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MAY LECTURE, 1938.

PLASTIC STRAIN IN METALS.

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SYNOPSIS.

The work of the author with Dr. Elam on the straining of metallic single crystals is described. The application of experimental results with single crystals to polycrystalline aggregates is discussed.

IN the May Lecture last year Professor Andrade [1] gave a very clear account of some of the main lines along which researches on metallic crystals have developed. I hope now to discuss some of the questions treated by Professor Andrade, but in greater detail than he was able to do in the time at his disposal. I propose also to put forward some thoughts about how our knowledge of metallic single crystals can help us to understand the mechanical properties of crystal aggregates.

I must begin by making the confession that I am not a metallurgist; I may say, however, that I have had the advantage of help from, and collaboration with, members of your Institute, whose names are a sure guarantee that the metals I have used were all right, even if my theories about them are all wrong. Perhaps I may be excused if I give an account of how I first came to have anything to do with metals. I was present at the Royal Society on the occasion when Sir Harold Carpenter described the fascinating series of researches which enabled him and Dr. Elam to prepare very large single crystals of aluminium. He showed test-pieces which had been pulled in a testing machine with the result that lines originally scratched on them at right angles to their longitudinal axes had become oblique during the plastic straining. These lines, it seemed, must provide the clue to the relationship between the crystallographic axes and the plastic strain. At that time the existence of slip lines on the surface of strained metals was well known, and it was known also that they are the traces of crystallographic planes. It was freely stated that they became visible, owing to slipping

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of the metal, just as the edges of cards in a pack become visible when the top of the pack is pushed sideways. This, however, is a very different matter from stating that the total strain is identical with that which is produced in a pack when cards slide over one another. The surface markings may, for instance, develop quite independently of what goes on inside the crystal, because the surface is known to be in a different physical state from the interior.

When the phenomena shown by Sir Harold Carpenter's strained crystals were regarded from the geometrical point of view, it was clear that one could completely determine the strain in the crystal: (*a*) if the strain was uniform, so that lines in the specimen which were originally parallel remained parallel when it was strained, and (*b*) if the extensions or contractions in six independent directions could be measured. We may, for instance, imagine that a square-sectioned bar is cut from a single crystal. In Fig. 1, *ABCD* is the square section which we may suppose marked with scratches on the surface, and *AF, BE, CG* are edges of the bar. If now we measure the proportional extension during strain of the six lines, *BA, BC, BE, AC, AE, EC,* then the strained position of every particle is determined. If we measure only five, then the strain is not completely determined, unless some further assumption is made. We may find, for instance, that the density is unchanged by the strain; then five, and only five, independent extensions or components have to be measured to determine the strain. The six components of strain need not, of course, be those shown in Fig. 1. One may, for instance, measure the extensions *BE, BA, BC,* and the angles *ABE, CBE,* and the angle between the faces of the specimen. Sir Harold Carpenter and Dr. Elam's original specimens were not suitable for making accurate measurements of the six components of strain. Accordingly, encouraged by Sir Harold, Dr. Elam and I collaborated in preparing and marking single crystals of such proportions that accurate strain measurements could be made. Fig. 2 (Plate XXXVII) shows one of our specimens after 70 per cent. extension. The strain was very uniform, even after such great extension.

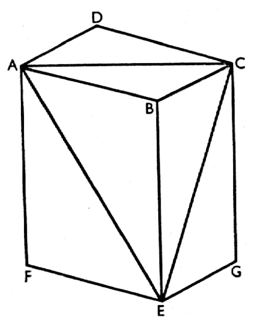

FIG. 1.—Measurement of Six Lengths to Determine Strain.

The usual method by which strains are analyzed is to find the positions and elongations of the axes of the strain ellipsoid, *i.e.* the strained

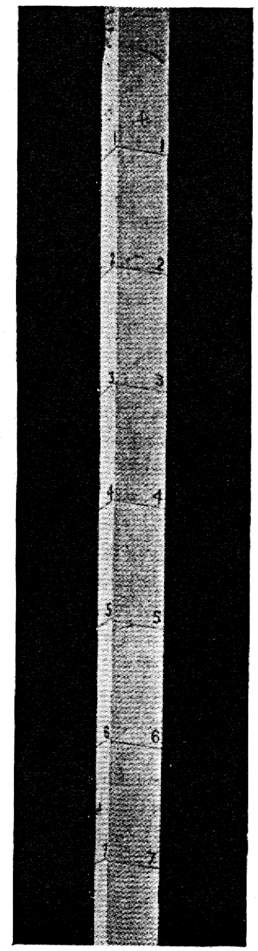

FIG. 2.—Marked Specimen Cut from Aluminium Single Crystal, after 70 Per Cent. Extension.

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PLATE XXXVIII.

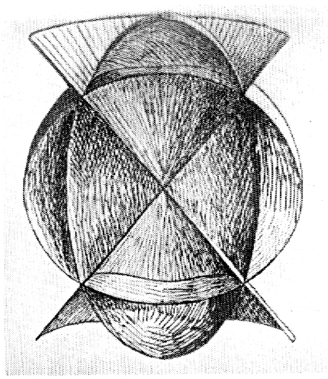

FIG. 3.—Unextended Cone and Strain Ellipsoid.

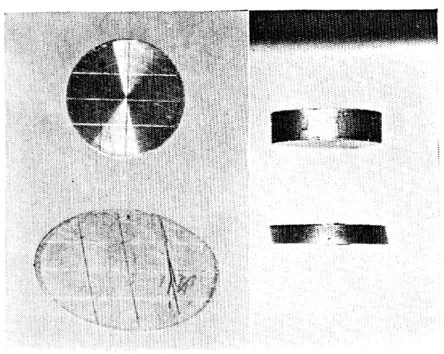

FIG. 5.—Front and Side Views of Compressed Disc Cut from Single Crystal.

shape and position of an originally spherical piece of material. In our case, however, we found instead the cone which passes through the intersection of the strain ellipsoid and the original sphere. This cone, which is shown in Fig. 3 (Plate XXXVIII) with the strain ellipsoid, evidently contains the strained positions of all directions which remain unstretched, and is therefore termed the unstretched cone. Our reason for adopting this procedure was that if the whole strain is, in fact, due to slipping parallel to one crystal plane, that crystal plane must form part of this cone, because slipping parallel to a plane gives rise to strain which leaves all directions in the plane of slipping unchanged in length. If part of the unstretched cone consists of a plane, it is a mathematical necessity that the whole cone must consist of two planes.

I will not trouble you with the method by which we calculated the position of the unstretched cone [2] in the strained specimen, but it is necessary for the argument that one should understand how this cone and the directions of the crystal axes were represented on plane diagrams. For this purpose we used the stereographic projection. Each direction in space can be regarded as marking a point on a sphere. The surface of this sphere is then projected on to a plane from a point on its circumference.

In the projection, great circles on the sphere, which contain all directions in space which lie in a plane, are projected into circles. Of these, the great circle which represents the plane parallel to the plane of projection is the smallest. I will call it the "bounding circle." The part of the projection which lies inside the bounding circle corresponds with a complete hemisphere, and if we are thinking about orientations in space, and are not concerned with the sense of directions on a straight line—*i.e.* if we do not consider whether a vertical line is pointing upwards or downwards, but only concern ourselves with the fact that it is vertical—then all orientations can be represented on a hemisphere, and so by the part of the stereographic projection which lies inside the bounding circle.

One property of the stereographic projection is that small circles on the sphere, which represent circular cones in space, also project into circles. Small circles can be distinguished from great circles, however, by the fact that projected great circles always cut the bounding circle in the projection at opposite ends of a diameter. Small circles never do so.

When we came to set out on a stereographic projection the points representing directions in our unstretched cone, calculated from the measurements made on our stretched single crystal specimen, we found that they did in fact lie on a circle which cut the bounding circle at opposite ends of a diameter.

Fig. 4 shows the stereographic projection of points on the unextended cone calculated from measurements made before and after a strain which extended a specimen cut from an aluminium crystal from 10 per cent. to 30 per cent. elongation. The circles drawn most nearly through the calculated points are shown in the diagram. It will be seen that they do in fact cut the bounding circle at opposite ends of diameters. This is a proof that, in the case to which this diagram refers, the unstretched cone really does degenerate into two planes, so that the total distortion can in fact be produced by slipping on either of these planes. It is impossible from two sets of external measurements made before and

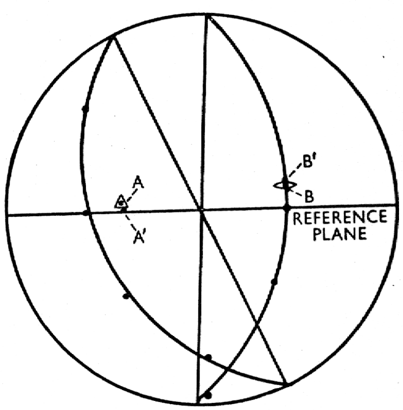

Fig. 4.—Stereographic Projection of Unextended Cone, with Diameters Marked to Prove that Cone is Two Planes.

after straining to say which of these two planes is the plane on which slipping takes place, but we always found with aluminium that one of the two coincides with an octahedral crystal plane. This plane we took as the slip plane, and we found that the direction of slip is the diagonal of a cube face or edge of the octahedron.

In Fig. 4, B' is the direction of slip calculated from the external measurements of lines on the specimen, and B marks the orientation of a crystal axis represented by (101), *i.e.* it is in the direction of one of the diagonals of a cube face, or an edge of the octahedron corresponding with the cubic symmetry of the crystal. The point A' represents the direction of the normal to the plane which is represented in Fig. 4 by the circular arc containing B'. The point A represents the crystal axis, determined by X-rays, which is the diagonal of the cube in cubic symmetry. The crystal axes A and B are evidently associated with one of the planes of the unextended cone, but not with the other. The plane has accordingly been taken as the plane of slip. It will be seen that the plane of slip is parallel to a face of the octahedron associated with the cubic symmetry of the crystal and the direction of slip is parallel to an edge of the octahedron.

This method is more complicated than that used by Professor Andrade and by practically all other workers in the field. They strain the crystal and observe marks on the surface, which they prove are the traces of a crystallographic plane. They then *assume without further proof* that the strain is of a simple type consisting of a shear parallel to the plane marked out by the surface markings, and then make the two angle or extension measurements which are necessary to determine the direction of slip if their initial assumption is true.

Professor Andrade offers the opinion, in one of his papers, that this simplified method is in some cases more accurate than the complete analysis that I have described. I do not agree with this contention, provided that *proper precautions are taken* to ensure that the specimen is strained uniformly. In some cases the simplified method is inapplicable, because the assumed strain by shearing parallel to a crystal plane does not in fact take place; in others the slip lines on which the method relies do not make their appearance.

Fig. 8 shows the stereographic diagram of one of the cases analyzed. The unextended cone is nothing like two planes; in fact this diagram was proved to correspond with compound slipping on two octahedral planes. For cases to which it is applicable, the simple method provides a quick means of identifying slip planes provided that one has made certain, by complete strain measurements, that the strain is due to shear parallel to a plane.

The accuracy of the complete analysis depends on the uniformity of the strain. If a tensile specimen slips unequally in different parts of its length, strain measurements on its surface will vary from place to place. For this reason, I developed a method of straining in which flat discs cut from a crystal were compressed between parallel steel faces. This method ensured that the compression at all points of the disc was the same, and thus secured uniformity in one, at any rate, of the components of strain.

Fig. 5 (Plate XXXVIII) is a photograph of a circular disc cut from an aluminium crystal, before and after compression. In spite of reduction to half the original thickness, the scribed lines are still quite straight, and with this technique there is no " barrelling " of the section perpendicular to the parallel faces.

The great uniformity of our compression specimens was obtained by a special technique. If one compresses a short cylinder of solid metal between parallel planes the friction at the top and bottom normally holds the ends from expanding laterally and the specimen assumes a shape like a barrel. If the compressing faces are ground and polished and then greased, the first thing that happens when a compressive load is applied is that the grease is squeezed out. This causes an outward tangential force due to viscous drag to act over the top and bottom of the specimen, that is, a force in the opposite direction to the friction which would act in the absence of grease. By compressing the speci-

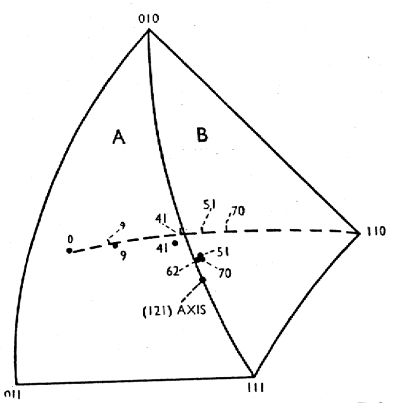

FIG. 6.—Change in Orientation of Axis of Specimen (see Fig. 2) Relative to Crystal Axes, During Extension of 70 Per Cent.
• Observed by X-Rays. ı Calculated.

men in very small stages one can in this way get far greater uniformity of strain than can be obtained in a tensile specimen.

When a single crystal is extended, the orientation of the crystal axes relative to the axis of extension varies as the straining proceeds. If the strain simply consists of sliding parallel to a crystal plane in a crystal direction, the cause and nature of this change in orientation becomes clear if we imagine the slip plane as fixed, and the orientation of the axis of the specimen as changing. The specimen axis must rotate in a great circle towards the direction of slip. In Fig. 6, 0 represents the initial position of a specimen axis in one of the triangles of cubic symmetry. The point (110) represents the crystal axis towards which slipping has occurred. The dotted line represents the great circle

along which the specimen axis would move if the slipping were of the type contemplated, and the calculated positions of the specimen axes for extensions of 9, 41, 51, and 70 per cent. are marked off on the dotted line. The positions of the specimen axis measured by X-rays are also shown. It will be seen that at 9 and 41 per cent. extension there is good agreement, but that as soon as the representative point reaches the boundary between the two symmetry triangles it does not continue along the calculated path, but remains close to the boundary of the two triangles. This is because symmetry requires that when the representative point gets into the right-hand triangle slipping shall start in the direction of the axis represented in Fig. 6 by (011). Slipping towards the direction (011) would move the representative point back to the boundary between the triangles. Thus slipping continues on two planes, and the representative point remains on the plane midway between the two directions of slip. Finally, it reaches a crystal axis shown by (121) in Fig. 6, which is the point midway between the two directions of slip (110) and (011).

This, and the similar case of a single crystal under compression, are the only two cases in which a preferred orientation of crystal axes due to straining has been explained, though the phenomenon of preferred orientation has been found experimentally by means of X-rays in a large number of drawn, rolled, and otherwise worked metals.

I have mentioned that with aluminium the slipping is on an octahedral plane in the direction of its edges. An octahedron has eight faces, but pairs of them are parallel to one another so that there are four possible slip planes, and on each of these there are three possible directions of slip, making twelve possible types of slipping in all. We have seen that, when a single crystal of aluminium is pulled, the strain is due to one only of these twelve. As Professor Andrade told you last year, we found that if the shear stress is resolved parallel to all the four possible slip planes in each of the three possible directions of slip, the operative slip is that one of the twelve possibles for which the shear stress is greatest. We found, further, that this law of maximum shear stress determines the same slip plane and direction for all possible positions of the specimen axis within one of the triangles into which the diagram of cubic symmetry is divided. When a single crystal of aluminium, or an aggregate of such crystals, is strained, the resistance to further straining increases as the plastic strain increases. When the slipping is on one crystal plane, the resistance to shear depends only on the amount of shear strain that has occurred since the crystal was in its original fully annealed state. Professor Andrade showed some curves giving the relationship between the plastic shear strain s and the shear stress S. Fig. 7 shows the relationship between S and s, derived from experiments on the crystals of identical material in tension and in compression. It will be seen that the fact that though in one case there was compression perpendicular to the slip plane, while in the other there was tension, no difference is observed in the S–s relationship.

On the other hand, the resistance seems to increase rather more rapidly when double slipping occurs than when the whole strain is due to single slipping. One of our specimens had its crystal axes in the

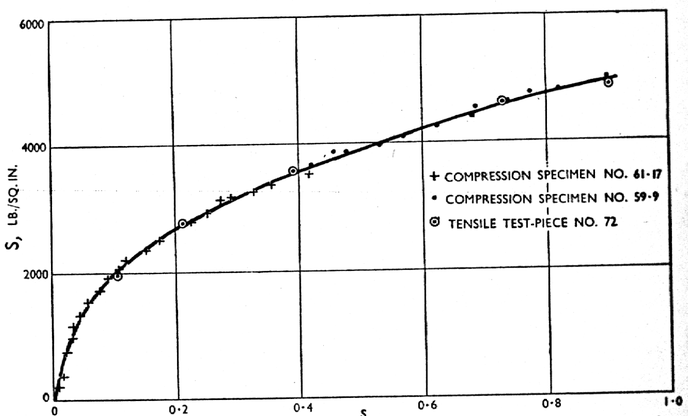

Fig. 7.—Shear Stress, S, and Shear Strain, s, of Aluminium Single Crystals Resolved on to Slip Plane and Direction.

•, + } In Compression. ⊙ In Tension.

symmetrical position where double slipping might be expected to take place. The complete analysis of double slipping was carried out for various stages of compression. The unstretched cone was worked out from the measurements of the specimen, and also calculated on the assumption of equal slipping on each of the two possible slip planes. The two cones are shown in Fig. 8, and it will be seen that they are only very slightly different. Thus, the strain is in fact very nearly due to the type of double slipping which the symmetry and maximum shear stress rule prescribes. Fig. 9 shows the S–s curve derived from the analysis of double slipping; it is of the same type as that for single slipping, but is rather higher.

Now we approach a complicated and difficult problem, namely the

analysis of stress and strain in an aggregate of crystals when the whole aggregate is strained plastically.

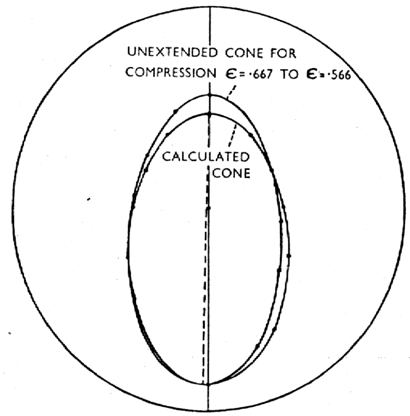

Fig. 8.—Stereographic Projections of Calculated and Observed Cones for Double Slipping.

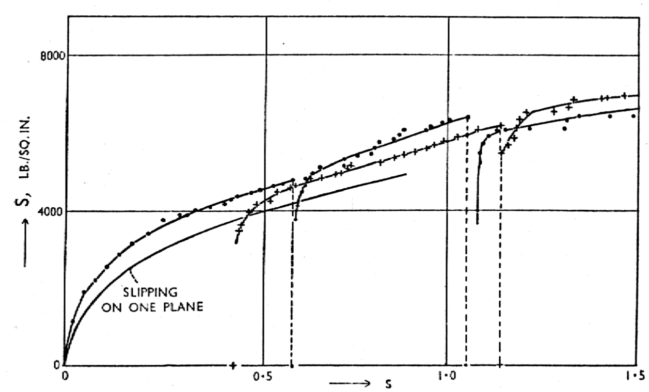

Fig. 9.—Shear Stress, S, and Shear Strain, s, for Double Slipping.

I think that I can say, without fear of contradiction, that no self-consistent or valid theory of plastic crystal aggregates has yet been put forward, though a number of invalid attempts have been made in this direction. The essential difficulty in connecting experimental results obtained with single crystals with those obtained in aggregates is to imagine how it is possible for slipping to go on inside crystals so that the boundaries of neighbouring crystal grains shall still be in contact after the slipping has taken place. All attempts made so far to correlate the mechanical properties of crystal aggregates with those of single crystals rest on the same fallacy, namely that each crystal grain can be treated as though its neighbours did not exist. The recent work of Cox and Sopwith,[3] for instance, visualizes a crystal aggregate as consisting of a large number of cylindrical single crystals combined together into a cylindrical aggregate. When the aggregate is extended parallel to the length of the cylinders each crystal extends just as a single crystal would if it were removed from its neighbours, and the total force required to extend the aggregate is the sum of the forces required to extend each crystal. If the crystals fitted together as a solid mass before straining they would certainly not, in this conception, fit together after straining, so that holes would be produced between the grains.

I have said that it is a fallacy to think of the grains in an aggregate as being independent of one another so far as strain is concerned, but it seems to me that a still more fundamental fallacy is involved in the existing way of thinking of stresses in the grains of plastic aggregate at all. When a cylindrical specimen cut from a single crystal is subjected to an end load, it is only possible to think about the stress at any point inside it because that stress can be assumed to be uniform. On the other hand, if two single crystal cylinders are stuck together along their length, and an end load is applied, the stress is quite indeterminate until they begin to stretch, because one may be subjected to an initial compressive load which is balanced by an equal tensile load in the other.

A crystal aggregate may be likened to a mechanical system in which each part bears on its neighbours with a frictional contact. A simple model which illustrates some of the properties of frictional systems is shown in Fig. 10. It consists of a board lying in the angle made by vertical and horizontal boards. The stress in it is quite indeterminate, and might have any value between certain limits. If, for instance, one were to push on the vertical board, bending it slightly, one could increase the compression in the sloping board without making it slip. Now suppose we push the sloping board till it slips. Amonton's law of friction, according to which the ratio of the tangential to the normal force at a sliding contact is equal to the coefficient of friction, now makes the forces everywhere determinate.

If, instead of obeying Amonton's law, the friction at both sliding surfaces were independent of normal force, the force system would again be determinate if the tangential force at each contact were known. To find P, the force with which the sloping board must be pushed in order that it may slide, we can solve the equations of equilibrium, calculating normal reactions at the points of contact. On the other hand, we can proceed more simply by what is called the principle of virtual work. We imagine that the force P pushes the system through a distance x at its point of application. The work done is then Px. If s_1 and s_2 are the distances through which the ends of the sloping board slide, and the friction forces are f_1 and f_2 the

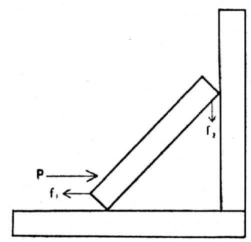

Fig. 10.—Model Illustrating Simple System with Friction.

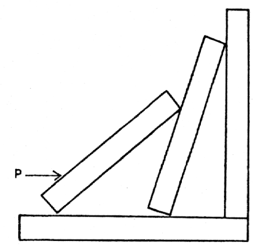

Fig. 11.—Friction System with Two Possible Modes of Slip.

energy wasted at the points of sliding contact is $s_1 f_1 + s_2 f_2$. The principle of conservation of energy then gives

$$P = f_1 \frac{s_1}{x} + f_2 \frac{s_2}{x}$$

The ratios $\frac{s_1}{x}$ and $\frac{s_2}{x}$ are determined by purely geometrical considerations. It will be seen that by this principle of virtual work we have determined the force P without bringing in the conception of stress at all.

Now consider the more complicated system consisting of two boards, which is shown in Fig. 11. When the outer sloping board is pushed, one of two things happens: either the inner sloping board remains fixed, the contacts at the two ends of the outer board slipping, or no slipping occurs at the contact of the two sloping boards, but all the remaining three contacts slide. One cannot arrange the boards so that all the possible contacts slide at once when the outer one is pushed. In systems like this the only general rule that can be given for determining the force necessary to cause motion is to assume that there is no slipping at as many of the frictional contacts as is possible in view of the geometrical constraints in the system. We can then calculate the force P which corresponds with each of the motions which satisfy this condition, using the principle of virtual work. The motion which actually occurs will be that for which P is least.

Now let us see how this principle can be used to determine the combination of shears or slips which will arise when any given strain is forced on a crystal by an external agency. Take first the case of a cubic single crystal extended in one direction, and able to expand or contract freely in all perpendicular directions. The single geometrical condition can be satisfied if one only of the twelve possible types of slipping is operative. In this case, the virtual work equation is $Ss = Px$, where s is the amount of slip corresponding with extension, x, so that if the shear strength S is the same for all the twelve possible types of slip, the principle of least possible energy dissipation for a given extension tells us that only that slip plane is operative for which s is least when x is prescribed. It is a matter of simple geometry to show that with single slipping, $\frac{x}{s}$ is identical with the "stress factor," *i.e.* it is equal to the ratio $\frac{S}{P}$, so that the condition that $\frac{s}{x}$ shall be the least possible is identical with the condition, derived from the conception of stress that the operative slip is that for which $\frac{S}{P}$ is the greatest of the twelve possible values.

We are now in a position to see how one can determine the system of complex slipping which will occur when any given strain is produced in a crystal. A strain has, as I stated earlier, six components, but when the strain is composed of shear strains only, without volume expansion, this is reduced to five. If these five components of strain are given, we can combine five out of the twelve possible shears or modes of slipping to produce the required strain. We could, of course, combine six, seven, or more shears to produce the same strain, but our study of the mechanics of frictional systems shows that the least energy is wasted, or virtual work done, with a combination of five only. To choose the five, we can only try every combination of five out of the possible twelve, and see which corresponds with the least virtual work or energy dissipated.

At first sight, this seems a formidable task, because there are 792 ways of choosing five things from a group of twelve. We must remember, however, that the range of choice is much more restricted than that contemplated in this estimate. In the first place, the three directions of slip on any one plane are not independent, since the strain due to slipping in one direction can be produced by combining shears in the two other directions. Thus, the twelve shears are divided into four groups of three shears each and only two can be assigned to any one group. This reduces the number to 648. Next it is found that the geometrical condition for a given strain cannot be satisfied if the five shears are chosen so that two are taken from one group, *i.e.* one slip plane, and the remaining three are chosen one from each of the three remaining groups. This reduces the number of choices to 324, all of which must be chosen so that two shears occur on each of two planes, one on the third and none on the fourth. Next it must be noticed that on a plane where there are two shears there are three ways of choosing the pair. Thus, if we work out any one of the 324 combinations, eight more can immediately be deduced without further analysis. This reduces the 324 in the ratio $9:1$, *i.e.* to 36. Finally, it turns out that a further geometrical inconsistency rules out one-third of these 36, so that, finally, we are left with an irreducible number of 24 combinations of five shears.

Since the resistance to shear S has been shown, experimentally, to be the same for all the twelve crystallographically similar shears, the energy dissipated in any combination of five shears is simply equal to S multiplied by the sum of the five component shears. Thus, to find which of the 24 combinations is effective, we must take each of the 24 possible combinations of five shears and determine their five values so that they give rise to the given external strain (which is specified, of course, by five components) when combined together. In each case we then form the sum of the five shears, without regard to sign. The smallest of the 24 resulting sums is that which, by the principle of virtual work, or least energy dissipation, corresponds with the operative combination of five shears. All this sounds complicated, but the whole process involves only the simplest mathematical operations, repeated a great many times.

I have now described how the system of complex slipping which will occur on application of any given externally applied strain to a single crystal can be determined. It remains to apply the results to crystal aggregates. If you look at a microphotograph of the cross-section of a drawn wire, you will see that the crystal grains are all elongated in the direction of extension, and contracted in the perpendicular direction. Each grain, in fact, suffers exactly the same strain as the surrounding material in bulk. With this strain, all the grain boundaries necessarily remain in contact, no holes forming between them. I have therefore taken the case of an aggregate in

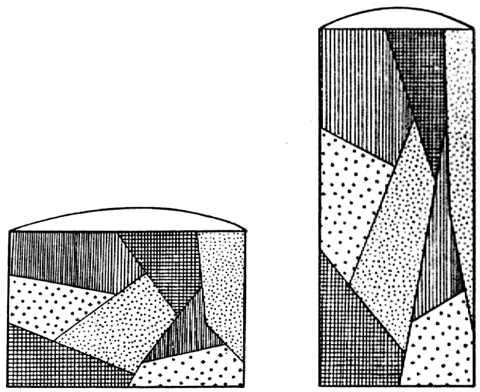

FIG. 12.—Crystal Aggregate: *a*, Unstrained; *b*, After 125 Per Cent. **Extension.**

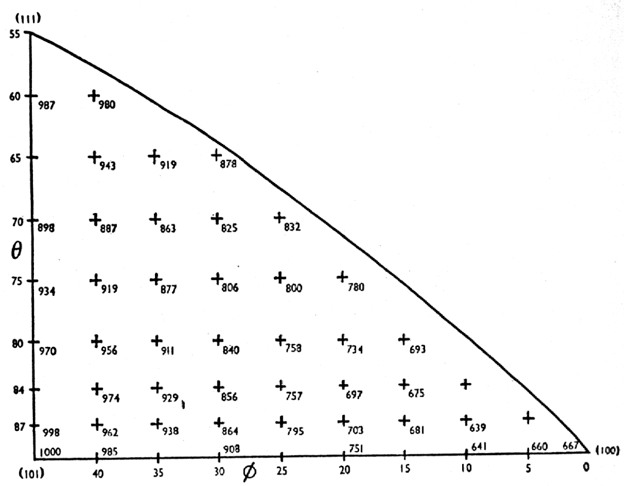

FIG. 13.—Stereographic Projection Showing Orientations for which Complete Calculations were Made.
Figures are Sum of Shears when Extension Per Unit Length of Aggregate is 272.
+ Crosses Show Orientations for which Complete Calculations were Made.

which the grains take up all possible orientations, and have imagined that the aggregate is strained by extending it by a small amount in one direction, while at the same time contracting it by half the amount in all perpendicular directions, thus keeping the volume unchanged. The diagrams shown in Fig. 12, which are drawn to scale, show on the left an imaginary section of a coarse-grained, round bar, on the right the same bar with the same grains when extended to $2\frac{1}{4}$ times its initial length.

I selected a number of orientations of the axis of extension in relation to the crystal axes, and have worked out by the method described above and with the help of Mallock's equation-solving machine, the particular combination of five shears which is effective at each orientation. The points representing the axis of extension are nearly uniformly distributed over the fundamental spherical triangle of cubic symmetry (see Fig. 13) so as to represent random orientation in the aggregate.

RESULTS.

The sum of the five shears necessary to give rise to an extension of the aggregate equal (in arbitrary units) to 272 is shown in Fig. 13 (in the same units for each orientation). From this, the direct stress P which must be applied to the aggregate in order that plastic strain by complex slipping may proceed, has been calculated. Then assuming, as is warranted by experiments on single crystals, that the increase in shear stress on a crystal plane in complex slipping depends on the sum of the shears in the same way that S depends on s in single slipping, one can deduce the load-extension curve for an aggregate from the S–s curve of a single crystal. The result is shown in Fig. 14. Fortunately, Dr. Elam had measured the load-extension curve with a polycrystalline specimen of the same material from which the single crystals had been grown. Her observed points are marked in Fig. 14.

The rotation of the crystal axes due to the five shears in each grain inside the aggregate was next calculated, in exactly the same way as the rotation due to single slipping. The rotation of the specimen axis relative to the crystal axis for an extension of 2·37 per cent. is shown, in Fig. 15, for each of the calculated orientations. This diagram is not a stereographic one; it shows in rectangular co-ordinates the co-latitude θ and longitude φ of the specimen axis referred to crystal axes placed with a cubic axis at the pole and a cubic plane as the meridian $\varphi = 0$. Comparison with Fig. 13 shows that this diagram is only slightly distorted when compared with a true stereographic projection. The arrows in Fig. 15 show the extent of the rotation;

the orientation at the beginning of the extension is represented by the point from which the arrow springs, and the final position by the point of the arrow. You will see that over a large part of the total area of the triangle there are two arrows radiating from each point. This is because at points within those areas two different combinations of five shears correspond with exactly the same sum of the shears. Any combination of these two sets of five shears taken in varying proportions could equally well occur. I have accordingly filled in the

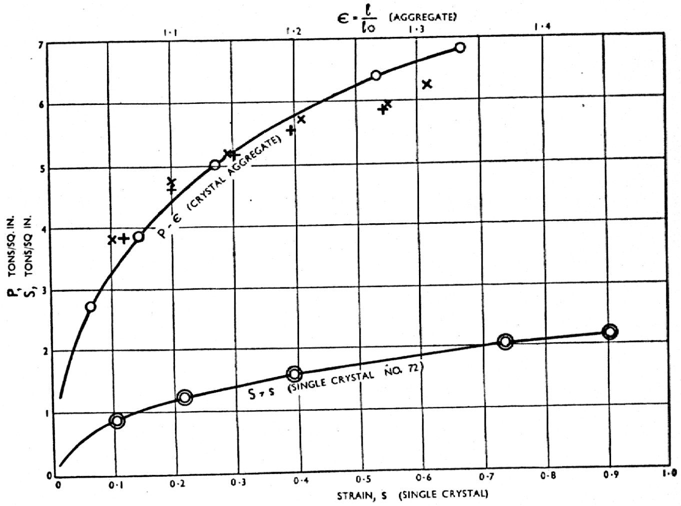

FIG. 14.—Load-Extension Curve ($P-\epsilon$) for Aggregate and Stress-Strain Curve ($S-s$) for Single Crystal.

○ Calculated from Single Crystal Measurements.
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angles between the arrows to show the range of possible movement of the specimen axis relative to the crystal axes. The whole triangle is divided into areas within which one or two combinations of five shears are effective. Each operative combination of five shears is denoted by a letter in Fig. 15. It will be seen that within the area *G* the axes of all grains rotate so that a (111) axis tends to come into line with the axis of extension of the aggregate. Moreover, the representative points of many grains which are in the area *EC* will move until they

cross the boundary between *G* and *EC* and will then move along unambiguous paths towards the (111) axis. Grains whose representative points are in the neighbourhood of the (100) corner of the triangle

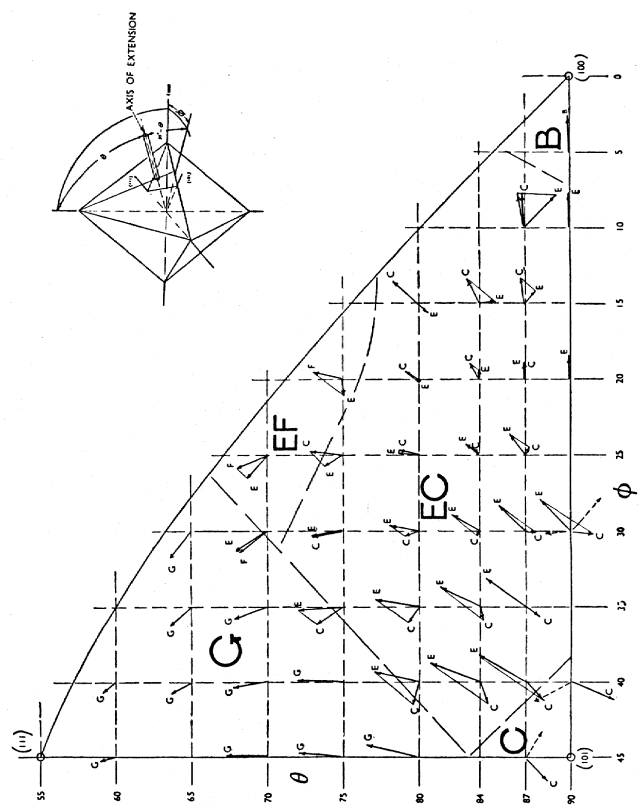

FIG. 15.—Rotation of Crystal Axes in Aggregate During Extension of 2·37 Per Cent.

will rotate until a cubic axis is parallel to the specimen axis. The crystal axes of grains which are near the (101) axis will tend to rotate towards either the (111) or the (100) axes. Thus, the aggregate will tend to attain a state in which the crystal axes of grains have either a (111) or a (100) axis, but no grains with a (101) axis in the direction of extension. For compression of a crystal aggregate, exactly the reverse rotation would occur; no grains would be expected with (111) or (100) axes in the direction of compression, but the crystal axes of all grains would tend to rotate until a (101) axis was in or near the direction of compression. These preferred orientations are in fact exactly those found by X-rays.

REFERENCES.

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[3] H. L. Cox and D. G. Sopwith, *Proc. Phys. Soc.*, 1937, **49**, 134.

OBITUARY.

AUGUST BOERNER.

August Boerner, a prominent figure in the German metallurgical and mining industries, died suddenly on November 27, 1937.

Born at Emmerich (Rhine) in 1884, Herr Boerner studied economics at the Handelshochschule, Cologne, before becoming secretary to William Merton, the former director of the Metallgesellschaft, Frankfort. Subsequently, he was appointed to the board of the Metallbank and of the Metallurgische Gesellschaft, of which he was the London representative in the years before the war. During the war, he was employed on the erection of new factories for the introduction of special processes, and afterwards was engaged in restoring the foreign interests of his company. In 1929, after 18 years with the Metallgesellschaft, Herr Boerner became director of the Krupp works at Berndorf in Austria, and four years later he was appointed to a similar post with the Ballestrem concern, where he proved himself of great value.

Herr Boerner's success lay in his tact and his natural technical ability; his early death is a great loss to German industry.

He was elected a member of the Institute of Metals on March 8, 1926.

JOHN ALLEN CAPP.

American metallurgy suffered a considerable loss by the death on January 6, 1938, after an operation, of John Allen Capp, Engineer of Materials to the General Electric Company, Schenectady, N.Y.

Mr. Capp was born at Philadelphia in 1870, and graduated in Mechanical Engineering at the University of Pennsylvania in 1892. After being connected for a short time with the Thomson-Houston Company at Lynn, Mass., he went to the main plant of the General Electric Company, where he became chief of the testing department. From its establishment in 1927 to the time of his death, Mr. Capp was head of the works laboratory.

Mr. Capp was a member of numerous technical societies, but he was most closely connected with the American Society for Testing Materials, whose President he became in 1919, and of which he was elected an Honorary Member last year. He was prominent in the establishment of standards in the metallurgical industry, and served on no less than eighteen of the Society's committees, most actively perhaps on Committee B-1—Copper and Copper Alloy Wires for Electrical Conductors—of which he was chairman from 1909 until his death.

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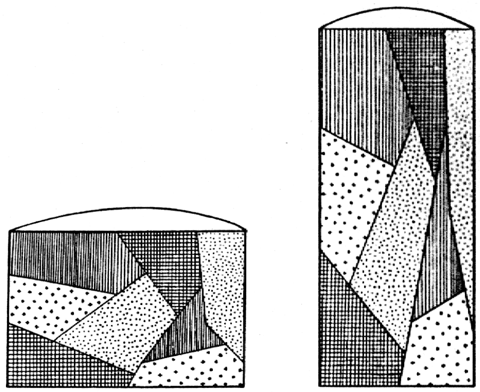

a *b*

Fig. 12.—Crystal Aggregate: *a*, Unstrained; *b*, After 125 Per Cent. **Extension.**

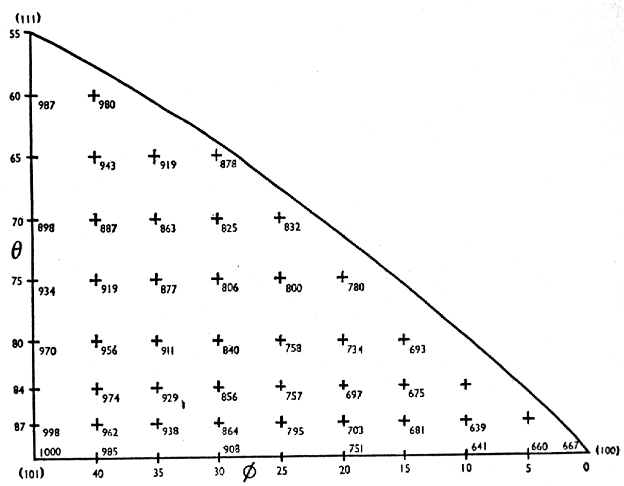

Fig. 13.—Stereographic Projection Showing Orientations for which Complete Calculations were Made.
Figures are Sum of Shears when Extension Per Unit Length of Aggregate is 272.
+ Crosses Show Orientations for which Complete Calculations were Made.

which the grains take up all possible orientations, and have imagined that the aggregate is strained by extending it by a small amount in one direction, while at the same time contracting it by half the amount in all perpendicular directions, thus keeping the volume unchanged. The diagrams shown in Fig. 12, which are drawn to scale, show on the left an imaginary section of a coarse-grained, round bar, on the right the same bar with the same grains when extended to $2\frac{1}{4}$ times its initial length.

I selected a number of orientations of the axis of extension in relation to the crystal axes, and have worked out by the method described above and with the help of Mallock's equation-solving machine, the particular combination of five shears which is effective at each orientation. The points representing the axis of extension are nearly uniformly distributed over the fundamental spherical triangle of cubic symmetry (see Fig. 13) so as to represent random orientation in the aggregate.

Results.

The sum of the five shears necessary to give rise to an extension of the aggregate equal (in arbitrary units) to 272 is shown in Fig. 13 (in the same units for each orientation). From this, the direct stress P which must be applied to the aggregate in order that plastic strain by complex slipping may proceed, has been calculated. Then assuming, as is warranted by experiments on single crystals, that the increase in shear stress on a crystal plane in complex slipping depends on the sum of the shears in the same way that S depends on s in single slipping, one can deduce the load–extension curve for an aggregate from the S–s curve of a single crystal. The result is shown in Fig. 14. Fortunately, Dr. Elam had measured the load–extension curve with a polycrystalline specimen of the same material from which the single crystals had been grown. Her observed points are marked in Fig. 14.

The rotation of the crystal axes due to the five shears in each grain inside the aggregate was next calculated, in exactly the same way as the rotation due to single slipping. The rotation of the specimen axis relative to the crystal axis for an extension of 2·37 per cent. is shown, in Fig. 15, for each of the calculated orientations. This diagram is not a stereographic one; it shows in rectangular co-ordinates the co-latitude θ and longitude φ of the specimen axis referred to crystal axes placed with a cubic axis at the pole and a cubic plane as the meridian $\varphi = 0$. Comparison with Fig. 13 shows that this diagram is only slightly distorted when compared with a true stereographic projection. The arrows in Fig. 15 show the extent of the rotation;

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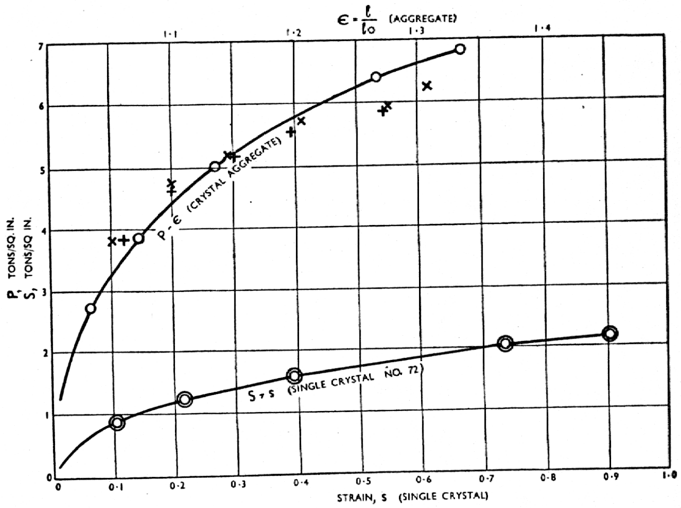

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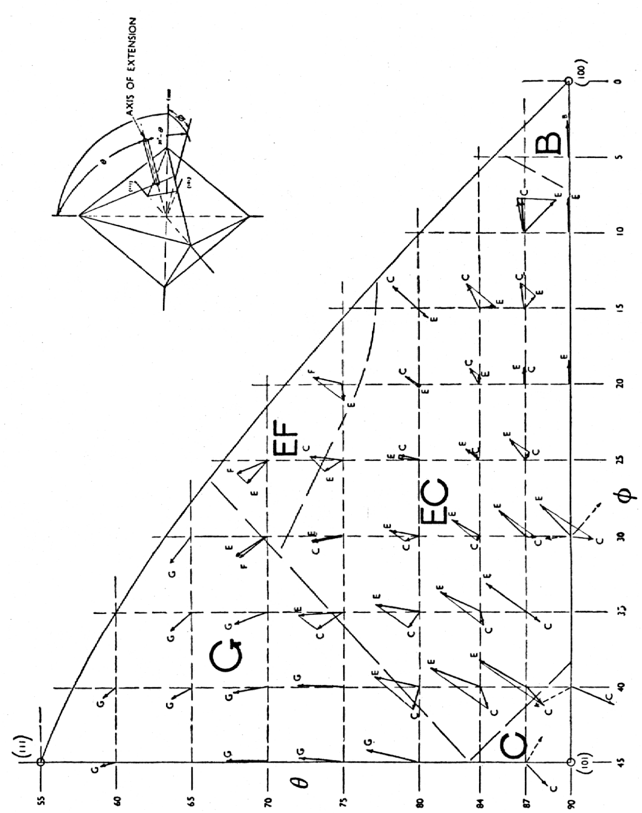

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