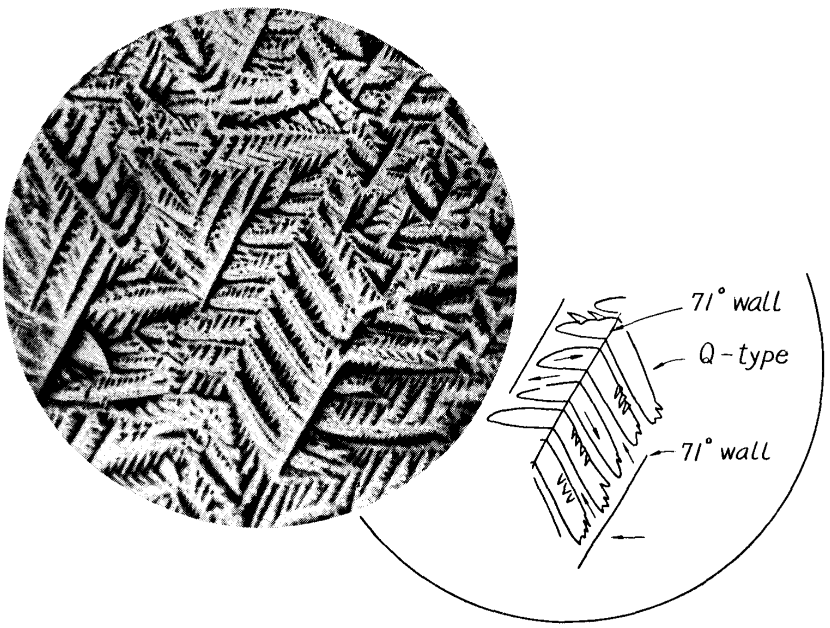

Photo. 21. Complicated third-kind tree pattern of the Q type on the crystal surface inclined from the (110) plane towards the (111) plane.

and thus the domain pattern dose not suffer any particular change and links continuously to the pattern on the (111) surface, as seen in Photos. 18~20.

VIII. Domain patterns on crystal surface ranging from the (110) plane to the (111) plane along the $[\bar{1}10]$ zone

When we proceed from the (110) surface towards the (111) surface along the $[\bar{1}10]$ zone, the third-kind tree patterns of the *Q* type(20) are increasingly developed and become smaller owing to the break-up of underlying domains, as is seen in Photo. 21. 180° walls enclosing the *Q*-type branch domains radiate many secondary branch domains as in the case of the second-kind tree pattern of the *Q* type observed on the crystal surface inclined from the (110) plane towards the (100) plane (Section V; Photo. 14). There is no reason that the domain pattern does not change continuously into that on the (111) surface (Photo. 20). It is to be noted that these domain patterns are seen in Figs. 5 and 6 of Martius and Gow's paper(21).

As the crystal surface deviates from the $[\bar{1}10]$ zone, the third-kind tree pattern varies continuously to a type transient to the first-kind tree pattern, as seen from Photos. 4 and 3, and finally to the pattern on the crystal surface along the $[01\bar{1}]$ zone.

IX. Domain pattern on the (111) surface

It may readily be inferred from the preceding two sections (VII and VIII) that the domain pattern on the (111) surface (Photo. 20) is a cross of patterns of the two sorts which have changed continuously from those on the (211) and on the (110) surfaces. Thick lines roughly parallel to the $<\bar{2}11>$ directions in Photo. 20 (also in Fig. 30 in [I]) correspond to the 180° or to the 71° walls as extensions from those seen on the (211) or on the (110) surfaces (Photos. 7 and 1), and thus they directly indicate the basic domain structure of the crystal. It is to be noted, however, that these thick lines do not directly indicate domain walls, but indicate free poles on underlying domains appearing on the crystal surface along the 180° or 71° walls concerned. This circumstance is similar to the case of the $<110>$ thick lines in the (100) domain pattern (Photo. 13) considered in Section VI.

As noted previously in Section XII of [I], two kinds of fine structure, *p* and *q*, are found in the area between the thick lines in Photo. 20. It may readily be seen that one of fine structures, *p*, is an alteration of the third-kind tree pattern and the other, *q*, is of the same nature as the complicated tree pattern found on crystal surfaces inclined from the (211) plane towards the (111) plane (*q* in Photo. 18 and Photo. 19).

Thus, the domain pattern on the (111) surface can be explained more easily than the (100) domain pattern.

Summary

Ferromagnetic domain patterns were observed, with the magnetic colloid tech-

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(20) Cf. Section VIII of [I].

(21) U. M. Martius and K. V. Gow, Canad. J. Phys., **33** (1955), 196.

nique, on the hemispherical surface of unmagnetized nikel crystals, and various complicated patterns were found on general crystal surfaces, which may naturally be regarded as due to the fact that nickel has more directions of easy magnetization, lower wall energy, and higher magnetostrictive energy than in iron. They were interpreted thoroughly, starting from the previously clarifid domain patterns on the (110) and (211) surfaces, by comparing them with one another and by pursuing the development and extinction of domains of the given types in them.

As we proceed towards the (211) surface, starting from the (110) surface which shows a modified parallelogram-net pattern composed of *K* and *L* domains magnetized respectively in the $[\bar{1}11]$ and in the $[1\bar{1}1]$ directions and accompanied by the first-kind, second-kind, and third-kind tree patterns, *L* domains degenerate and *K* domains develop gradually, and finally *K* (or *K'*) domains form a simple plate pattern on the (211) surface.

Crystal surfaces inclined slightly from the (211) plane towards the (100) plane show complicated but symmetrical tree patterns composed of branch domains magnetized in the $[\bar{1}\bar{1}1]$ and in the $[11\bar{1}]$ directions with fringe branch domains magnetized antiparallel to the basic domains. These tree patterns are replaced gradually by new patterns (G) complicated by the appearance of domains magnetized in the $[\bar{1}\bar{1}\bar{1}]$ direction, as we approach the (100) surface.

When we leave from the (110) surface towards the (100) surface, the second-kind tree pattern changes gradually from the *P* type to the *Q* type and, further, the *Q*-type branch domains radiate many secondary branch domains. As we approach the (100) surface, these domain patterns are replaced gradually by new patterns (*F* and *G*) complicated by the appearance of domains magnetized in the $[11\bar{1}]$ and in the $[\bar{1}\bar{1}\bar{1}]$ directions. Thus, the domain pattern on the (100) surface is composed of the two regions packed, respectively, by the *F* and *G* patterns; the underlying structure of each region is a parquet of board-like domains separated by 71° walls.

On crystal surfaces inclined from the (211) plane towards the (111) plane, we observe another complicated but symmetrical patterns similar in appearance as well as in nature to those on crystal surfaces inclined in the opposite sense. On the other hand, as we proceed from the (110) plane towards the (111) plane, we see that the third-kind tree patterns of the *Q* type are increasingly developed and become smaller and that 180° walls enclosing the *Q*-type branch domains radiate many secondary branch domains. These tree patterns of the two sorts interlace in the domain pattern on the (111) surface, in which thick lines roughly parallel to the $\langle\bar{2}11\rangle$ directions correspond to the 180° or to the 71° walls as extensions from those found on the (211) or on the (110) surfaces. Further, complicated domain patterns observed on high-index crystal surfaces were clarified similarly.

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