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THE TWINNING OF SINGLE CRYSTALS OF TIN

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ABSTRACT. Experimental methods are described for the production of single crystals of tin and for the determination of their orientations by optical measurements. The conditions under which parts of the crystals can be caused to twin by impact or by tension are investigated, and the determination of the energy relations for certain controlled cases is described. It is found that when twinning occurs, energy amounting to 8×10^5 ergs is converted into heat per cm^3 of crystal twinned. The process of twinning in relation to the crystal structure of tin is discussed.

§ 1. INTRODUCTION

The behaviour of the crystals constituting a metal test-piece under stresses large enough to cause permanent distortion of the test-piece has been the subject of many investigations. It has long been known that one of the ways in which yield occurs is by the glide of lamellae over one another, and experimental work on specimens consisting of single crystals of metals has shown that in many cases the whole distortion can be attributed to such glide[1,2]. It has been shown, however, by S. W. J. Smith, Dee and Young[3], that the formation of Neumann bands in α iron is due to twinning of the volume of which the Neumann band is the trace on the surface of the specimen. The process described is a definite movement of each layer of atoms relatively to the neighbouring layers, so that the atoms then occupy positions in a lattice inclined in a definite direction, that of a twin crystal, to the lattice of the original crystal. The paper cited above gives an adequate account of the geometry of the process of mechanical twinning, but no experimental investigation has been made of the mechanical conditions governing twinning, or of the quantitative energy considerations involved[4].

In order to investigate such conditions, it is necessary to utilize specimens consisting of single crystals, in order that effects occurring inside the volume of a crystal may not be modified by restraints imposed by neighbouring crystals and by inter-crystalline materials. The material with which the present investigation is concerned, namely tin, is particularly suitable, both on account of the ease with which large single crystals can be produced and because it has a crystal lattice which appears to be particularly susceptible to twinning by shock. Work on other aspects of the mechanical properties of single crystals of tin is described and referred to by Obinata and Schmid[5].

The experimental work described below consists in the preparation of the crystals, the measurement of their orientation by a new optical method, a qualitative investigation of the conditions in which twinning occurs, and a quantitative examination of the energy involved in the process.

§ 2. PREPARATION OF THE CRYSTALS

The crystals were prepared by the following method from Chempur tin comprising tin 99·987 per cent, copper 0·00132 per cent, antimony 0·00118 per cent, lead 0·00585 per cent, iron 0·00055 per cent, bismuth 0·00352 per cent, arsenic 0·00005 per cent, nickel 0·00003 per cent, silver 0·00018 per cent, but no zinc, cobalt or sulphur. The tin was melted in a crucible over a bunsen burner and maintained at a temperature of about 300° C., the temperature being measured by means of a thermocouple. Into this was lowered a glass tube of which the bore was the required diameter of the crystal, drawn out at its centre to a narrow capillary. The length of the tube was such that the surface of the liquid tin came up to the bottom of the capillary. When the tube was lowered into the tin it was closed at the top by means of a rubber tube and a clip so that no tin could enter the tube at the lower (open) end. After the tube had been immersed in the tin for a few minutes the clip was opened, allowing the tin to enter, and suction was applied to the rubber tube to draw the tin up the capillary until it solidified at the top. The glass tube was then raised out of the molten tin, the tin inside it solidifying progressively as a rod as it cooled. The tube was raised by means of a lever to which it was clamped, the lever being moved by a clock mechanism which could be adjusted to give any desired speed of raising. It was found that when the rate was of the order of 0·5 cm. per minute a single crystal of diameter 5 mm. and length 6 cm. could usually be obtained. With somewhat slower raising, crystals up to 1 cm. in diameter were obtained.

It was found that when the crystals had cooled they could be made to slide out of the tube without suffering any damage, i.e. without showing either slip bands or Neumann bands. This is due to the fact that tin contracts by about $2\frac{1}{2}$ per cent on solidification. The surfaces of the crystals so prepared were sometimes pitted, but when the tube had been allowed to heat up sufficiently before the tin was admitted, this pitting was usually very slight and sometimes apparently absent. After a crucible full of tin had been in use for some time and had been melted and cooled a number of times it was found that single crystals could no longer be obtained, crystal boundaries being always seen in such specimens. This was taken to be due to impurities in the melt.

Crystals with flat faces were also obtained by inserting slips of mica diametrically in the tubes, so that the tubes were divided into two semi-cylinders. A spectroscopic comparison of the composition of the crystals and of the original tin showed that the amounts of bismuth and lead were slightly reduced by crystallization; the other impurities showed no reduction.

§ 3. DETERMINATION OF THE ORIENTATION

The first step in the investigation of any of the properties of single metallic crystals is the determination of the orientations of the crystal-axes to the geometrical axes of the specimens. The basic method by which this can be done is by the use of X rays, but the process is complicated and laborious. Various alternative methods have been described from time to time, some depending on measurements on the specimen after it has been distorted[6,7], and some being based on the appearance of the surface after it has been etched[8,9]. The method used in the present investigation is of the latter type, modified so that the orientations can be read off directly and quickly.

The specimen, having been cooled and removed from the tube in which it was prepared, was next etched to prepare its surface for optical examination. It was found that a 5-per-cent aqueous solution of ferric chloride was a suitable etchant

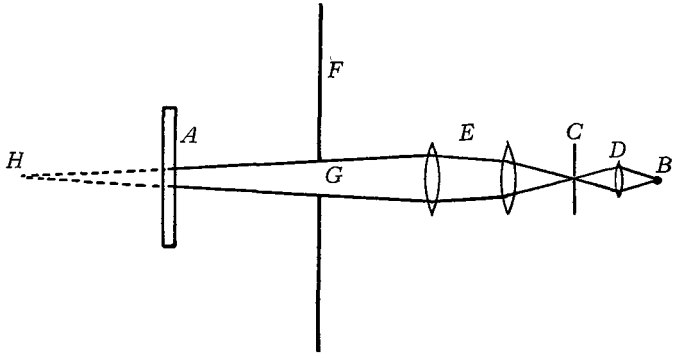


Figure 1.

for tin. A preliminary visual inspection of the specimen served to reveal any crystal boundaries that were present, and if the whole specimen, or a large enough part of it, consisted of a single crystal, the following property was utilized for the determination of the orientation. It was found that when a slightly converging beam of light was allowed to fall on the surface of the specimen, which was cylindrical in shape, the reflected light did not travel in the directions normally followed when light is reflected from a cylindrical surface. It was instead reflected in a number of definite directions inclined at angles to the geometrical normals of the cylinder.

The directions in which the reflected light travelled were investigated by measuring the positions of the spots of light formed on a suitably placed screen. The optical system employed was that represented in figure 1, in which B is a straight filament lamp, the line of the filament being perpendicular to the plane of the diagram, C a slit, on to which light from B is concentrated by the condenser lens D; E is a system of lenses forming an image of the slit at H. A Microid micro-projector is used to give this optical system. The specimen, placed at A, is mounted

on the rotating axis of a goniometer, while a white screen F with a hole cut in it to allow the beam of light to pass is arranged to receive the light reflected from the specimen.

The light received on the screen consists of a number of well-defined spots, some of which are joined by faint streaks. The number of spots observed while the specimen is completely rotated about its axis depends on the orientation of the crystal-axes and the state of the surface of the specimen. In the most favourable cases as many as 20 definite spots are obtained.

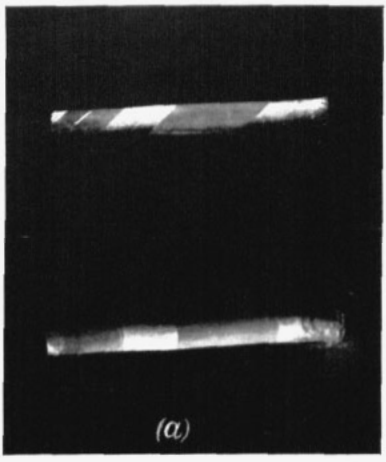
The positions of the spots are measured in terms of two angles, namely the setting of the goniometer when the spot is on a line through G normal to the plane of the diagram, and the angular displacement of the spot from the plane of the diagram along this line. The spots are formed by reflection from planes whose normals do not coincide with the geometrical normal to the surface, so it is reasonable to suppose that the faces concerned are the elementary crystal facets of which the apparently cylindrical surface must in reality be composed. In order to verify this, the angles between the faces giving rise to the various spots were calculated. The tin crystal is known to have a tetragonal lattice in which $c/a = 0{\cdot}541$, and from this ratio the angles between the various simple faces can be calculated. The identification of the angles obtained in a typical experiment with those calculated from the lattice constants is shown in table 1.

Table 1

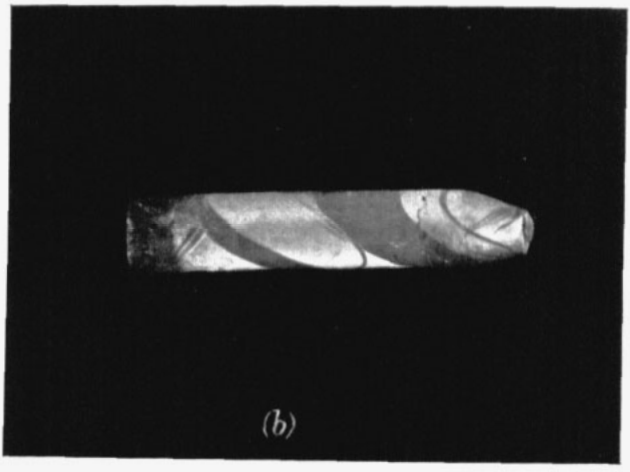
	101	001	011	$\bar{1}01$	110
001	27° (28½°)				
011	40° (40°)	28° (28½°)			
$\bar{1}01$	56° (57°)	30° (28½°)	40° (40°)		
110	72° (69½°)	89° (90°)	70° (69½°)	67° (69½°)	
301	28° (30°)	56° (58½°)	61° (63°)	84° (85½°)	50° (53°)

The left-hand figure in each space shows the experimental value of the angle between the reflection normals associated with the two spots concerned, while the right-hand figure, in brackets, gives the value of the angle calculated from the lattice constants. The six spots are referred to by their crystal planes, which were found by a method described below. The agreement between the two sets of figures is such as to preclude any possibility of error in the identification of any spot. The spots observed in various experiments have all been identified as 001, 100, 010; 101, 011, 110; 301, 031; 111, or the corresponding faces with the signs changed. It was found further that the faint streaks joining the spots were only present where one of the three indices was different for the two spots concerned.

The definite identifications of the spots in this manner made it possible to pick out by inspection any required spot from the characteristic pattern on the screen. In particular, the 001 spot is at the centre of a square of the 011 spots, to each



(a)



(b)

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of which it is joined by lines; the distance of these spots from the central spot is fixed for any given distance of the screen from the specimen, and a circle marked on the screen facilitates the identification of a part of this arrangement when it is not all visible. With the visual identification of the 001, or any other, spot, the measurement of its orientation becomes very simple. A holder is fitted so that the specimen can be placed at a definite distance (5 cm.) from the screen, with its axis parallel to the line through G, perpendicular to the plane of the diagram. The specimen is rotated until the required spot is on this line, and the angle between the corresponding normal and the axis of the specimen is read off directly from a scale of angles marked on the line through G. Hence the orientation of any axis to the axis of the specimen can be determined immediately, the accuracy of a determination being estimated as within 1°.

It was found that with specimens prepared in the way described above, in the majority of cases the 001 axis was nearly normal to the axis of the specimen. Specimens were, however, obtained with orientations having various other values.

§ 4. MECHANICAL TWINNING OF TIN

When certain conditions are satisfied, the effect of the application of a force, either impulsive or steady, to a single crystal of tin is to cause parts of the crystal to become twinned with respect to the original crystal. The conditions under which this happens will first be described generally, and then quantitative results will be given.

Qualitative description. Twinning takes place most readily when an impulsive force is applied to the end of a cylindrical single crystal, the 001 axis of the crystal being roughly perpendicular to the length of the specimen. The twinned portion is always bounded by parallel planes of the 301 type or by the ends of the specimen. Subsequent applications of the same type of force may extend the region twinned or may cause a second part of the crystal to twin; when this occurs, the second part is usually bounded by planes parallel to those of the first part, but occasionally by a second pair of planes of the same type. The plate shows at (*a*) two perpendicular views of a crystal in which two parts between planes parallel to each other are twinned, the darker parts being the parts which have twinned.

The plate shows at (*b*) a crystal on which three different sets of parallel planes have come into operation as twinning planes.

It is possible by continual longitudinal tapping to cause the whole crystal to take up the twin orientation. The twinned part is of the form of an elliptical cylinder obtained by inclining the axis of the original cylinder by about 5° to the normal to the circle forming its base. This angle between the untwinned and twinned parts is visible at (*a*) in the plate.

If the surface of a part of a crystal that has been twinned but not re-etched is examined optically, it is found that the reflection pattern corresponding to the original orientation persists. Etching in ferric chloride solution to remove the surface layer reveals, however, an arrangement of spots corresponding to the

orientation of a twin about the 301 plane, which separates the twinned and untwinned parts. A part of a crystal twinned as described above, or a crystal with its 001 axis nearly parallel to the length of the specimen, will not undergo any further change if further longitudinal impact is applied, unless the force is sufficient to cause the specimen to bend with irregular distortion of the lattice. The reason for this is considered in the discussion of results (§ 5).

If, however, a tension is applied to a specimen that has been twinned, it will sometimes revert to its original (untwinned) orientation. This occurs suddenly and a distinct click is audible as any portion of the crystal changes its orientation. The reversion to the original orientation is demonstrated by etching and optical examination.

Reversion to the original lattice can also be brought about by transverse impact in a direction perpendicular to the axis of the specimen in a plane containing the normal to the 301 plane of the original twinning and the axis of the specimen. Twinning on other planes owing to undue violence prevents a succession of more than one or two of the alternate twinnings and untwinnings which should otherwise be possible. Longitudinal compression of a suitable specimen in a vice causes twinning to occur in the same way as by impact, a characteristic click being heard as the twinning takes place.

In general twinning may occur when a compressional force, either impulsive or steady, is applied in a direction perpendicular to the 001 axis, or when a tension is applied parallel to the 001 axis. The limiting variations from these definite orientations within which the twinning occurs have not yet been determined.

Quantitative results. The observations described in the preceding paragraphs indicate that when twinning is brought about by longitudinal impact, the volume of the crystal in which twinning takes place is in some way dependent on the conditions of the impact. This variation was studied by using a ballistic pendulum to apply definite known impulsive forces to the specimen.

Two brass cylinders, each of mass about 200 gm., were suspended with their axes in the same horizontal line by means of a system of threads so that they could only swing in the vertical plane containing their common axis. A hole was drilled to a depth of about 1 cm. in the end of one of these cylinders, and the specimen on which observations were being made was held firmly in contact with the bottom of this hole, and projecting towards the second cylinder, by means of three set screws and a ring of rubber sponge. When both cylinders were at rest the free end of the specimen was just in contact with the end of the second cylinder.

When the second cylinder was displaced from its position of rest by a given amount and released, it struck the end of the specimen, giving to it and its holder an amount of kinetic energy that could be determined from the subsequent swing of the first cylinder. The displacement of each of the cylinders was observed by the movement along a horizontal scale of pointers attached to them. By using a specimen of which the orientation was such that no twinning took place on impact, a calibration curve relating the displacement of the striker and the swing of the holder was obtained; this is the curve A of figure 2. When specimens were used in

which twinning took place, the points shown in figure 2 were obtained. The horizontal distance between a point and the calibration curve gives some indication of the loss of kinetic energy, and it is apparent that even with the same specimen and the same displacement of the striker, this energy-loss may vary very widely. Hence while some kinetic energy is lost in these collisions, this loss of energy is not directly related to the initial displacement of the striker.

A measurement was also made of the amount of twinning that took place during each collision, the volume twinned being calculated as the product of the cross-section of the specimen and the axial distance between the boundaries of the twinned part. These measurements were made with a travelling microscope.

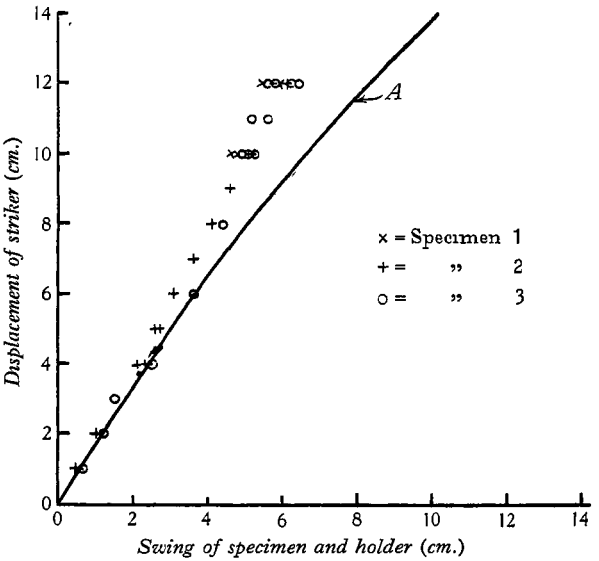

Figure 2.

The calibration curve of figure 2 corresponds to a definite loss of kinetic energy during a collision. A point to the left of the calibration curve corresponds to a greater loss of kinetic energy, and this difference of energy-dissipation was calculated for each collision. A correction, based on a consideration of the momentum, was made for the kinetic energy of the striker after collision.

The points in figure 3 are those obtained when this loss of kinetic energy is plotted against the volume twinned in the same impact. The points, while showing that the accuracy of the observations is not high, indicate that the relation is approximately linear, i.e. that the loss of kinetic energy in an impact which results in twinning is proportional to the volume twinned thereby. The numerical value of this relationship is that the energy dissipated is 8×10^5 ergs per cubic centimetre twinned.

It is noticeable from figure 2 that when the initial displacement of the striker

is less than a definite minimum for each specimen no energy loss occurs; this corresponds to collisions in which no twinning takes place. The minimum displacement with which twinning occurs will probably depend on the orientation and cross-section of the specimen; the results obtained so far only indicate that it is greater when the cross-section of the specimen is greater.

If the atoms of the twinned part of a crystal occupy a lattice identical with, but inclined to, the original lattice, it follows that the potential energy of the atoms in the twinned lattice will be the same as that of the atoms in the untwinned lattice; hence none of the kinetic energy that is lost in the collision can be more than temporarily changed into potential energy of the lattice. A small part of the energy

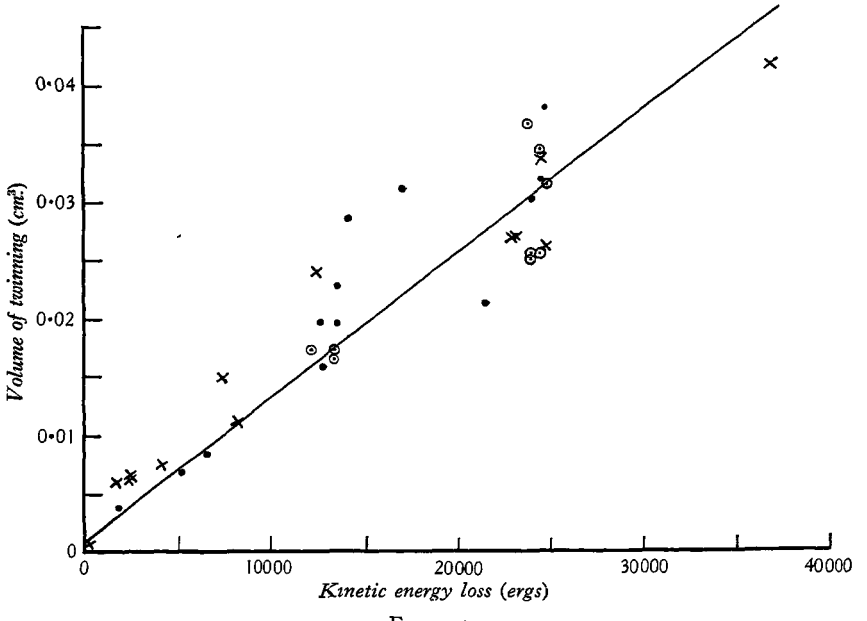

Figure 3.

will be converted into sound as the characteristic click that always accompanies twinning, while the remainder must take the form of heat.

It follows that the temperature of a part of the lattice that has twinned must be higher immediately after twinning than it was before. The energy-loss given above, 8×10^5 erg/cm^3, would, if completely converted into heat, represent a rise of temperature of 0·05° C. in the twin crystal. This temperature-rise was roughly measured by inserting a thermocouple into a hole drilled transversely in the specimen and observing the deflection of a galvanometer connected to the thermocouple when the specimen was caused to twin by tapping it. The corresponding rise of temperature was found from a calibration of the thermocouple against a thermometer over a wider range of temperature. In a typical experiment the rise of temperature obtained was in two parts, coinciding with two impacts, and amounted

to 0·01° and 0·03° C. Further tapping caused no further observable rise of temperature. The fact that the observed rise of temperature is less than the calculated rise is due to the twinning being somewhat irregular as a result of the distortion of the lattice consequent on the drilling of the hole in the specimen.

§ 5. DISCUSSION OF THE RESULTS

In the foregoing sections of this paper it has been assumed that the phenomenon that has been described and measured is a process of twinning. It is necessary now to examine critically the evidence that this is the case.

We may define twin crystals as crystals such that the crystal axes of each form a mirror image of those of the other about the surface separating them. For the present purpose we must identify one of the twin crystals with the original or unchanged specimen, and the other with the part that has been altered by the treatment applied to the crystal.

In the first place it can be shown that the changed part is itself a single crystal; this has been demonstrated in the following ways: (i) after etching, the surface of the changed part can be made by the method of § 3 to show a definite series of reflection spots which are quite different in their disposition from those of the unchanged crystal, and are not altered by further prolonged etching; (ii) when the changed part of the crystal is stretched, in certain cases it yields by glide, with the formation of slip bands; (iii) by the application of a suitable force, either impulsive or steady, the orientation of this part of the specimen can be made to revert to that of the original crystal, as determined by the reflection spots; (iv) that the effect is not confined to the surface layers of the specimen can be shown by polishing and re-etching the specimen; the arrangement of the reflection spots is not altered by this treatment.

The relation between the lattices and the plane separating them must now be considered. The plane of separation is found by calculation from the reflection spots of both parts of the crystal to be within 2° of the position of a plane of 301 type of both lattices. Since such a plane of separation must be a definite low-index crystal plane, it follows that the measurements are sufficiently accurate to show that it is a 301 plane.

A more elegant method of showing the two crystals to be twins about the 301 plane depends on the relation between the reflection spots of the two surfaces. The diagram, figure 4, represents the section of the lattice of tin by the 010 plane, the crosses and dots representing the atoms in alternate layers. The structure is a tetragonal lattice with c/a equal to 0·541, with atoms at the corners of the unit cell and at the centres of the rectangular faces; such a unit cell is indicated in the bottom left-hand corner of the diagram. The sections of the densest planes perpendicular to the plane of the diagram are also shown on the left-hand side of the diagram.

The line AB represents the trace of a 301 plane on the plane of the diagram; the crosses and dots surrounded by circles to the right of this line represent a lattice which is a twin of the original one about this plane. The traces of the more important

planes of the twinned crystal are marked on this part of the diagram, their identity being indicated by figures enclosed in round brackets. The planes of the original lattice are indicated by dotted lines in the same part of the diagram. It can readily be seen from the diagram that the following pairs of planes in the twinned and untwinned parts (the round brackets indicating the twinned lattices) are only separated by small angles, the values of which are marked on the diagram: 100, ($\bar{1}$01); $\bar{3}$01, (001); $\bar{1}$01, (101); 001, (301); 101, (100). It follows from the fact that the reflection spots are caused by the reflection of light from these crystal planes that certain spots in the reflection pattern of the twinned lattice will be only slightly displaced from the positions of spots coming from the untwinned lattice; other

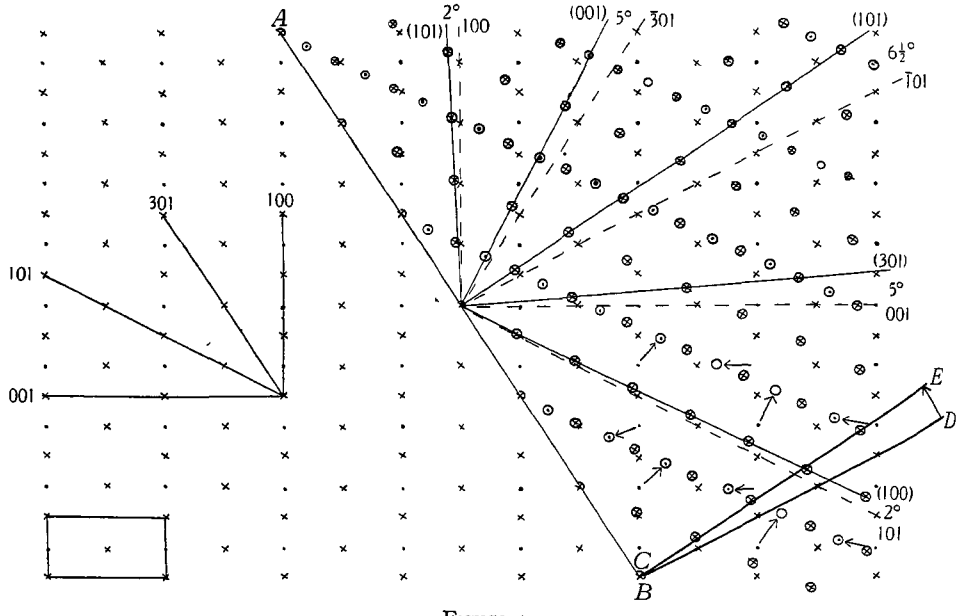

Figure 4.

spots, however, that are present in the untwinned pattern will not appear in the twinned arrangement. The most prominent spots to which this applies are the 011 spots of the untwinned lattice. Figure 5 represents the relative positions of the various spots of which some or all may be seen when reflection takes place from the two parts of the crystal, the same convention as to notation being observed as before. (The figure strictly represents the positions which the spots would occupy on a sphere whose centre is the point of reflection.) It can be seen by inspection of the spots actually observed when reflection takes place from the two parts of the specimen, either consecutively or simultaneously, that the relations between the two lattices are as indicated in figure 4.

In all cases in which these methods were applied, the twinning plane was found to be of the 301 type, of which there are four sets in the crystal lattice. Twinning on three of these planes is clearly visible at (*b*) in the plate.

It is next necessary to consider the movements of the atoms which correspond to the process of twinning, i.e. their movements from their positions in the original lattice to their equally stable positions in the twin lattice. A mechanism suggested by Edwards[10] is obviously contrary to the data described above, and will be disregarded. It is clear from the lattice diagram, figure 4, that the simplest movement of the atoms indicated by crosses is a rotation of each $\bar{1}01$ plane through $6\frac{1}{2}°$ towards the 101 plane (i.e. anticlockwise in the diagram), as indicated by the line *CD* rotating to the position *CE*. Each atom concerned (i.e. three out of every four in the whole lattice) is now in its position in the new lattice. The atoms in the alternate planes cannot take up their new positions in such a simple manner; their probable movement is indicated by the arrows on the lower right-hand corner of the diagram. That the scheme described is correct for the more densely packed planes is confirmed by the observation described above, that the axis of the twinned part is rotated through an angle of about 5° to that of the untwinned part. It can be seen at (*a*) in the plate that the sense of this rotation agrees with that expected from the

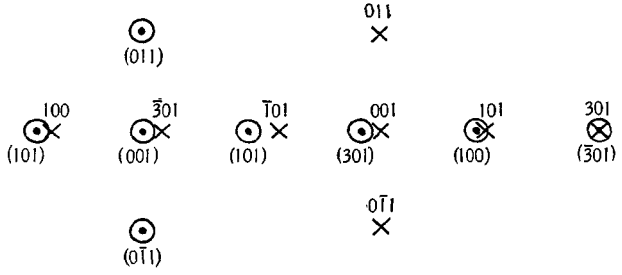

Figure 5.

lattice diagram, since the geometrical axis of the specimen is roughly in the 001 plane of the untwinned lattice.

We can now see why twinning only occurs when certain relations between the directions of the applied force and the crystal axes are satisfied. The lattice diagram shows that the force applied must cause shear to occur in a definite sense between the planes in which twinning occurs. A sufficient impulsive shear stress will give the atoms sufficient kinetic energy to overcome the forces that retain them in their original arrangement, and to allow them to take up their new positions. The kinetic energy will afterwards be dissipated as heat. When the force applied is steady, the elastic displacements of the atoms eventually reach a value such that they are in positions where forces act to bring them into the new lattice.

In either case, there must be a sufficient component of shear stress in the right direction in a set of 301 planes for twinning to occur. When a compressive force is applied perpendicularly to the 001 axis, there may be such components in all four of these sets of planes; the crystal shown at (*b*) in the plate shows regions of twinning on three of these sets of planes. Tension in a single crystal rod perpendicular to the 001 axis, or compression parallel to this axis, will not provide components of shear in the right direction in any of the twinning planes; hence no twinning occurs in either of these cases. When tension is applied in a direction nearly parallel to

the 001 axis, the result may be either twinning or glide, depending in some way not yet analysed on the exact orientation.

When there is a component of shear stress in the appropriate direction in two or more of the twinning planes, the plane on which twinning takes place appears to be the one in which this component is the largest, although the numerical results are not yet sufficient to establish this principle definitely.

It has often been observed in the past* that when twinning has been caused by straining in a polycrystalline metal, recrystallization tends to start from regions at which twinning has occurred, and it is suggested that this is due to instability of the twin crystal. This phenomenon has not been observed in the present investigation, although twinned crystals have been kept above the recrystallization temperature for some weeks. An explanation lies in the fact that with single crystals, in which twinning has occurred throughout the whole cross-section, there is no region in which the conditions approximate to those of an intercrystalline boundary, i.e. there is no region of misfit necessitating the presence of atoms not in a lattice. In a polycrystalline specimen, on the other hand, a twinned section of a small crystal will not fit perfectly the neighbouring crystals on which it abuts; further, the change of shape due to the shift of 5° which occurs with twinning will set up a state of strain in a polycrystalline specimen although not in a single crystal. Both these factors explain why a twinned region of a polycrystalline specimen may serve as a nucleus for recrystallization while a twinned single crystal does not.

From the regularity with which the transformation occurs, and the agreement found between various specimens in the present experiments, it would seem that whereas the resistance to glide is a structure-sensitive property, the incidence of twinning is non-sensitive. This may be due to the fact that the process of glide chiefly concerns a few (possibly specially constituted) lattice planes, while twinning concerns every atom in the twinned lattice. Since every atom takes part in the twinning process, it is possible to express the energy relation that results from the ballistic experiments as the mean energy per atom that must be supplied to cause twinning by impact. The figure obtained is 2×10^{-17} erg per atom. The mean energy per atom, however, does not give any exact information, because different atoms play different parts in the twinning process and probably require different amounts of energy. It is clear, however, that the energy is small compared with that which would entirely overcome the cohesion of the lattice and cause melting.

§6. ACKNOWLEDGMENT

In conclusion, the author wishes to record his appreciation of the interest taken in this work by Mr D. J. Macnaughtan, Director of Research of the International Tin Research and Development Council; and of a grant from the International Tin Research and Development Council; and to make acknowledgment to the Governors and Principal of the Sir John Cass Technical Institute for facilities provided. Finally, his thanks are due to Prof. E. N. da C. Andrade, F.R.S., for his continued interest in this work and his many valuable suggestions during its progress.

* See, for instance, reference (3).

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DISCUSSION

Prof. B. P. HAIGH. The effective demonstration of the mechanical reversibility of the process of twinning and of its thermally irreversible character suggests that it may be an important feature of mechanical strain in other metals as well as in tin. It seems possible that twinning and untwinning may be the direct cause of elastic hysteresis, the nature of which has not yet been explained.

In a paper contributed in 1927 to the Faraday Society* the present writer showed that hysteresis exhibits different characteristics in three distinct stages in the course of fatigue tests on mild steel. In the first and third stages slip bands are produced on the surface of the test piece subjected to cyclic variations of stress; and the plastic hysteresis observed in these stages may be attributed in large measure to the process of slip which probably includes both the production of the amorphous phase and its partial recrystallization with liberation of heat. In the second stage, however, no slip bands are observed, but heat continues to be liberated during long periods which may include many millions of cycles of stress. The characteristics of twinning, demonstrated so clearly by the author, suggest that twinning and untwinning occurring in a cyclic process during successive variations of stress may be a probable cause of this elastic hysteresis as exhibited in the second stage of fatigue tests; and it appears that the subject deserves further investigation with this possibility in mind. It is clear that tin is admirably suited for the investigation of twinning phenomena and that if twinning is not as readily observed in other metals it may be because untwinning occurs more easily on relaxation or reversal of stress.

Prof. E. N. DA C. ANDRADE. The author has accomplished a valuable piece of work in measuring for the first time the energy per cm^3 required to produce twinning in a given crystal, and probably owes his success in this difficult task to his ingenious method of utilizing shock to produce the twinning and measure the energy. The obvious course of direct thermal measurement would be very difficult to carry out with the same degree of precision. Many interesting extensions of his work suggest themselves: for instance, how does this energy vary with the temperature of the crystal? One would naturally suppose that less energy would be necessary to produce twinning at higher temperatures, since the heat agitation throws the atoms further from their equilibrium position, but a quantitative estimate of the variation would

* B. P. Haigh, *Trans. Faraday Soc.* **24**, February (1928)

throw light on the complicated question whether twinning or glide takes place in a given lattice at a particular temperature.

It would be of very great interest for the same question to know what direction of blow, relative to the crystal axes, is most favourable for twinning. Can the author give us any closer estimate than the general indication of § 4 of his paper?

The fact that the whole of the twinned part of the crystal turns through 5° indicates that the modification of the lattice is propagated from the twinning boundary. The readjustment of the atoms into the twinned lattice without any atom moving through more than the interatomic distance is conceivable, if the twinning takes place simultaneously throughout the volume. It might be worth while to find out whether twinning would take place if the crystal were enclosed in an unyielding cylinder and struck, and, if so, whether it would be in close narrow bands alternating in orientation.

I was struck by the use of the optical method for identifying the crystal axes. It has been utilized once or twice previously, notably by Bridgman,* but it seems to have been too much neglected if it is as simple as it appears to be from the author's demonstration.

Mr E. J. DANIELS. The author's method of determining orientation appears to be more readily applicable in metallographic investigations than those discussed by Tammann in the paper to which he refers. The observation, recorded on page 739 of the paper, that twinning produced by compression can be reversed by tension giving again an untwinned crystal, seems very illuminating in connexion with a suggestion of Elam† that certain results given by annealing of crystals bent in various manners can only mean that some of the strain set up by bending one way is reversed when the metal is bent in the reverse direction.

AUTHOR'S reply. Prof. Haigh puts forward a very interesting suggestion regarding the relation between twinning and fatigue; it would seem, however, that a considerable amount of experimental work must be done on metals other than tin before the conclusions arrived at with respect to tin can be regarded as generally applicable to metallic crystals. At the same time, it seems likely that the mechanical reversibility of the twinning process is shared by every metal in which twinning can occur.

I should like to thank Prof. Andrade for the suggestions he has made for future work on twinning. I am not yet in a position to answer any of the specific questions that he raises, but I hope to deal with them in a future communication.

In reply to Mr Daniels, it seems clear that any distortion resulting in the formation of a lattice identical with, but inclined to, the original lattice can be reversed by the application of a force bearing the same relation to the new lattice as the previous force bore to the original lattice. The fact that this takes place as described in the paper indicates that the twinned lattice is identical with, though inclined to, the untwinned lattice.

* *Proc. Amer. Acad. Sci.* **60**, 305 (1925).
† C. F. Elam, *Distortion of Metal Crystals*, p. 175.