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THE MECHANISM OF CALCITE AND NITRE TWINNING UNDER PLASTIC DEFORMATION

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The process of twinning under plastic deformation may be described as a sequence of four distinct stages*.

1. Elastic deformation of the single crystal.
2. Formation of "elastic twins".
3. Formation of stable twin layers.
4. Thickening of the twin layers.

A new method is described for the interferential investigation of the pressure figure, which makes it possible to observe distortions of the crystal surface during the formation of "elastic twins". It is shown that the character of load distribution on the contact surface is of paramount importance.

It is demonstrated that increase or decrease in length or thickness of the "elastic twins" are determined by conditions on their boundary surfaces. The formation of polysynthetic twins is explained. Methods are given for regulating the thickness of layers.

Introduction

Two types of deformation are distinguished when schematically describing the plastic deformation of crystals: slipping and twinning.

Slipping is depicted as the translation of one part of the crystal lattice (Fig. 2). Twinning can be represented either as the shearing of each layer or as the rotation of the entire deformed part of the specimen through 180°. If the points of the crystal lattice do not possess sufficiently high symmetry, additional rotation of each group of atoms is necessary about an axis perpendicular to the shear plane. (See the CO_3 groups in Fig. 3.) Considerable number of facts indicates that both kinds of

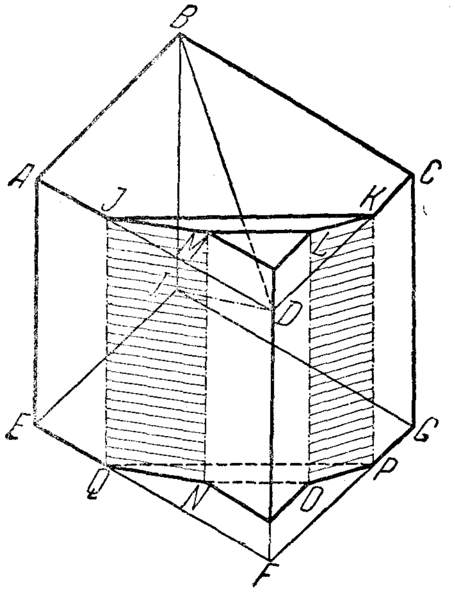

Fig. 1. Twin layer in calcite.

ABCDEFGI–cleavage rhombohedron; *D* and *I*–vertices of the triangular pyramids; *ID*–three-fold axis; *JKLMNOPQ*–twin layer; *JKPQ* and *MNOL*–twinning planes; *BDFI*–shear plane; *FD* and *BI*–shear directions

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[*] The term "twin" refers here to that part of the specimen, in which deformation has brought about a change in the orientation of the axes (the axes are reflected in the twinning plane). The plane of symmetry is called the twinning plane. The plane containing the direction shear and perpendicular to the twinning plane is called the shear plane (Fig. 1).

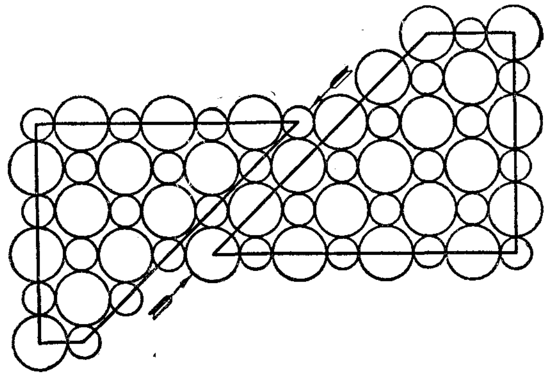

Fig. 2. Schematic representation of "shear" of the crystal lattice under plastic deformation

crystal deformation are accompanied by temporary and permanent structural changes of a more complicated character.

A. F. Joffe with coworkers has discovered the appearance of Laue spot asterism during the "slipping" of rock salt (¹). This phenomenon was made the object of extensive investigation.

I. V. Obreimov with coworkers has shown that separate blocks are formed in a single crystal of rock salt during plastic deformation. The blocks were found to be turned at different, though small, angles to one another. The observed asterism may be explained as the result of the formation of these blocks.

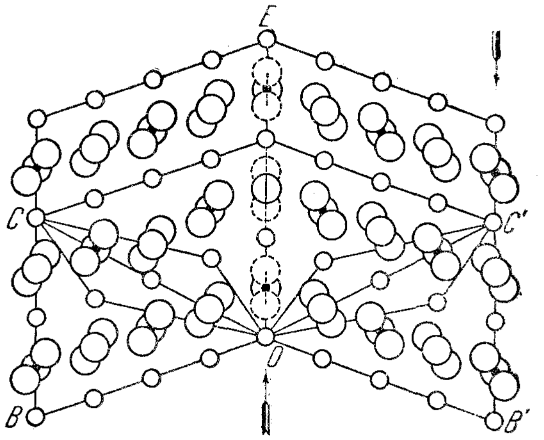

Fig. 3. Twinned lattice of calcite.

1. Large circles-oxygen; 2. Medium circles-calcium; 3. Small circles-carbon; *OE*-twinning plane; plane of drawing-shear plane; *OB'* and *OB*-cleavage planes along rhombohedron; *OC'* and *OC*-three-fold axes

The slip bands serve as boundary surfaces between the blocks (²). Measuring — on the advice of I. V. Obreimov — the latent energy of the rock salt deformation, the author of the present paper succeeded in establishing that the greater part of the latent energy was localized in the form of internal energy of the deformed lattice and only an insignificant portion remained as the energy of residual stresses (³).

The observed strengthening of crystals also contradicts the primitive scheme of slipping represented in Fig. 2.

Twinning appears to be a simpler phenomenon.

If during slipping the number of blocks grows with an increase in the degree of deformation, twinning can be carried out in such a way as to transform the polysynthetic twin into a thick solid homogeneous crystal.

In this way by twinning it is possible to improve a specimen. By reversed twinning it is possible to reestablish mechanically its initial monocrystalline character. This is utterly impossible in the case of slipping.

Such would be the picture of twinning, if we were to compare the initial and resulting states of the specimen.

A number of conflicting views are held on the mechanism of the process.

The formation of mechanical twinned crystals has been chiefly studied on calcite. The plastic deformation of calcite is accompanied exclusively by twinning. The absence of slipping in calcite makes calcite crystals particularly convenient specimens for the investigation of the twinning process.

E. Reusch (⁴) undertook the first special investigation of mechanical twinning.

According to Reusch one part of the crystal gradually turns with respect to the other. When the angle of rotation becomes sufficiently great, the crystal passes into a new stable state.

Reusch illustrated this mechanism by a drawing which is reproduced in Fig. 4. *ABCD* is the section of the rhombohedron by the shear plane. *P—P* is the effective load. Under the influence of the load point *M* descends to position *O* and then proceeds to *M'*. In this way a twin layer *EGIK* is formed, points *C* and *D* being displaced to *C'* and *D'*.

All writers made extensive use of this Reusch scheme, but did not give due attention to the remarkable details described by Reusch in his paper.

In his experiments Reusch used small prisms of calcite. The faces of the prisms represented the cleavage planes (rhombohedron). The bases of the prisms were cut away perpendicularly to the faces. Cardboard was pasted to the bases, and the prisms were then placed under a screw press.

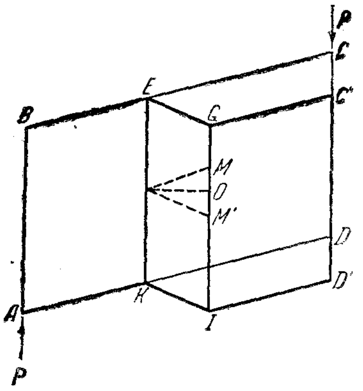

Fig. 4. Twinning of calcite according to conceptions of E. Reusch.

ABCD—section of the rhombohedron by the shear plane; *P–P*—load; *EGIK*—twin layer

The load was not measured. From the description given by Reusch it follows that the twin layers appeared almost immediately as the load was applied to the specimen. Reusch called the twin layer a "plane".

When the screw of the press was turned more, the plane was extended over the entire length of the specimen.

Reusch once noticed how a plane, that had put in an appearance, disappeared after pressure was removed. He interpreted this phenomenon as a return to the initial state of those molecules that had under pressure turned through less than one half of the angle *MLM'* (Fig. 4).

Reusch succeeded in showing that the "planes" which appeared during twinning were twin layers (lamellae). He studied the reflection of light from the face of a twinned crystal and established the fact that those parts of the specimen surface, which corresponded to the outcrop of the twin layers ("planes"), reflected light at a different angle than the other parts of the face.

Reusch subsequently made still another remarkable observation (⁵). He twinned thin plates of calcite. The method of twinning consisted in the following: the plates, 1.5—2 mm thick, were placed on a rubber pad and loaded from above by a steel rod. The end of the rod had the shape of a rounded hatchet blade. This blade was placed parallel to the major diagonal of the top rhombic face of the specimen *AC* (Fig. 5). When pressure was brought to bear on the crystal near the second (minor) diagonal *BD*, "rectangles" appeared within the specimen (Fig. 5, *TYVX*).

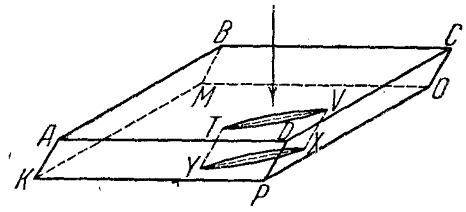

Fig. 5. Reusch's "rectangles" [experiment according to description given by Reusch (⁵)].

ABCDKMOP—calcite plate faced by cleavage planes along rhombohedron; arrow—place of application of the load; *TYVX*—"rectangle"

Such rectangles sometimes disappeared immediately after pressure was removed, in other cases somewhat later. The rectangles were very thin. Coloured interference fringes were observed on them, these fringes being parallel to *TY* and *VX*. Hence the thickness of this "rectangle" (layer) was non-uniform, and — as Reusch pointed out — the section of the "rectangle" had the form of a section of a very flat lense. (In Fig. 5 curves *TV* and *XY* with some exaggeration give the form of the section of such "rectangles"). The appearance of the "rectangle" is followed by the formation of a twin layer ("plane") cutting the whole specimen. This is accompanied by the appearance of continuous interference colour in place of the interference fringes. Hence the planes are transformed into plane-parallel layers.

These interesting observations were not made the object of more detailed scientific investigation.

In 1878 Baumhauer (⁶) suggested a new method for twinning of calcite, by which a knife blade was pressed on one of the edges of a triangular pyramid.

Mügge (⁷) employed a method of twinning by which a rhombohedron was compressed along its major space diagonal.

V. Voigt has shown (⁸) that if the load is referred to the entire area of the resulting twin, the relative elastic shear strain cannot exceed the value of $0.4 \cdot 10^{-3}$.

If we adhere to the views of Reusch, we must require the relative elastic shear to be comparable with the shear accompanying twinning, namely 0.656. According to the experiments of Voigt, elastic shear is thousand times smaller than this value. From this Voigt drew the conclusion that experimental data contradict the conceptions of Reusch on the mechanism of twinning.

In 1938 the author of the present paper published a communication concerning observations on the process of the mechanical twinning of calcite (9).

The most outstanding phenomenon, which attracted author's attention was the appearance of a wedge-shaped leaf in the twinning plane, which grew in size with an increase of the load and diminished when the load decreased.

When pressure was removed, the leaf disappeared altogether. In outward appearance this phenomenon strongly resembled elastic twinning; this was the name it was given.

Further investigation showed that calcite and nitre did not twin at once in considerable volumes. It was established that the following four stages should be distinguished in twinning:

1. The elastic deformation stage.

In this stage deformations are slight and the average loads also comparatively small.

Local stresses can be quite considerable. This depends on how the load is applied, on the shape of the specimen, on how it is mounted, etc.

2. The stage of reversible distortions of macroscopic regions of the crystal, observed in the form of "elastic twins".

Some observations on elastic twins have been published earlier (9). The characteristic feature of this stage is the wedge-like shape of the distorted region and the proportionality of its dimensions to the applied load.

Under certain conditions elastic twins are not completely reversible; after the load is removed, "stopped elastic twins" remain.

3. The stage of the formation of stable twin layer.

This layer is formed in that place where there is a well developed elastic twin. This layer is very thin (2 μ), but stable.

4. The stage of the twin thickening.

Under the influence of the applied load the twin layer grows thicker, as if "devouring" adjacent parts of the initial crystal. In this way it is possible to obtain a thick twinned block of a regular crystalline structure.

Below follows a description of the experiments which prompted these assertions.

1. The rôle of concentrated loads in twinning

The contact of the crystal with some hard object is essential for mechanical twinning. According to Baumhauer (6) a knife blade suits this purpose. Reusch (4) suggests the end of a steel rod having the shape of a rounded hatchet blade.

In all the known methods concentrated loads are essential for the initial stage of twinning.

To elucidate the rôle of load concentration it was decided to use knives (rods) and pads made of materials of different hardness.

Rectangular prisms of calcite served as specimens.

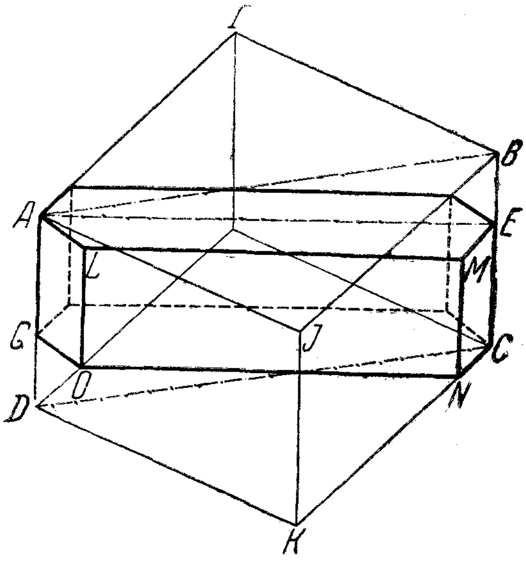

Fig. 6. Shape of specimens.
$AIBJDKC$—cleavage rhombohedron; $ABCD$—shear plane; BC and DA—shear directions; A and C—vertices of triangular pyramids; $LMNO$—specimen face; $ALME$—top and $GONC$—bottom faces of the specimen

The pieces of calcite were cut by a wire wetted in water with emery. Fig. 6 shows the shape of the specimen and the disposition of its faces with respect to the cleavage planes of the crystal. *ABCDIJK* are the vertices of the cleavage rhombohedron. *A* and *C* are the vertices of the obtuse trihedral angles of the rhombohedron. *ABCD* is the shear plane. *BC* and *DA* are the directions of shear. *LMNO* is the face of the specimen parallel to the shear plane.

This face was thoroughly polished and shined. The parallel face, designated in the figure by the dash line, was treated in the same manner.

ALME and *GONC* are the specimen top and bottom faces, perpendicular to the direction of shear.

These faces were likewise thoroughly polished and shined.

AB and *CD* are the minor diagonals of the top and bottom faces of the cleavage rhombohedron.

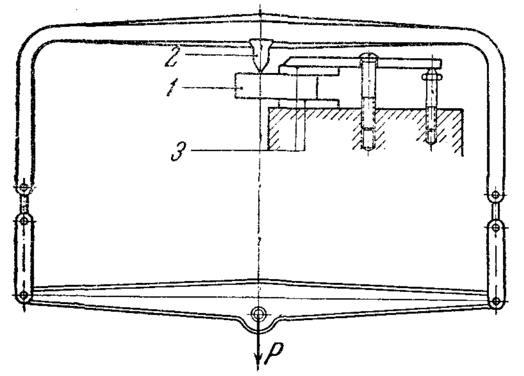

Fig. 7. Fastening of the specimen.
1–specimen; 2–knife; 3–cardboard pad; P–weight

When ready, the specimen was fastened by a clamp, as shown in Fig. 7. The top and bottom faces of the specimen were protected by cardboard pads (*3*, Fig. 7). A knife (*2*, Fig. 7) attached to a holder was placed on the free end of the specimen (console *1*, Fig. 7). A small plank with a weight was fastened to the holder.

Knives were prepared of various materials, their edges being blunted so that the crystal came into contact with a surface of cylindrical shape. The distance between the knife and the edge of the clamp was 2—4 mm. In some experiments pads of foil or cardboard were inserted under the knife. Table 1 gives the results of all the experiments.

It is interesting to note that the hardness of calcite according to Mohs' scale is 3. The foregoing data confirm that twinning is closely associated with the action of a concentrated load. If, owing to the plasticity of the knife or pad, the load is not concentrated, twinning is very much hampered.

For a more detailed investigation of the origin of "elastic twins" and the rôle of load concentration, the crystal surface was studied by the interferential method. The set-up, schematically represented in Fig. 8, was used for this purpose. The crystal was placed on a thick glass (sometimes on a cardboard or rubber pad) and loaded on top by a plano-convex lense, convexity towards the specimen. The place of the load application was examined through this lense by means of a microscope in reflected light (the specimen was illuminated by means of a vertical illuminator through the

Table 1

Dependence of pressure effect upon hardness of knife or pad

Material of knife or pad	Hardness according to Mohs	Observed effect
Cardboard (pad)	—	No traces of damage to the crystal in the place of the load application. "Elastic twins" do not appear altogether. Very great loads lead to fracture along one of the cleavage planes in a section distant from the point of application of the load. Mean shear stress in transversal section of the specimen reached 600 g/mm^2
Lead (pad)	1.5	
Tin (knife)	1.8	
Aluminium (knife)	2.9	
Copper (knife)	3	Pressure figure (cracks) appears in the point of the load application. Already for transversal section stresses, equalling 20—30 g/mm^2 over the section, "elastic twins" appear near the point of the load application (second stage). Under stresses of 150—200 g/mm^2 the "elastic twins" become ordinary twins (stages 3 and 4)
Iron (knife)	4	
Glass (rod with fused end, spherical and cylindrical lenses)	6	

object glass of the microscope and the plano-convex lense).

Newton's rings and a central grey spot could be observed in the microscope field of vision. Part of the spot was the region of the crystal contact with the lense. The regular configuration of the rings in the beginning of the experiment testified to the flatness and smoothness of the crystal surface (Fig. 9). Upon loading an elastic deformation was first observed. The growth of the central spot and change of the interferential picture indicated the presence of a homogeneous elastic deformation (Fig. 10). When the elastic deformation was sufficiently great, the appearance of clearly defined dents parallel to the twinning plane could be observed; at the same time the rings underwent marked deformation.

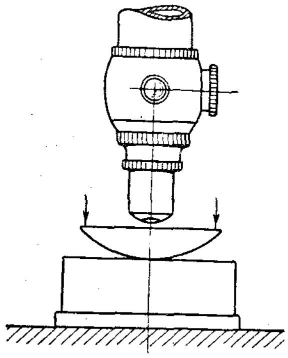

Fig. 8. Set-up for interferential investigation of pressure figure.

Crystal rests on soft pad and is loaded by lense. Crystal surface is examined in reflected light through the lense

Fig. 9 represents a photograph taken at the first moment of contact between the lense and the crystal surface, when the lense exerts a slight pressure on the crystal. Fig. 10 corresponds to considerable, but still elastic deformation (first stage). Fig. 11 shows that a further increase of the load has led to the appearance of elastic twins. The rings are sharply fractured in points of intersection with the elastic twins. Fig. 12 (a different specimen) illustrates the uniform increase in ring diameter from one elastic twin to another. This prompts the conclusion that the crystal surface has acquired a saw-like shape, the height of the teeth being of the order of one ring of visible light or 0.25 μ. When the load was removed, the distortion of the rings first slightly diminished (Fig. 13), then disappeared altogether (Fig. 14). Presumably Fig. 11 represents the second stage of twinning, when there appear macroscopic distortions of the crystal. When the load was removed (Fig. 13), phenomena of a hysteresis character were observed, which can be considerable in the second stage.

Experiments performed with the aid of a cylindrical lense yielded similar results, bands being observed instead of rings. These interferential bands were parallel to the axis of the cylindrical lense. Sufficiently great loads led to the appearance of a certain number of elastic twins at small distances from one another. The twins appeared with least difficulty when the axis of the cylinder was parallel to the twinning plane. When the load was increased, the elastic twins were transformed into thin twin layers. This is easily accomplished, if the crystal rests on a soft padding. When carefully performed these experiments need not damage the surface of the specimen.

It is characteristic that the twins are situated exclusively on one side of the area of contact between the lense and the specimen. (Let us call it the right-hand side.) The appearance of twins is frequently observed in places where there is some kind of a hard grain between the lense and the surface of the specimen. If such a grain coincides with the centre of the lense (or the axis of the cylinder) or is on the left-hand side, twinning does not occur.

It can be assumed that the formation of the twinning nucleus is caused by overpressure. This nucleus can be quite small. For it to develop into an elastic twin, it is necessary for a sufficient shear stress to be present in a volume comparable with the dimensions of an elastic twin. Only one side (for example, the right-hand side) of the contact area can satisfy this last condition.

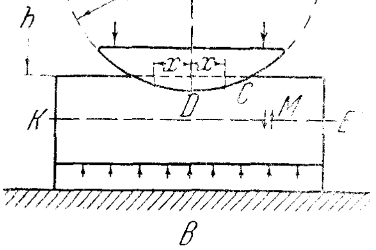

Fig. 15. Scheme of contact between lense and crystal

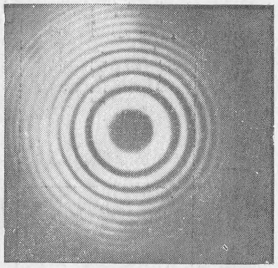

Fig. 9. Spherical surface of lense touches plane surface of crystal

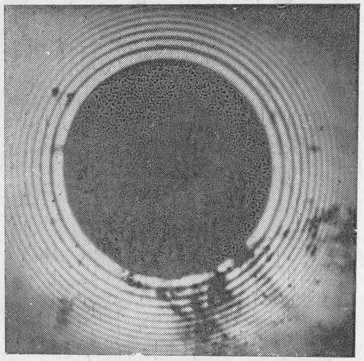

Fig. 10. Load is increased

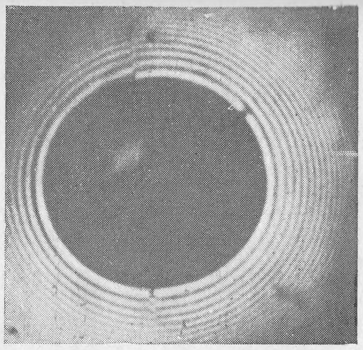

Fig. 11. Further increase of the load leads to the appearance of an "elastic twin"

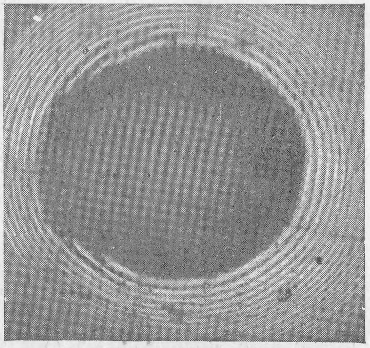

Fig. 12. Formation of saw-like surface (different specimen)

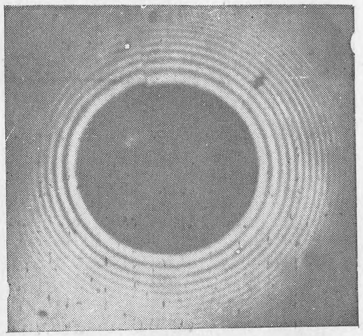

Fig. 13. Partial removal of load diminishes shear

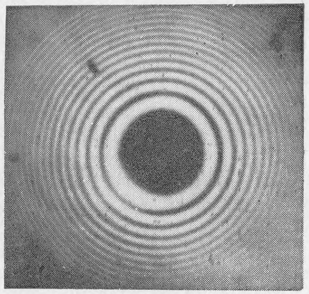

Fig. 14. Elastic twin disappeared completely under somewhat smaller pressure than in Fig. 11

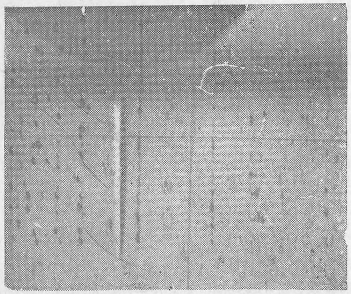

Fig. 19. Elastic twin under heel in nitre

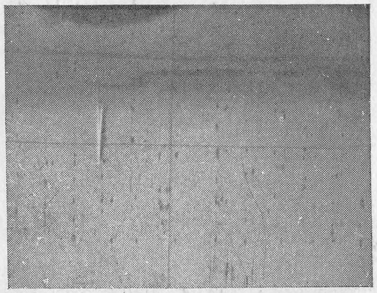

Fig. 20. After load is removed (heel raised)—"stopped elastic twin" remains

Fig. 15 represents schematically the contact surface of the crystal with a cylindrical lense. The cylinder axis lies in the twinning plane; the direction of pressure coincides with the direction of slipping during twinning. The specimen axis KE is perpendicular to the twinning plane. The specimen has been placed on a soft padding and subjected to pressure in the centre of the top face. The twinning plane is perpendicular to the plane of the drawing, the shear plane coincides with it.

Owing to the symmetrical position of the supporting surface with respect to the axis of pressure AB, we can assume a uniform distribution of the reacting forces of the support. Fig. 15 shows that the shear stress in point C of the contact surface can be expressed approximately by

$$\tau = \int_{-x}^{x} F(x)\,dx,$$

where $F(x)$ is a certain function depending upon the elastic properties of the specimen and load cylinder, and also upon their shape.

If we assume that the surface of contact is of exact cylindrical shape and neglect strain and stress along the x axis, it is possible to obtain a quite simple expression for this function:

$$F(x) = c\left(\sqrt{r^2 - x^2} - h\right),$$

where c is a constant depending upon the elastic properties of the crystal. The other symbols are explained in the figure. Under such assumptions the shear stress

$$\tau = c\left(x\sqrt{r^2 - x^2} + r^2 \arcsin\frac{x}{2} - 2hx \right).$$

In point D the shear stress in the twinning plane is apparently equal to zero. In points on both sides of D it must have opposite signs. τ attains a maximum on the border of the contact area:

$$x_c = \sqrt{r^2 - h^2}\,.$$

If to the right side of AB $(x > 0)$ this stress has the same sign as a possible shear accompanying twinning M, to the left of AB it must be of the opposite sign $(x < 0)$.

Such a distribution of stresses is in good agreement with observations on twinning when the lense was pressed into the crystal.

It is essential to establish the reason why thick elastic twins are not observed. It would seem that the inhomogeneities on the contact surfaces could accidentally be so closely situated, that the nucleus would be quite long, and since the shear stress changes very monotonously — the creation of conditions suitable for the formation of a thick elastic twin would appear quite probable. This, however, is never observed. Elastic twins are never more than several tenths of a micron thick.

It is difficult to suppose that the size of all the regions of overpressure, in which a twinning nucleus is formed, does not exceed this figure, or that the formation of bigger twinning nuclei is for some reason impossible.

If we consider the contact surface to be of perfect smoothness, the formation of thin "elastic" and customary twins can be explained as follows.

Let us suppose that a shear stress τ_I (the elastic limit of the first stage) is needed for the formation of a twinning nucleus, and that a smaller shear stress τ_{II} (the elastic limit of the second stage of twinning) is necessary for the development of the nucleus and its further growth.

When in some point on the contact surface the stress attains the value of τ_I the process of twinning (second stage) begins there, part of the crystal surface turning through a large angle (38°) (Fig. 16). The surface at the right-hand end of the turned part must be lifted and at the left-hand end lowered by $S_{\max} = (\delta/2)\operatorname{tg}38^\circ$, where δ is the thickness of the elastic twin measured directly at the surface of the crystal. The absolute value of S must gradually diminish on both sides of the twin. The character of this change of S with distance is

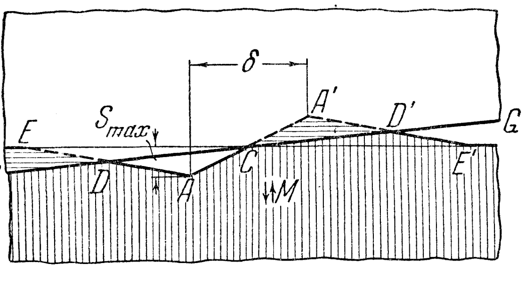

Fig. 16. Redistribution of load due to elastic deformation when twin is formed at point C of contact between lenses and crystal

determined by the elastic properties of the crystal. Fig. 16 shows a schematic section of such a distortion at the border of the contact area. As can be seen from Fig. 16, τ must differ substantially from its former value (the value τ had before the appearance of the elastic twin). Taking into account the distortions due to the presence of an elastic twin, we obtain:

$$\tau' = c \int_{-x_C}^{x_C} \sqrt{r^2 - x^2}\, dx - $$
$$- c_1 \int_{x_E}^{x_C} f_1(x)\, dx - c_2 \int_{x_C}^{x_{D'}} f_2(x)\, dx.$$

Here we neglect the internal stresses created by the presence of a small twinned region. It should be noted that τ' rapidly diminishes with an increase in the thickness of the twin δ. When the value of τ' becomes smaller than the elastic limit for the second stage of twinning τ_{II}, the twin will cease to become thicker. A further increase of the load will lead to the formation of a thin twin passing through the whole section of the crystal. A new nucleus can form near this place, giving rise to a neighbouring elastic twin (Fig. 12).

Twinning by means of a cylindrical lense can be executed without difficulty only in that case when the axis of the lense lies in the twinning plane. This was first discovered in performing experiments with copper knives.

When the blade of a copper knife was situated in the twinning plane, elastic twins developed comparatively without difficulty. If the blade was turned by a small angle, the twins disappeared. In this case a considerable increase of the total load also did not produce twinning. An explanation for this was found after it became known that the surface of the calcite swelled during the formation of an elastic twin. The hardness of copper according to Mohs is 3. The hardness of calcite is approximately equal to the hardness of copper (also 3, according to Mohs).

Therefore, an essential condition for the development of the twinned crystal is the requirement that the copper blade should coincide exactly with the groove A (Fig. 16). If the blade of the copper knife is placed transversally, it will be rumpled and the load will be distributed over a large area.

It is necessary to add that concentrated loads may be created inside the specimen. Therefore, sometimes elastic twins appear when a specimen is bent by a crack; the elastic twins grow, if the separated surfaces press each other.

The removal of pressure in these cases also leads to a disappearance of the elastic twins. The cracks do not disappear.

The experiments described in this paragraph make it possible to conclude that the second stage of twinning (the formation of elastic twins) occurs exclusively in the presence of concentrated loads. The load may be concentrated in one point (spherical lense) or on a straight line perpendicular to the plane and the direction of shear.

2. The properties of elastic twins (The second stage of twinning)

Elastic twins appear first under the influence of concentrated loads.

An increase of the load causes a growth of the elastic twins in length, width and thickness. The correlation of dimensions remains, however, the same. The reach along the direction of shear (length) considerably exceeds the width (perpendicular to the direction of shear in the twinning plane). The length depends chiefly upon the load. The width depends to a much smaller degree upon the acting load: it is closely connected with the character of the distribution of forces on the surface of the specimen. In twinning by means of a spherical lense the width of an elastic twin exceeds the diameter of the contact area 1.5—2 times.

If the cylindrical lense or a knife are used, the width is completely determined by the length of the contact area along the trace of its intersection with the twinning plane. The thickness of the elastic twin is more intimately associated with the load.

If an elastic twin is illuminated somewhat from the side, interference of light can be observed both in transmitted and reflected light. The colour of the interference fringes makes it possible to judge the thickness of the elastic twin.

Fig. 17 schematically shows the position of light source, specimen and microscope in observing interference in transmitted light. The clamp and holder pictured in Fig. 7 are not shown.

Fig. 18 reproduces a photograph of an elastic twin, which is situated in the twinning plane.

but occupies only a part of the specimen section. The elastic twin is intersected by a number of curves of the interference fringes. There is a grey interference (zero order) at the point of the wedge.

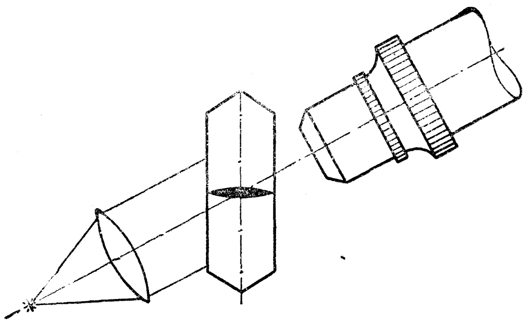

Fig. 17. Position of source of light, specimen and microscope for observation of fringes of equal thickness on the surface of the "elastic twin". Clamp and holder pictured in Fig. 7 here not shown

The coloured fringes of higher order are located closer to the specimen surface.

The thickness of the elastic twin increases with the length. The fringes undergo corresponding displacement. As in these observations a small magnifying power of the microscope may be used the length and width of the elastic twin are measured simultaneously with the thickness.

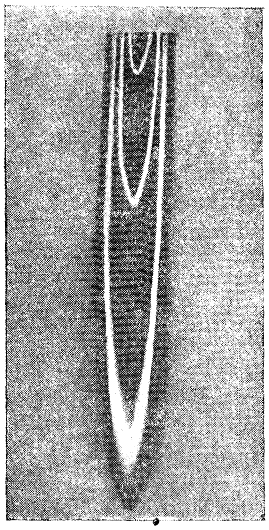

Fig. 18. Fringes of equal thickness on the surface of the "elastic twin"

Measuring the load, it is easy to observe the change of all three dimensions of the elastic twin. The length and width comprise millimetres, and the thickness — microns.

In "long" elastic twins the width practically does not depend upon the load. During the first moment the width grows with an increase of the load. It happens that the width becomes equal to the width of the specimen; then the elastic twin has the shape of a wedge with rectangular faces. In such cases the fringes straighten out and become parallel to the edge of this wedge. For these experiments it is very convenient to use specimens with a cross section of about 10×10 mm.

The fringes become most distinct, if by means of a polarization prism the ordinary ray is extinguished. (The electrical vector of the transmitted light must be parallel to the projection of the optical axis onto the focal plane.)

The influence of the polarizer may be explained by the difference in the refraction indices of the maternal crystal and the twin for ordinary and extraordinary rays.

A more elaborate investigation of this question, in connection with the study of the properties of the twin boundary surface and planes of secondary cleavage, will be concluded in the near future.

To estimate the thickness of the elastic twin use may be made of the well-known relation:

$$d = \frac{\Delta}{2n_{1-2}\cos r}.$$

Assuming that $n_{1-2}\cos r$ differs but little from unity, we obtain $d = k\lambda/2$, where k is the order of the fringe. In so far as elastic twins usually disappear completely when the load is removed even in the case of 3—4 fringes, it may be considered that the thickness of elastic twins equals approximately one micron.

The trace of the elastic twin intersection with the face has a thickness of the same order. This was ascertained by means of the microscope.

Sometimes a well developed elastic twin does not disappear after the load is removed. This may be observed without difficulty on crystals of nitre (Fig. 19 and Fig. 20, see *Plate 1*). "Stopped elastic twins" in calcite are obtained by careful twinning. On such crystals the density of the interference fringes diminishes from the point to the surface of the specimen. It may be considered that approaching the surface of the specimen the wedge shape gradually diminishes. In one case a stopped elastic twin was obtained in calcite with eight fringes, the fringes disappearing and passing into a monotonous colour of a high order in the thick part of the wedge. With an increase of the load all elastic twins become thin plane parallel layers of the twinned crystal. (The third stage of twinning.)

These observations together with other data obtained while studying the effect of annealing (10) permit the assertion to be made that within the elastic twin there exists a stable twinned part of the crystal. The existence of polyatomic transition layers appears quite probable, though sufficient proof of this is as yet lacking. The reversibility of the elastic twins cannot be ascribed to the elastic properties of calcite. We can speak here about the reversible spontaneous rearrangement of the lattice after the load is removed. Two different types of elasticity have to be distinguished in the twinning of calcite.

Elasticity under small deformations without local overpressures and reversible rearrangement of the parts of the lattice subjected to local overpressures.

3. The formation of polysynthetic twins and thick twinned blocks

A group of twins situated close to each other is called polysynthetic. This type of twinning is the most characteristic. Separate twin layers and the gaps between them are from 2—3 microns to a millimetre thick.

When the elastic twins become ordinary twins very thin twin layers are first formed. Further deformation leads to the formation of thick layers.

When pressure on the crystal is exerted by means of a slightly rounded knife blade, one elastic twin is formed which subsequently becomes a plane-parallel layer.

If the crystal is loaded by a lense (heel), a system of elastic twins is formed (a saw-like surface, see Fig. 12). Each such elastic twin can later become a layer.

Using a lense with a big radius of curvature, we can obtain a very dense system of layers of the polysynthetic twin.

Only thin layers are formed at the contact, beyond it twinning does not occur altogether. It was, therefore, important to elucidate the conditions of the formation of the thick blocks of twins, observed in calcite. With this purpose twinning was performed in such a way that the edge dividing the surfaces of the twin and the crystal never lost contact with the heel.

Fig. 21 shows how this experiment was carried out. The dot-and-dash line indicates the section of the rhombohedron by the plane of the drawing, coinciding with the shear plane.

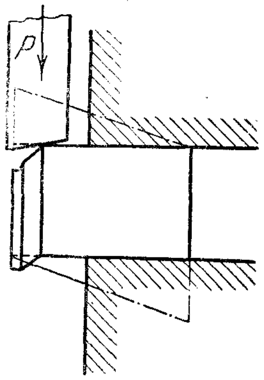

Fig. 21. Position of specimen and loading rod, when pressure is transmitted on the border between twin and crystal throughout twinning

In twinning by such a method the surface of the twin is at an angle of 38° to the surface of the specimen. The heel loses contact with the twin, but remains in contact with the above mentioned edge. Inasmuch as thick twins can be formed only as the result of the successive twinning of layers situated on the border of the twin, it was supposed that it was sufficient to maintain a constant contact of the heel with every successive layer to obtain a thick solid twinned block. Shear during twinning in this case would resemble shear in a pack of cards. Obviously there were great overpressures and no shortage of twinning nuclei under the heel on the border of the twin. Twinning of the boundary layer did not, however, take place because the heel and the twin lost contact to the left of this border; the boundary layer was constantly on the left side of the contact area and had no chance to twin. The heel was pressed into the specimen and a new twin separated from the former by a layer of untwinned crystal was formed at a small distance to the right of the boundary.

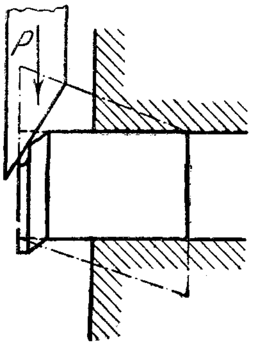

Fig. 22. Twinning under pressure on the twinned part of the crystal

To make the twin thicker it was necessary to have the boundary surface at the right-hand side of the contact area. Fig. 22 shows the relative position of the specimen, heel and clamp in this case.

The fact that the normal component did not play a substantial part in this was tested separately. It was found that on the border of the twin twinning was accomplished without the participation of additional "nuclei" necessary for twinning in a fresh place of the crystal. All twins on the right-hand side grow thicker under altogether small mean shear stresses. All the layers of the untwinned crystal are in this case "devoured". Fig. 23 illustrates the observed changes in the thickness of the layers of the polysynthetic twin.

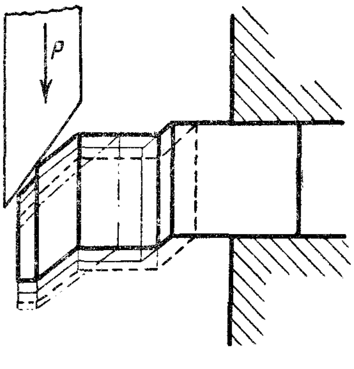

Fig. 23. Thickening of twins under load.

Continuous lines show crystal and thin twin layers. Dash-lines indicate the result of thickening of the second layer at the expense of the specimen. Dot-and-dash line shows result of thickening of the first twin layer at the expense of adjacent layer. Thin continuous lines indicate expansion of second twin at the expense of adjacent layer

The contour lines show the contours of the layers before the beginning of additional deformation (the scale of the thickness is considerably increased compared with the scale of the specimen transversal dimensions).

The dash-line shows the thickening of the first layer at the expense of the specimen to the right.

The thin continuous line indicates the thickening of the first layer at the expense of the layer on the left.

The dot-and-dash line shows the thickening of the second layer at the expense of the layer on the right. All boundary layers were situated to the right of the contact area. A displacement of each of the three boundaries separately and of all three simultaneously was observed during the experiment.

The fourth stage of twinning is the thickening of the thin twins at the expense of adjacent regions of the crystal. Such a thickening is not accompanied by any macroscopic elastic phenomena. This is the purest form of plastic deformation. On the other hand, this process is similar to the process of the development of the elastic twin from the "nucleus" during the second stage. The twin layer in this case plays the rôle of the nucleus; since all over the boundary surface conditions are similar and the load is uniform, twinning takes place all over the surface at the same time. This leads to a parallel transfer of the whole boundary. The direction of the boundary transfer is determined by the direction of the acting forces. If the forces act in an opposite direction, the boundary will also be transferred in the opposite direction.

In this way it is possible to reconstruct the initial structure of the crystal. Apparently this is what the mechanism of the well-known phenomenon of reversed twinning consists in.

It is also necessary to establish why a spontaneous change of thickness of the twin layers, similar to the change of thickness of the elastic twins, does not occur.

Here we can only assume that irreversibility is due to the thickness of the twin layer. It is possible that very thin layers are unstable because of the influence of the adjacent parts of the principal crystal.

Thick twins are stable because such influence is rapidly damped with an increase in the distance.

Conclusions

1. The "elastic twin" has the shape of a very thin wedge of considerable length and width. Its thickness, like the length, grows with an increase of the load and decreases when the load is removed.

The thickness and wedge shape of elastic twins have been determined by interference fringes of equal thickness.

In visible light the order of the fringes begins from zero and reaches four.

"Stopped elastic twins" are formed in nitre, in certain cases in calcite. Their stability can be explained by the influence of the internal parts of the thick portion of the wedge, which are completely twinned.

2. A "twinning nucleus" is essential for the formation of an elastic twin. "Nuclei" arise at the contact surface only in those cases when there are concentrated loads. A distributed load does not lead to the twinning of a single crystal.

Very large stresses are necessary for the formation of a "nucleus".

Further twinning requires comparatively small stresses. It is important that the direction of the acting forces should correspond to the direction of shear in twinning.

3. Polysynthetic twins are formed in those cases when contact between the rod (heel) and the surface of the twin is broken in the process of twinning. The heel continues to press on the surface of the specimen. This leads to the formation of a new layer of the polysynthetic twin, separated by a layer of untwinned crystal.

Twinning by means of a distributed load was found to be feasible if there is already a twin layer in the crystal. In this case twinning is localized on the boundary surfaces of the twin. Thick twins are formed exclusively by this method.

4. A new method has been employed to investigate pressure figures, consisting in the observation of the distortion of Newton's rings by the place of contact of the heel with the crystal.

It has been proved that the formation of an elastic twin leads to the swelling of the crystal surface on one side and to the lowering of the surface, on the other. The swelling and lowering of the surface correspond to the directions of shear in twinning.

REFERENCES

[1] A. F. Joffe, M. Kirpicheva a. M. Levitzkaya, ZS. f. Phys., **22** 286 (1924).

[2] I. Obreimov a. N. Brilliantov, Sow. Phys., **12**, 978 (1937); Н. Бриллиантов и В. Старцев, Журн. экспер. и теор. физ. (N. Brilliantov a. V. Startzev, Journ. Exper. a. Theor. Phys.), **9**, 592 (1939); V. Startzev, Journ. of Phys., **3**, 107 (1940); C. R. Acad. Sci. URSS, **30**, 124 (1941).

[3] R. Garber, Sow. Phys., **9**, 111 (1936); Р. Гарбер, Журн. экспер. и теор. физ. (R. Garber, Journ. Exper. a. Theor. Phys.), **8**, 746 (1938).

[4] E. Reusch, Pogg. Ann., **132**, 441 (1867).

[5] E. Reusch, Pogg. Ann., **147**, 307 (1872).

[6] Baumhauer, ZS. Krystallogr., **3**, 588 (1872).

[7] O. Mügge, N. Jahrb. f. Mineralog. u. Paläontol., **1**, 32 (1883).

[8] V. Voigt, Wiedem. Ann., **67**, 201 (1889).

[9] R. Garber, C. R. Acad. Sci. URSS, **21**, 228 (1938); Journ. of Phys., **3**, 179 (1940).

[10] R. Garber, Journ. of Phys. (in press).