

Researches on polished surfaces

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RESEARCHES ON POLISHED SURFACES.

BY G. T. BEILBY, F.R.S.

Lecture delivered on November 21st, 1907.

THE ideal polished surface is one which perfectly reflects a beam of light according to the well-known law of reflection; if any stray light leaves the surface at angles other than that of the incident beam, the polish is imperfect. A beam of light falling on the clean, undisturbed surface of a liquid is reflected in this way whether the liquid is transparent like water, or opaque like mercury. For the critical examination of a polished surface the specimen is placed on the stage of the microscope and an oblique beam of suitable intensity is focussed upon it by a condenser; all stray light is as far as possible excluded from the microscope. If the surface is clean, is free from structure, and is perfectly polished, no light ought to pass through the microscope to the eyepiece, and the field of vision should appear perfectly black. If the surface is imperfect, some rays will pass through the microscope to the eye and a picture of the surface may be obtained. It is hardly necessary to remind expert microscopists that the pictures produced in this way do not necessarily represent the true nature of the structure or irregularities of the surface; but at least they may be taken as a sure indication that some irregularity of the surface or a structure of some kind does exist. The delicacy of this test may be pressed to its extreme point by using an illuminant of great specific intensity. In some experiments which will be referred to later, a critical image of the sun was focussed on the centre of the field of vision on a polished surface which had been very slightly etched. By

this searching light it was found that surface irregularities of only a few molecules in thickness could be detected. Under this illumination the minute dust specks which are always present in the atmosphere of a room, can be watched as they alight on the surface like brilliantly luminous balls, sometimes rebounding from their first impact and then rolling swiftly over the surface before coming to rest. Indeed, these microscopic "fire balls" may become so distracting in certain states of the town atmosphere that it is necessary to exclude them by carefully screening the surface under examination.

While this method of illumination by means of a very intense oblique beam, is invaluable for the detection of surface structure or irregularities which are of ultra-microscopic dimensions, it requires to be used with caution when it is desired to follow the microscopic changes of structure which occur during polishing and other surface operations. For this purpose illumination by a reflected or transmitted beam, either strictly normal or slightly oblique, is most trustworthy, but when light of considerable obliquity has to be used, the most trustworthy results are obtained when it is first somewhat diffused by reflection from a white surface. In some cases it is advantageous to combine illumination by a unidirectional beam with a moderate illumination by diffused light. In this way it is possible to bring out, and, if need be, to exaggerate particular structural features by the judicious use of light and shadow. It is hardly necessary to observe that this kind of illumination generally involves the use of objectives of fairly large working distance. It ought further to be remarked that pictures obtained in this way should always be interpreted in conjunction with those obtained by other methods of illumination and with lenses of greater resolving power. To the expert microscopist of the older school it is a truism to say that no micro-structure can be confidently interpreted

till it has been viewed at various degrees of magnification and by different methods of illumination.

It is now seven or eight years since my attention was first arrested by the appearances of minute structure disclosed by the critical method of examination on surfaces which to other methods of examination appeared smooth and structureless. In some cases the surfaces lighted up brilliantly under the oblique beam and displayed in the microscope an appearance of regular structure to which the name of "spicular" was given. By the study of a variety of solid surfaces and of thin translucent films supported on glass, the true nature of the structure to which this "spicular" appearance is due was ascertained. By employing transparent or translucent films it was possible to apply illumination by transmitted light, so that lenses of the highest resolving power became available. In this way the "spicular" appearance by oblique light was definitely associated with a very fine and extremely shallow granular structure in the film. So long as this granular structure is not too shallow to be visible by transmitted light the "spicular" appearance can be produced by an oblique beam of very moderate intensity, and the "spicular" structure then corresponds very closely with the true structure as seen by transmitted light. When the granular structure becomes so shallow as to be barely visible even by slightly oblique transmitted light and a more intense oblique beam has, therefore, to be used to produce the "spicular" appearance, the diffraction discs of which the picture is built up become larger, and the pattern they depict departs further and further from the true structure.

I may remind you that the relation between the structure of a transparent body, as shown by these two methods of illumination, is familiarly seen when a diatom is examined respectively by transmitted light and by dark

ground illumination. Expert microscopists recognise that the latter method is less trustworthy when minute structural detail is being sought for. My own experience is that the method of dark ground illumination through the substage condenser is not so satisfactory as the direct method by an oblique beam thrown on the surface from above. The only advantage which may be claimed for the former method is that by it lenses of higher resolving power and smaller working distance can be used, but I cannot recall any instance in which any obvious gain resulted from this.

Throughout the lecture it will be necessary to refer to certain structural forms as "surface tension forms"; it is, therefore, desirable that I should explain more fully what is meant by this expression. I may remind you that surface tension in liquids is that property in virtue of which a liquid surface behaves as if it were a stretched elastic skin which completely encloses the mass of liquid within it. The behaviour of this skin has sometimes been likened to that of a thin sheet of india-rubber, and up to a certain point this analogy may, no doubt, be helpful, but it completely breaks down in one very important particular. The contractile force of the rubber sheet is not constant, but beginning at zero for the unstretched sheet, it increases as the surface is stretched. In the liquid skin on the other contrary the contractile force per unit area is constant, not only under all increases of its area by stretching, but also under all decreases by contraction down to the point at which the range of the molecular attraction is reached. As the area is increased by stretching, additional molecules pass from below the surface and take their places in the skin, and as it decreases, molecules pass from the skin into the interior where their attractive force is balanced by that of the surrounding molecules, and they become neutral so far as surface tension is concerned. This idea of an

almost indefinitely contractile skin, if once firmly grasped, supplies a clue which enables us to understand the varied and often strikingly-unlike forms which result from surface tension in liquids, and, as I hope to demonstrate to you, *in the more minute aggregation of solids also.*

In any moderately large mass of liquid the force of gravity keeps the surface horizontal

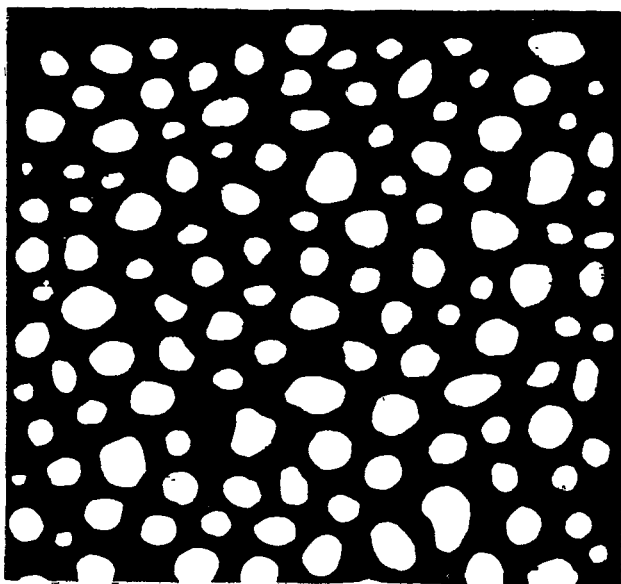


FIG. 1.

and flat, but when the force of gravity becomes small as compared with the contractile force of the surface skin, as it does when the mass of liquid is very small, the contractile force begins to overpower the gravitational force and the surface becomes convex. As the mass is further decreased the convexity of the surface increases till a point is reached at which the whole mass becomes spherical, this being the form in which

perfect equilibrium of the skin is reached. The soap bubble, the raindrop, the dewdrop, the lead-drop, and the mercury globule, all assume the spherical form under this influence. The effects of gravity and surface tension on small liquid masses can be very conveniently studied in the case of mercury, because mercury can lie on most surfaces without wetting them. If the mass of mercury is sufficiently small it is per-

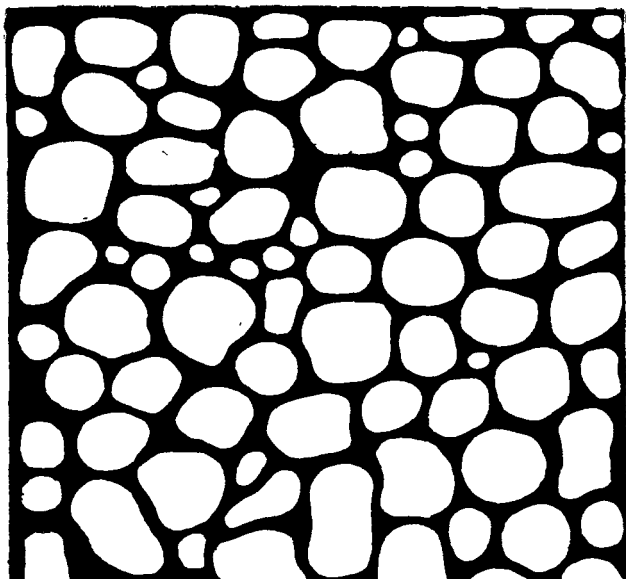


FIG. 2.

fectly spherical. As the mass is increased the side of the sphere which rests on the supporting surface is slightly flattened; as the mass is further increased the whole sphere is flattened, but the surface still remains convex, but a point is reached at which gravity so completely overpowers surface tension that a truly flat upper surface is developed.

When an oily liquid is allowed to spread on the surface of water a new element requires to

be considered. If the oily layer is of sufficient depth the force of gravity will be in the ascendant and the upper surface of the layer will be flat and parallel with the water-surface. But if the thickness of the oily layer is sufficiently reduced, the effect of gravity practically disappears, and surface tension becomes the main controlling force. But now it is not alone the surface tension of the oil which must be con-

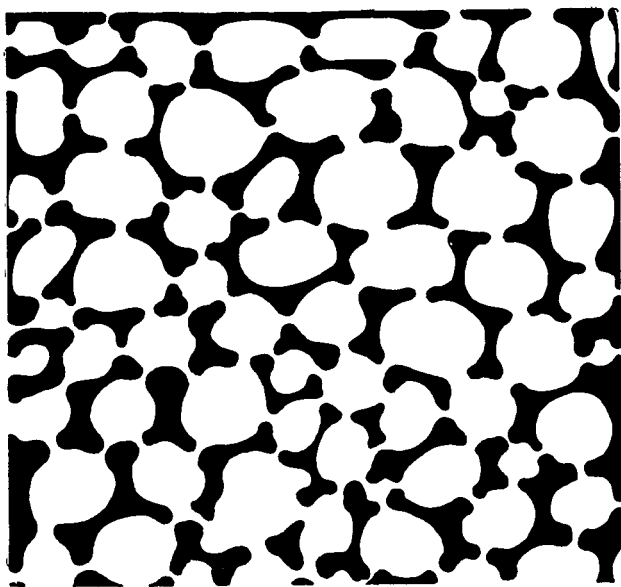


FIG. 3.

sidered, but also that of the water. The latter acts normally to the surface and its general tendency is, therefore, in the same direction as that of gravity, namely, to draw the oil over the water surface in a uniform layer. As the thickness of the oil film is reduced the equilibrium between the surface tension of the water and that of the oil, becomes unstable, and a state is reached in which the oil is partly pulled over the

surface of the water by the surface energy of the water, and partly drawn up into drop-like forms by its own contractile energy. This condition of instability lasts for a considerable time during which the forms assumed by the oil film are both interesting and beautiful. I hope to show you some of these changing forms by directly projecting the image of an actual film on the screen, but in case this experiment should

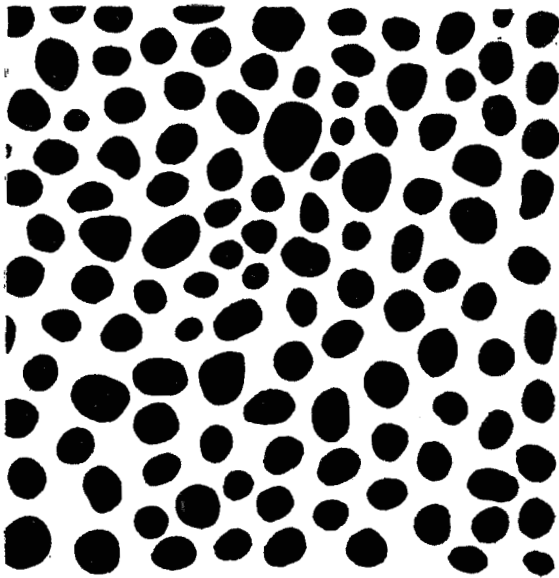


FIG. 4.

fail, the drawings on the wall have been prepared to show these forms in a somewhat diagrammatic way.

When the centre of the water surface is touched with a needle which has been dipped in an oily liquid, a film shoots out over the surface in all directions. At first this film appears quite continuous, but presently it becomes punctured all over with small round holes caused by the retraction of the oil under the contractile

force of its own skin. As the retraction proceeds the holes become larger and the film between them becomes thicker. The larger holes as they extend their area swallow up the smaller holes which they encounter in their extension. As the holes enlarge, the spaces between them become mere connecting ridges. Presently, the ridges show signs of irregular thickening at certain places and of thinning at others. This continues till the thick portions have grown at the expense of the thinner parts, and finally the

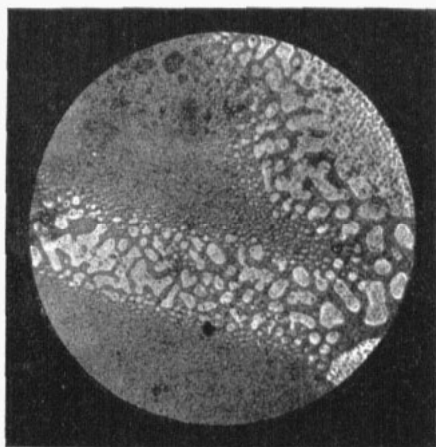


FIG. 5.

ridge divides at a thin place by the drawing up of the oil into the thickened parts on either side. The separated portions assume the form of rods with rounded ends which gradually approach more and more to the circular form. This is a very much simplified history of what actually occurs, but if the changes are narrowly watched with a magnifying glass they are seen to be complicated by the fact that on every portion of the film surface there are changes proceeding which are a repetition, on a much smaller scale, of

those occurring on the film as a whole. The recognition of this feature, the repetition of these changes of structure on a smaller and smaller scale, is of importance, as it supplies a valuable clue to the origin of certain structural forms which are to be found stereotyped in films produced by the direct aggregation of solids. The wall diagrams, figs. 1, 2, 3, 4, show four steps in the film changes; first, the perforation of the film by small holes; second, the enlargement of these holes and the gathering up of the film into mere ridges between them; third, the

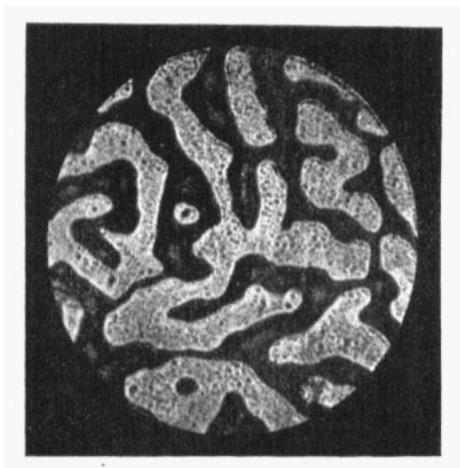


FIG. 6.

dividing of the ridges into separate pieces, and fourth, the final state in which the oil is gathered into isolated discs, or flattened droplets.

By allowing thin films of a solution of eosin in water, to which a little gum had been added, to dry slowly on glass plates, most of the steps in the passage of the continuous film to the final stage, when the film has collected in discs or flattened droplets, can be stereotyped in a convenient form for reproduction as photo micrographs. Two specimens of these are shown. In

the first slide, fig. 5, 6, the openings in the film are of all sizes and shapes from small round perforations to the large openings surrounded by ridges. These ridges also show thick and thin portions, and some of them have already divided, and the separated portions have drawn themselves into more or less circular forms. At the sides of the photograph the film is granular and unperforated. This granular texture is here seen to be a stage which precedes the actual perforation. The granulation is caused by the heaping up of the substance in

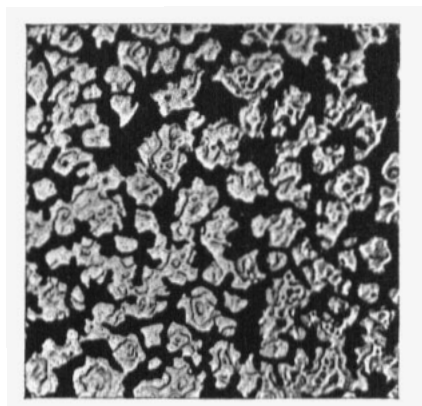


FIG. 7. $\times 440$.

tiny ridges round central depressions. The photograph was made by transmitted light, so that the bright spots are thin places, and, therefore, depressions in the film. A number of these depressions nearer the centre of the plate have actually perforated, showing the clear glass below. This granular film structure is of peculiar interest, and will be referred to later when the structure of thin metal films is being considered. The ridges round the large holes also show the granular structure. Their presence illustrates what was said as to the repetition of

smaller and smaller forms on the larger elements of structure.

It is to be noticed that though the greater part of the substance has been drawn up into the bolder forms, yet a thin transparent film still remains on the surface, and in this the structure is repeated on a smaller scale.

The various forms assumed by liquid films under the influence of their contractile skin are thus seen to range from a minute pitting, or granulation, which can be of great uniformity even over a large surface, to the bolder open-work patterns in which the liquid has been

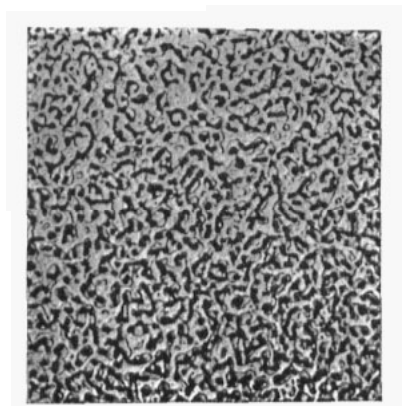


FIG. 8. × 440.

drawn up into comparatively massive ridges. Having thus become familiar with the surface tension forms which are met with in thin mobile liquid films, we are prepared to pass on a study of the corresponding forms which have been discovered in thin films of metal in the solid state.

It is not necessary on this occasion to describe the varied methods by which the metallic films were deposited on glass or mica; for the present purpose it is sufficient to say that films of gold, silver, and platinum, were obtained in thick-

nesses which ranged from a few millionths of a millimeter up to several hundred times that amount. These films being firmly adherent to the glass or mica can be regarded as in a condition analogous to that of a thin oil film on the surface of water or to the eosin film on the glass surface, but with this fundamental difference, that while the water-oil combination was throughout in the mobile liquid condition, the metal-glass combination was supposed to be in a condition of solid immobility. The mobility which was actually found to have occurred in

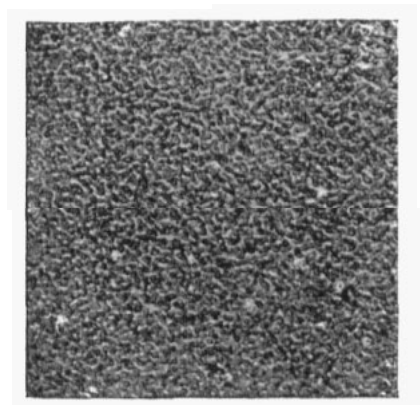


FIG. 9. × 440.

the metal films was produced by heating them in an air bath to temperatures ranging from 250° to 400° . These temperatures are far below the melting points of the metals, as well as of the mica and glass supports.

The slides now shown are photographs, at an original magnification of 400/500 diameters, of gold films of three degrees of thickness. The first was about as thick as ordinary gold leaf, and before annealing showed the usual rich olive green translucence by transmitted light. The other two were considerably thinner than this,

and were blue, not green, by transmitted light. (Slide, gold films.) The thick film, fig. 7, after annealing, shows very plainly that surface tension has been at work, and we are, therefore, obliged to conclude that the molecules have been in a state of free movement under the influence of this force. The forms assumed by the gold are remarkably like those which were taken by the eosin solution, fig. 6, or like the more transient forms which were seen in the oil film on water (fig. 3). As with the eosin, so with the gold, there is a structure within a structure. The drawing up of the opaque and more massive figures has left a thinner film of gold on the

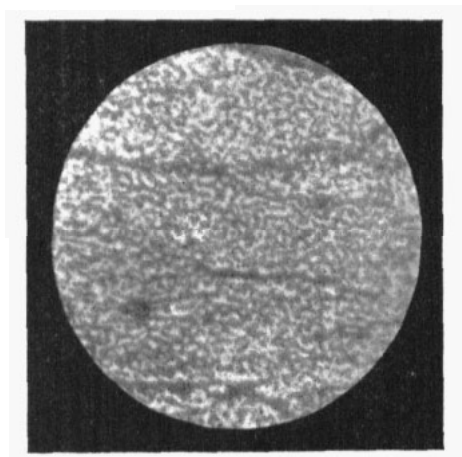


FIG. 10. × 1000.

glass which in its turn has been drawn into perfectly transparent reproductions of the same type of figures on a rather smaller scale. In the next film, fig. 8, which was less massive, the opaque figures are much smaller and show that the final stage in aggregation under surface tension had been reached, the aggregates being mainly in the form of rods or rounded patches. The transparent part of the film is peculiarly

interesting on account of sinuous interlaced pattern which has been developed, no doubt, under the combined attractive force of the supporting glass surface on the one hand, and that of the more massive gold aggregates on the other. The third and thinnest film, fig. 9, is free from massive opaque aggregates, it was entirely transparent and completely covered the surface of the glass. As a whole it is very much more uniform and is much more typical of the thin film structure than the two first films are. It would be

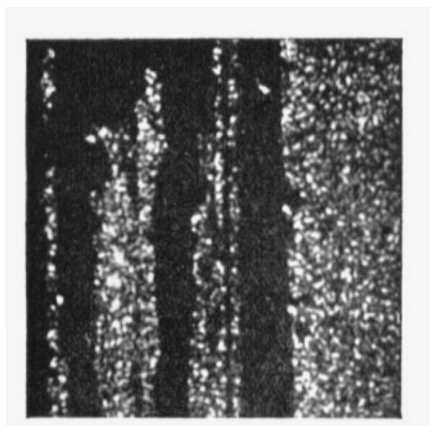


FIG. 11. $\times 580$.

easy to multiply illustrations of this phenomenon to any extent, but only two more slides will be shown to further illustrate an important point.

At the outset it was stated that the "spicular" appearance had been traced to a certain structure which has an objective existence. The structure of even the thinnest of the gold films is sufficiently bold to show distinctly by transmitted light. The silver film now exhibited, fig. 10, though of very fine texture is sufficiently thick to show the granular structure and its surface tension origin very distinctly even

by transmitted light. By obliquely incident illumination the silver film, fig. 11, shows a structure which corresponds very closely with that of the previous photograph. While the more prominent mounds, or granules, which have caught the light appear as ill-defined discs, their more shallow neighbours are fair-

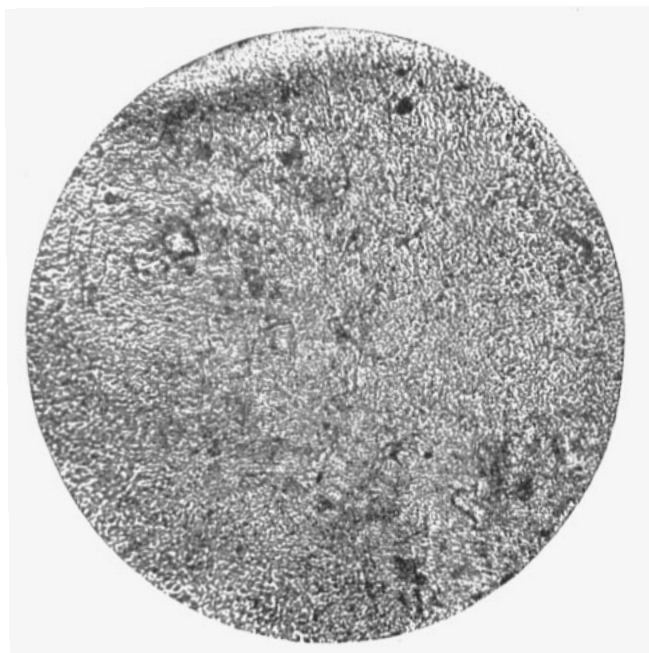


FIG. 12. × 350.

ly well defined. In this photograph a line has been scraped across the film so as to show the torn edges against the dark glass surface. The continuity of the film over the whole surface is thus made clear; it is a film, not a disjointed collection of mounds. The tendency of oblique illumination to exaggerate the details of structure can be distinctly seen in this photograph.

The granules are made to appear as if their depth or thickness is approximately equal to their diameter, whereas measurements of the thickness of the film show that the granules must really be very slightly convex, their depth being only a small fraction of their diameter. It has already been pointed out that this exaggeration is of value when it is desired to push the critical

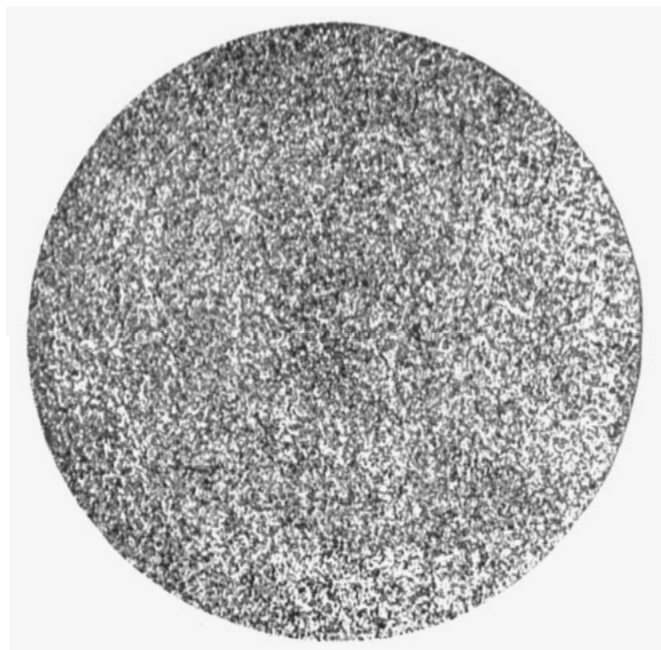


FIG. 13. $\times 350$.

examination of surfaces beyond the range of ordinary microscopic vision. The next slides are intended to illustrate this point. A very thin platinum film was photographed by the two methods of illumination, oblique and transmitted. By transmitted light the structure has been resolved by high magnification into the usual granular structure. A very intense

oblique beam was necessary to produce a photograph by a reasonably short exposure, the spicular appearance, though more brilliant, is obviously much less truthful than that obtained with the silver film. The last photograph of this series is of the polished face of a calc-spar crystal, which had been so slightly etched that by all ordinary methods of examination it



FIG. 14. × 350.

showed no departure from a perfect polish. By illuminating the surface by a condensed beam of sunlight it was possible to obtain a photograph which shows the spicular appearance quite distinctly. From data which cannot conveniently be discussed on the present occasion it was calculated that the etching had only disturbed the surface to a depth of about one millionth of a millimeter, which is equal to about three times

the diameter of the molecule of calcium carbonate. Thus, having traced the minute surface structure to the last point at which it can be definitely resolved by the microscope, and having at the same time traced the association between the spicular appearance and this structure, we are justified in considering it as probable that the ultra-microscopic structure which

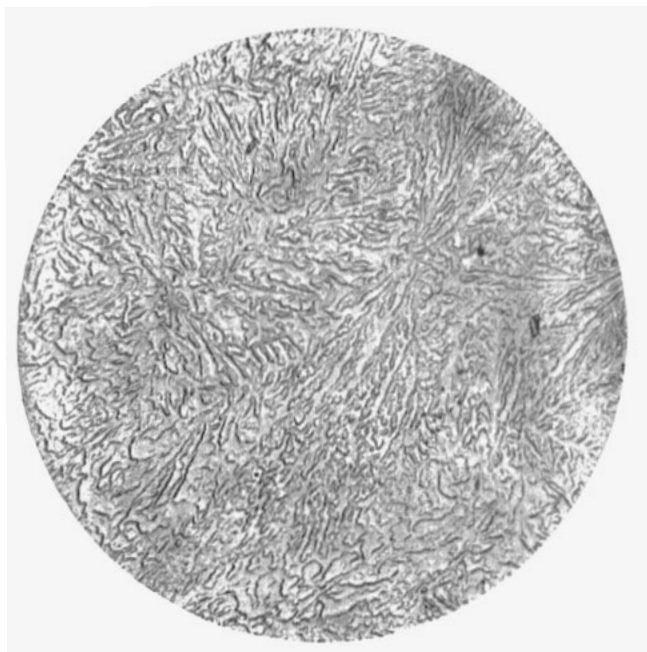


FIG. 15. × 350.

is indicated by the spicular appearance is caused by the presence of the same type of structure, but on a smaller and smaller scale till molecular or nearly molecular dimensions are reached.

Another proposition has, I think, been fairly established, namely, that an increase in the mobility of the molecules of a solid which is still far short of the freedom of the liquid state, is sufficient to enable the force of surface tension

to assemble the molecules of a thin film into new forms of aggregation.

The molecular mobility which occurs at the moment of the partial solution of a solid surface, or on the separation of a solid from solution, are also occasions which may be seized by the forces of surface tension with the result that the forms of structure which are due to these forces are found both on surfaces which have been slightly etched by solvents, and in solid films which have been deposited from solution. At the surfaces of solids and of liquids alike,

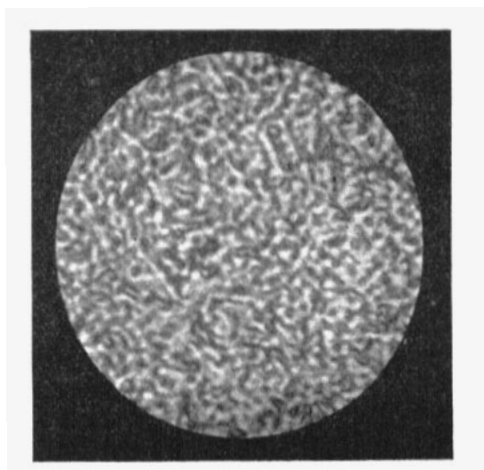


FIG. 16. GOLD. $\times 1000$.

these potential forces are always present and ready, as it were, to take advantage of any increase in the mobility of the molecules to impress their characteristic forms of aggregation upon them. To illustrate this point the behaviour of two very widely different substances will be referred to—gold and glass. The polished surface of a plate of pure gold was very lightly etched with chlorine water, so lightly, indeed, that the surface appeared to be only slightly dimmed where the solvent had acted; but

when examined by a lens of high resolving power under normally reflected light the originally smooth surface was seen to have given place to a fairly uniform structure of exactly the same type as that seen in the thinnest annealed gold film. The first slide shows the original smooth surface, and the second, fig. 12, shows the now familiar surface tension forms of one of the finer types. The fire-glazed surface of a glass slip was lightly etched by exposing it to the action of hydrofluoric acid gas mixed with air. As was the case with the etched gold,

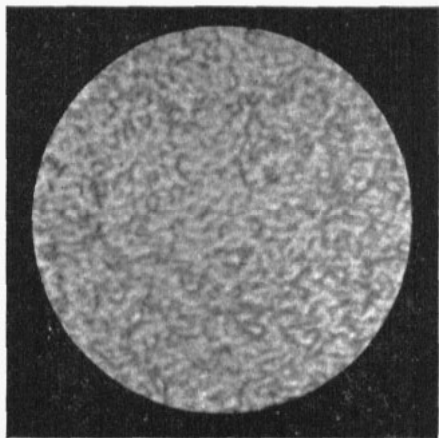


FIG. 17. GLASS. $\times 1000$.

the surface appeared to be only slightly dimmed by the action of the acid, but on examination by the same lens, and by transmitted light a surface structure was disclosed, so remarkably like that developed on the gold plate, that it would be very difficult to distinguish the two photographs if they were looked at apart, figs. 16, 17. By continuing the etching so as still further to remove the surface layers, the crystal-line structure of the gold was disclosed, in this case it happens to be a broken and distorted

structure, as the plate had been prepared by hammering it out to four times its original area, fig. 14. The glass surface was more deeply etched, and in this case, also, a different structure was disclosed, fig. 15. Whether this is to be regarded as a surface tension form of structure, or as a crystalline form, or as a compromise between the two forms, cannot very well be discussed on the present occasion, but I am disposed to look upon it as a compromise. Microscopists are familiar with the compromises of

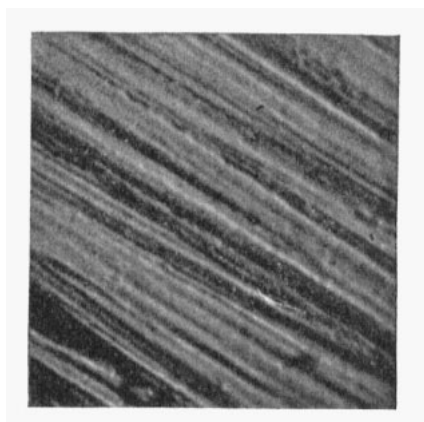


FIG. 18. × 1500.

this description, which are seen when very thin films of salt solutions are allowed to crystallise on a glass slip. If the film of solid salt is below a certain thickness, the forms assumed are purely those due to surface tension. As the thickness of the film is increased, the crystalline force gradually overpowers the surface tension, and the deposit becomes more and more sharply crystalline. My own observations have shown that there is a definite limit for each substance below which the crystalline force is completely controlled by surface tension.

Having familiarised ourselves with the influence of surface tension on the aggregation of molecules of various degrees of mobility, we are now prepared to pass on to the consideration of the particular kind of mobility which is conferred on the molecules of a solid by various forms of mechanical disturbance.

A surface may be disturbed in various ways when a moving point, made of some material harder than itself, is passed over it. The sur-

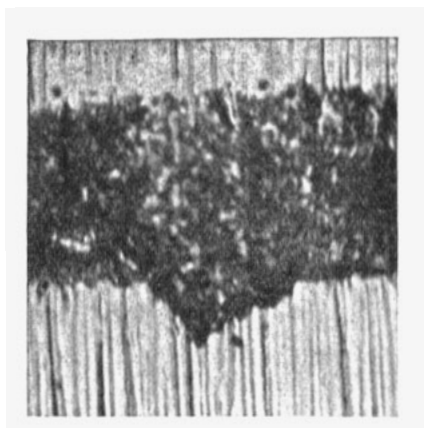


FIG. 19. × 1500,

face of the greater number of solids can be "scratched" by the point of a hardened steel needle, and the number of substances which cannot be scratched by a diamond point is extremely small. To the mineralogist the scratching test conveys a great deal of information by which he is enabled to classify mineral substances of every type. "Softness," combined either with tenacity or with friability, at one end of the scale, and the corresponding qualities associated with "hardness" at its other end, can provide a sufficiently extensive series of pigeon holes for the reception of every kind of mineral from metallic gold, or soap stone. at one end of

the scale, to the diamond, or corundum, at the other. Now, I am going to make an exceedingly strong statement, it is this: *In every one of these substances, if it is sufficiently homogeneous to be polished at all, the fundamental principles on which polishing depends are absolutely identical.* This may be supplemented by another equally strong statement: *The polished surface on a solid substance is as truly due to the presence of a surface tension skin as is the surface of a liquid.*

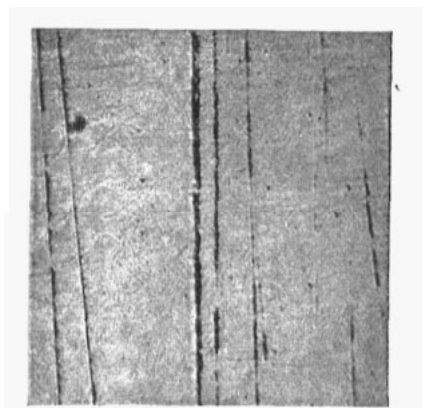


FIG. 20. × 775.

The first illustrations by which I shall attempt to justify these propositions are probably familiar to some of my audience, for they were published some years ago and have been reproduced on various subsequent occasions. My excuse for producing them now is that their selection originally, when this theory of polishing was first put forward, has been justified by the fact that fuller experience and observation, while it has supplied many new illustrations, has produced none which are better fitted for their purpose.

When a soft metal like silver is filed, even a very casual inspection of the surface shows that

it has been ploughed into ridges and furrows by the projecting points of the file. If the file cuts are fine, there is nothing in the appearance of the surface to show that any abrupt breaks in the regular removal of the metal have occurred. But if a coarser file is used there is evidence of the tearing out of metal in irregular pieces and the ridges and furrows are far from smooth. The ploughing effect in soft metals is so familiar that it might readily pass without arousing any special interest or any idea that its existence called for a more intimate explanation. The

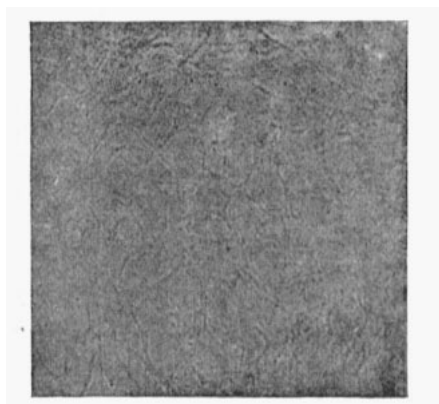


FIG. 21. $\times 775$.

convenient statement, that softness and toughness are intrinsic properties of these metals, and that ploughing and smearing are, therefore, a natural response to the mechanical treatment by tools or abrasives, does not necessarily strike us as unsatisfying.

But this as an explanation is bound to appear less and less satisfactory if the attempt is made to apply it to hard and brittle substances in which their quantities of softness and toughness are conspicuously absent.

Speculum metal gets its name from the fact that it was found to be a peculiarly suitable

material for the manufacture of mirrors for telescopes and other optical appliances. It is an alloy of copper and tin, and it is so hard and brittle that it cannot be worked by ordinary tools. In some states it is as brittle as glass and can easily be shattered by a blow with a hammer. Yet it is a remarkably easy substance to polish. Herschel, who had great experience in the grinding and polishing of mirrors for astronomical telescopes, believed that these two operations were identical, polishing being merely a finer kind of grinding. His idea was that the essential feature of polishing was the gradual flattening of the surface by the *removal of*

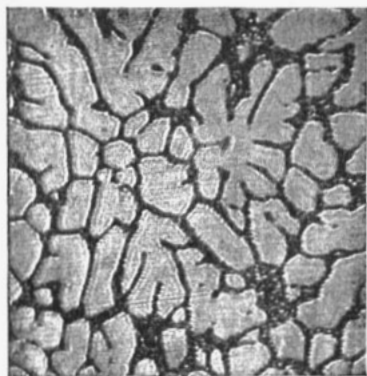


FIG. 22. $\times 775$,

material. This is an exact description of the operation of grinding, but the essential feature of the polishing operation is left out. What this essential feature really is will be made clear by the next set of photographs.

The first slide, fig. 18, shows the furrows ploughed on speculum metal by the finest watch-maker's file. The photograph was made with an oil immersion lens of the highest resolving power and the magnification of the original negative was 1,500 diameters. Even on the

most sharply focussed portions, every part of the surface is smooth and rounded, there are no suggestions of crystal facets or angles. Even in the large furrows the varnish-like effect over the surface is very evident.

The second slide shows the effect of several successive polishings with the finest emery, the wide and irregular furrows left by the file have now given place to the much finer furrows left by the emery. The furrows now number about 150 to the millimeter.



FIG. 23. $\times 775$,

The third slide, fig. 19, shows a surface of the same metal, across which a scratch had been drawn with the point of a very fine needle, the width of the scratch was about $1/75$ of a millimeter, or the $1/1800$ th of an inch. The surface was again polished on the same emery paper across the scratch. The scratch has acted as a trench in which the shavings ploughed out by the emery have been intercepted, and are seen in a heap, the top of which nearly reaches the surface level, and is in fairly good focus. It is seen that these "shavings" are really rounded bodies which are much more like drops than

like shavings or turnings. Their appearance is a further incidental proof of the flow which accompanies the ploughing action. ¹

Leaving this side issue and returning to the simply furrowed surface, the fourth slide, fig. 20, shows the effect of polishing on rouged leather across the line of the emery furrows. This is somewhat striking. The extremely fine particles of rouge appear to have gripped the surface layer all over simultaneously, and to have flowed and dragged it across the emery furrows partly filling them up and partly bridg-



FIG. 24. × 775.

ing them over. The flattening over of the surface is bringing into view the outlines of the crystalline grains of which the metal is built up.

The fifth slide, fig. 21, shows the effect of further polishing, still in the same direction, on the rouged leather. The emery furrows have now been completely flowed away, and a smooth layer has spread over the whole surface. Owing to their greater hardness the crystalline grains have been left slightly in relief, the intergranular spaces containing a softer eutectic have been worn down to a lower level.

The sixth slide, fig. 22, shows the same surface after treatment with solution of potassium

cyanide which has dissolved away the flowed layer and fully disclosed the crystalline structure below.

The seventh slide, fig. 23, shows the surface layer again restored by polishing.

This series of photographs shows very clearly the spreading of a definite layer over the surface by polishing, and its removal by a solvent.

The extreme readiness with which the surface of speculum metal can be flowed in spite of its hard and brittle character at once explains

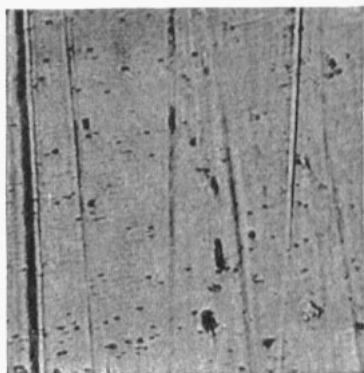


FIG. 25. × 775.

why this alloy lends itself so admirably to the making of highly polished mirrors.

The next series of slides will show how the same phenomena occur in antimony, one of the most brittle and fragile of the common metals. For these observations a portion from a well-developed crystal of antimony was selected. One of its faces was smoothed by rubbing it to and fro on a very fine file, but the metal was so brittle and fragile that it splintered very badly during the filing. It was then rubbed on the finest emery paper, and while it still splintered, some portions of the surface were ploughed with comparatively smooth furrows. The first slide,

fig. 24, of this series shows the antimony surface as it was left after polishing on emery. The larger of the pits left by the splintering are still visible as rough angular gaps, but the outlines of the smaller pits are closing in and rounding under the surface flow caused by the emery.

The second slide, fig. 25, shows the effect of cross polishing on rouged leather. As in the case of speculum metal, the rouged leather appears to have seized the upper layer of molecules and pulled it over the surface like a skin. The remarkable effect of roofing

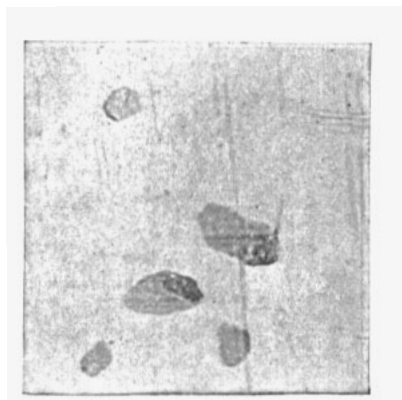


FIG. 26. $\times 775$,

or flooring over the ridges and furrows is well seen, while the forms and disposition of the holes in the layer exactly resemble the holes which one would expect to find in spreading a viscous paint or varnish over an irregularly furrowed surface. The smoothing of the surface in the antimony is mainly due to this flooring over effect of the viscous layer, while in the speculum metal the whole of the substance of the ridges appeared to be ultimately flowed down, and the furrows were really obliterated, not disguised.

The third slide, fig. 26, shows that the effect of further polishing is to produce a smooth surface from which the traces of the furrows have almost disappeared. When this smooth surface was treated with a solvent, however, the surface skin was removed and the *fourth slide*, fig. 27, shows that the original furrows and pits are still there.

Returning to the third slide, fig. 26, I would direct your attention to the group of dark pits, some of which it is quite evident have been sealed over by the polished layer. The fifth slide shows some of these pits on a larger scale.



FIG. 27. × 775.

The darker shade of the covering film over the pits shows that it is much less power of reflecting light when it is not backed by the solid metal. The antimony in a film of this thickness is translucent, or perhaps transparent.

The sixth slide, fig. 27, shows a very large pit in process of being covered over by the flowed surface layer. The viscous appearance of the film as it spreads out from the edge of the pit is in harmony with the equally suggestive appearances of the earlier slides.

It may safely be predicted that anyone seeing

these photographs for the first time, and knowing nothing about their origin, would, without doubt, believe that he was looking at a layer which had been painted across a surface while the material was in the condition of a viscous fluid. If this observer were told that the viscous-looking surface layer was in reality a substance so brittle and fragile that it could easily be reduced to a fine powder in an ordinary pestle and mortar, and that it could not be filed with the finest watchmaker's file without splintering, he might be justified in considering that he was being treated to some ingenious paradox, and it would only serve to heighten this sense of paradox if he were further shown that this viscous-looking layer was even harder than the original material, so that it formed an enamel-like protective coating over the more fragile material below.

In my own case the paradox appeared to have only one possible solution, namely, that what *appeared* to have happened really *had* happened, and that we must take it as established that the surface layer had for a brief period been in the condition of a viscous-liquid. Further, as the surface film in its final state differed most markedly in its physical properties from the original crystalline antimony, it must be accepted that the metal in its final form this flowed film is to be regarded as in a perfectly distinct state or condition from the original substance. If these conclusions are correct, then the observations on surface flow have led us to recognise that a crystalline solid can by mechanical disturbance be made to pass through an intermediate mobile phase into an amorphous or non-crystalline state. So important a conclusion could hardly be made of general application till it had been proved experimentally with a great variety of substances; but during the last few years these observations have been repeated in a variety of ways on many different substances, so that I am now

confident the above conclusions can be applied quite generally.

The next set of slides illustrate surface flow in a substance of a totally different character from the metals or alloys. Calcium carbonate occurs in nature as the beautifully crystalline mineral Calc-spar, or Iceland spar. These crystals are familiar to the optical physicist, to whom their doubly refractory property, combined with their transparence and freedom from colour, has made them invaluable. For other reasons Calc spar has been of great value in researches on surface flow. By careful selection it is possible to find crystals which, by cleavage,

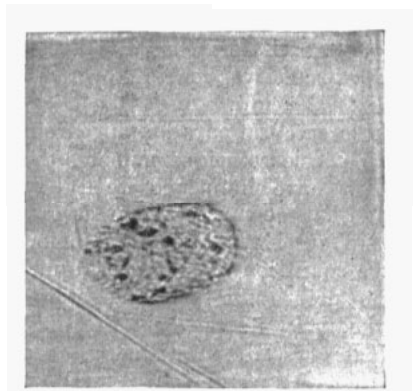


FIG. 28. × 775.

can be made to give surfaces of high natural polish, and as the operation of cleaving can be carried out so as to avoid any rubbing of the cleft surfaces, it is possible in this way to obtain surfaces which are crystalline right to their outside layer of molecules. It is obvious that surfaces of this description are very valuable for purposes of comparison with those which have been artificially polished or otherwise prepared.

When a fresh cleavage face of a calc spar crystal is lightly etched by placing on it a

drop of very dilute hydrochloric acid the surface may, or may not, show a slight depression where the acid has acted, but it shows no regular markings. But if the surface, before etching, has been firmly stroked a few times in one direction, with the point of the finger covered with soft chamois leather, the effect is altogether different when the drop of acid is applied. The drop spreads slightly, flattening to a hemisphere; after 10 or 15 seconds it is removed by touching it with a torn edge of soft filter paper. The pit thus produced has well defined edges, and its flat bottom is covered with furrows and ridges running in the direction of the strokes with the finger.

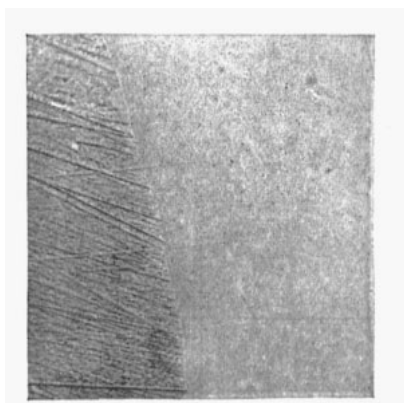


FIG. 29. × 215.

The first slide of this series shows a crystal which has been treated in this way. Two etched pits are shown, the larger of which was about two millimeters in diameter. The magnification is very small, as the object of this photograph is only to show the general appearance of these pits in relation to the crystal face as a whole.

The second slide, fig. 29, which is at a magnification of 215, necessarily takes in only a small part of the etched portion, but so as to

include the unetched surface as well. The unetched portion has a smooth glass-like surface; only a few faint scratches being visible under the most searching examination. Faint cleavage lines crossing the face indicate that the stroking, or polishing, had not been parallel with any of the natural cleavages. The polishing furrows, which are disclosed by the removal of the smooth surface layer, show that the passage of the leather over the surface had disturbed the upper layers to a considerable depth, while the perfect smoothness of the unetched

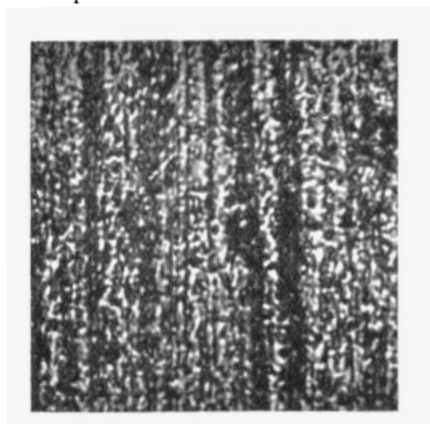


FIG. 30. × 700.

parts shows that the mobile layer which resulted was sufficiently deep to flow over and mask the ploughed furrows. The number and character of the flow lines disclosed by etching with acid is to some extent influenced by the number of strokes given, but these lines were distinctly developed by a single firm stroke in which it was roughly estimated that the pressure exerted did not exceed 4 lbs. per square inch. In this case, while the flow lines were obviously fewer per unit of surface the depth of penetration was not obviously shallower. Some indication of the depth to which the

ploughing has penetrated is given by the additional time required for the acid to dissolve and remove all traces of the disturbance. In the course of a research which is still in progress, careful measurements have been made of the thickness of the flowed layers and the special characters of each successive stratum have been studied. These observations throw further light on the subject of surface flow. When I was asked some months ago to give a paper to the Optical Society, this particular subject was selected in the expectation that it would be pos-

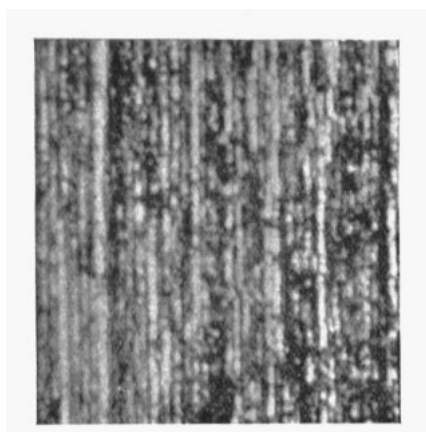


FIG. 31. × 700.

sible to lay the results of these more recent observations before you ; but I regret that the pressure of other work has made it impossible to do so.

The third slide shows the effect of longer continued etching, the ploughed lines are now very few, only the deepest having survived. The crystalline lamellae are now distinctly seen cut through by these deeper furrows or scratches.

The three substances which have been selected for the establishment of the theory of surface flow all have characters which place them far

apart from the class of soft ductile substances. The reasons for this selection are obvious, for if the theory can be established in the case of the most unlikely substances its application to the more likely follows as a matter of course. It has been tested by observations on extremely hard substances, on quartz in the form of rock crystal, on agate and even on the diamond, and in every case the results have been entirely confirmatory. Obviously the method of attack has to be modified to suit the particular material, and the phenomena are not all equally suitable for demonstration to an audience.

The ductile metals present characteristics of their own which give them a special interest. Owing to the freedom with which they respond to surface ploughing, the surface tension effect can be observed on a bolder scale than is possible with hard brittle materials.

Fig. 30 is a gold plate on which the slight flow lines left, after polishing with the finest emery, have been etched so lightly as only to remove the outer vitreous layer. The ridges are now partly broken up into rounded, or drop-like forms, while the surface, as a whole, shows a structure similar to that developed on similarly etching a flat polished surface of gold or glass—figs. 12, 13, 16, 17.

Fig. 31 shows the flow lines left on a lead surface which has been cut with a knife. The surface has not been etched, but the drop-like forms of the ridges have been exaggerated by the use of an obliquely incident illuminating beam.

The foregoing illustrations have shown that, alike in the hard non-malleable speculum metal, in the highly brittle and fragile antimony, and in soft brittle calc spar, the production of a polished surface involves the liquid-like flow of a thin layer on the surface. In some respects glass is unlike any of these materials; it is harder, and it is not supposed to be crystalline. The adjective "vitreous" is indeed generally used in contradiction to "crystalline." Under

favourable circumstances the natural surface which results from the cooling of glass articles from the fused, or partially fused, condition, may approach very closely to the state of perfect polish. In this case the molecular mobility due to fusion, or softening by heat, brings the outer skin under the influence of surface tension. The de-vitrification to which some kinds of glass are peculiarly liable during prolonged heating, is partly due to crystallisation of the silicates of which ordinary glass is composed, and partly to decomposition of silicates at the surface by

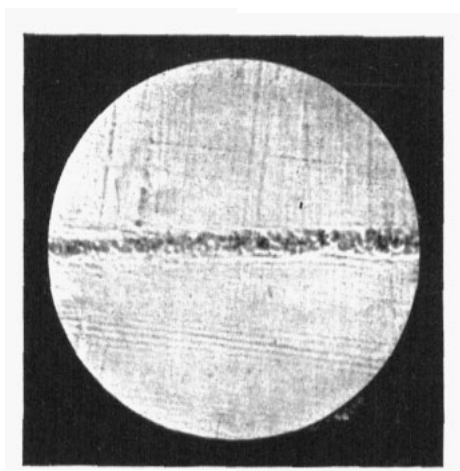


FIG. 32. $\times 1000$.

the hot flame gases which contain oxides of sulphur. The existence of a definite skin on fire-glazed glass can be shown by lightly etching the surface with hydrofluoric acid vapour diluted with air. The surface is only slightly dimmed by this treatment, but the microscope shows that the vitreous reflecting surface has been completely removed, disclosing a finely granulated structure immediately below that surface. The photographs of etched glass have already been shown—figs. 13, 15, 17.

These illustrations show that fire-glazed glass is covered by a thin surface layer which in some respect, at least, is distinctly different from the substratum over which it is laid. All glass cutters must be aware that this surface skin is very decidedly harder than the body of the glass underneath. When the surface of fire-glazed glass is first attacked in emery grinding, it resists the action of the abrasive very strongly, and if too fine powder is used, parts of the glaze are left on the surface practically untouched. The glass once freed from its surface skin responds more rapidly and with greater uniformity to the action of the abrasive.



FIG. 33. × 100.

From what has gone before we have seen that the layers of molecules on the surface of various hard brittle substance can be made to flow like a liquid so that either the smoothest of flow lines or flattest of liquid-like surface may result. The next slide will show that in one of these respects at least, glass is no exception to this rule. This glass surface, fig. 32, was held against a polishing disc armed with the finest

emery paper, with the result that fine flow lines have been developed all over the surface, while at the point where these flow lines cross, a scratch, which had been made previously, there are distinct signs of an attempt to bridge the gap by the flowing glass (compare fig. 19). In this hard substance the layer of molecules, which can be kept in fluid motion by the polishing agent, is, necessarily, much thinner than in softer substances, in speculum metal, for instance, but all the observations point quite clearly to the reality of the flow in this case as in the

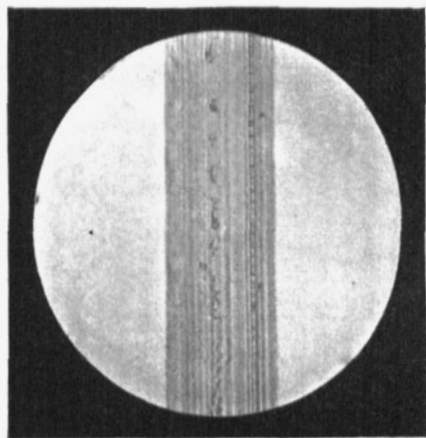


FIG. 34. $\times 700$.

others. When glass is marked by the passage over it of a hard point, it may either be scratched, or furrowed, or cleft. A *scratch* is caused by the splintering of the glass along the track over which the hard body has moved. A *furrow* is ploughed when the hard body is so formed and guided that its points lay hold of a layer only a few molecules in depth. A certain amount of the glass is shaved off, but the perfectly smooth coating of the groove which is left shows that the surface layer has passed through

the mobile or liquid condition. A cleft results when a fine wedge-like point is drawn along the surface. The entry and passage of the thicker part of the wedge may result in furrowing or splintering at the outer surface, but these are not essential features of the true glass-cutters cleaving scratch, which, to be effective, must have forced the glass apart till a cleft is started. The photograph, fig. 33, shows a splintering scratch at a low magnification. The conchoidal pits, which are irregularly broken out along the

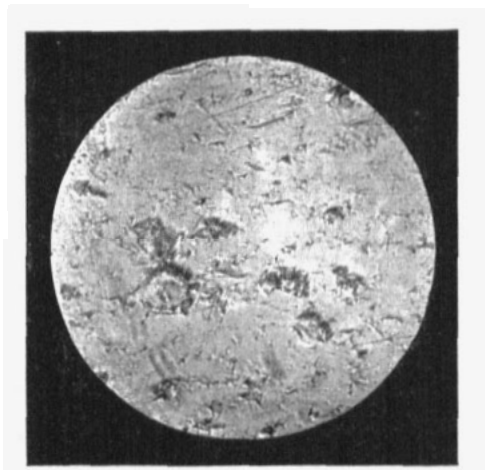


FIG. 35. $\times 700$.

track, are very characteristic and will be referred to again in connection with another photograph. Even in this rough scratch, it is not difficult to detect traces of ploughing and flow. The next slide, fig. 34, shows a series of grooves ploughed by drawing the edge of an uncut diamond along the surface under a slight pressure. The magnification in this case is high, about 700 diameters, and the resolution is also good, if reduced to the magnification of the preceding slide it would only show as a narrow faint trace. The smooth-flowing sur-

face of the grooves is quite comparable in this respect with the flow lines on speculum and other metals. The lines ruled on spectrum gratings ought to be single, clean furrows, free from broken edges or interruptions of any kind. The next slide shows a single furrow, along one side of which the edge has been slightly broken and distorted, but without any true splintering. The next three photographs show a cleaving or cutting scratch. In the first, which is at a low magnification, the point of entry of the

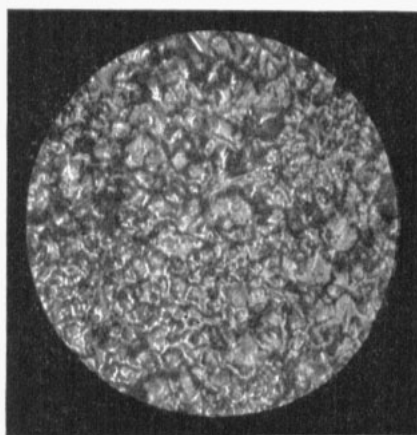


FIG. 36. $\times 700$.

diamond is shown. A certain amount of splintering has occurred as the diamond was pressed through the surface layer, but along the track there has been no free splintering of the edges. The track itself is the straight but slightly broken light line, and the dark band which follows it is the shadow caused by the cleft which has been opened in the substance of the glass below the surface. This explanation of the dark band could not have been arrived at from this photograph alone, but a closer examination with a lens of much higher resolving power reveals

the fact. By focussing for the surface with this lens the light broken band is brought out in greater detail, and it is seen that is a complete track with practically unbroken sides. The broad band of shadow remains, but it is now seen that it completely lacks definition along its outer edge, which is, therefore, out of focus. By focussing down on the outer edge of the shadow, it comes out quite sharply, and it is found by measurement on the fine adjustment that this boundary is .1 mm. below the surface. The

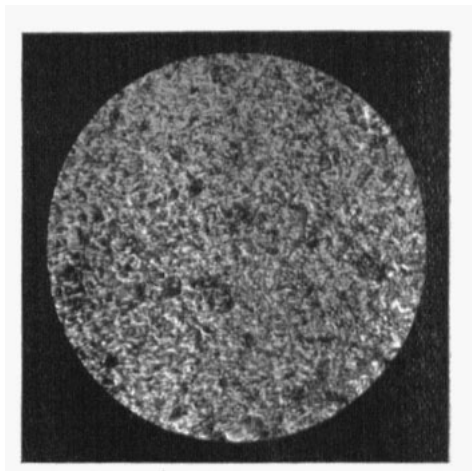


FIG. 37. × 700.

cleft has penetrated the glass at a slight angle, so that there is almost total reflection from its surfaces; the broad dark band is, therefore, the projection of the shadow of the cleft. The furrow made by the diamond appears to have been filled up by flow as the diamond passed along. The width of the furrow is about $1/200$ of a mm. From the study of the various ways in which scratching may occur we are prepared to pass on to consider the various steps involved in the grinding and polishing of glass. I have prepared a set of slides from photographs made at

various stages in these operations. Most of these were made with a 4 mm. objective having an N.A. of .95.

The large part played by splintering in the grinding of glass at once marks it off from the other examples of polishing which have already been illustrated. Among the metals the behaviour of antimony most nearly resembles that of glass, for in its case also, splintering occurs very freely in the earlier stages of grinding; but in antimony this is, to a great extent, counterbalanced by the freedom with which the

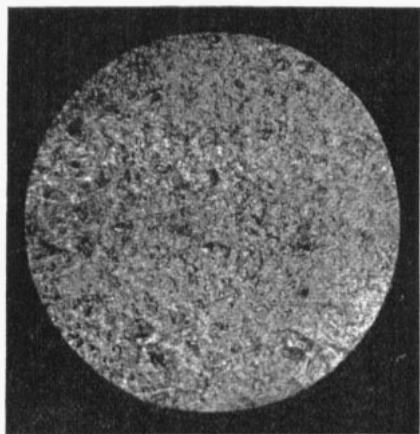


FIG. 38. $\times 700$.

metal flows during polishing, thus filling up, or bridging over, the pits which have resulted from splintering. While splintering plays a very large part in the grinding of glass, ploughing plays only a small one, at any rate, till the later stages are reached. It has been shown that from the nature of the case only a very shallow furrow can be ploughed in so hard and brittle a material as glass, and there is great danger that splintering may occur even in the final stages of grinding. After the actual photographs have

been before you, we shall be better able to discuss these questions.

The first slide, fig. 35, is a photograph at a high magnification of a piece of good commercial ground glass. This is merely shown for comparison with the following specimens, which were all hand ground, with emery powders of known degrees of fineness. The next slide, fig. 36, shows the first effect when moderately fine emery is applied between two glass surfaces which are being ground together. The surface is indented in many places by the points of the

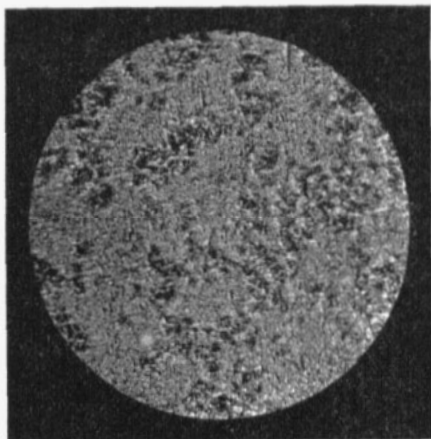


FIG. 39. $\times 700$.

emery grains, and in some cases it has been splintered and pitted. A considerable part of the original skin is, however, still intact. In the next photograph, fig. 37, the whole of the surface skin has disappeared, and the surface is pitted all over, some of the pits being of very large size. In the next slide, fig. 38, smaller pits have for the most part taken the place of the larger ones, though one or two large pits are still visible; definite traces of flowing action may now be detected. In the next slide, pitting

has ceased, and very marked flow has occurred. The outlines of the larger pits are assuming smooth, rounded outlines instead of their former irregular forms. Further results of flow are visible in the next slide, fig. 39; the surface still seems to be very irregular, but there no pits which do not show evidence of partial filling up or covering over. The flowed material is marked by the sinuous surface tension forms which it has assumed. At this stage, as re-

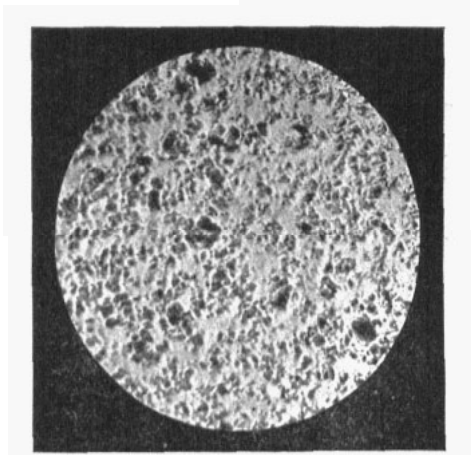


FIG. 40. × 700.

peated grinding with the finest emery did not appear to produce any improvement in the appearance of the surface, emery powder was abandoned and fine wet rouge was applied by means of a hard wood rubber. The next slide, fig. 40, shows the remarkably quick effect of the rouge polishing, the rocky-looking texture of the emery surface has disappeared, and has given place to large patches of a structureless viscous-looking material. The larger pits are now brought out with striking distinctness. In the next slide, fig. 41, these effects are carried to a further stage and the number and size of the

pits is considerably reduced. The rounded edges of the remaining pits show unmistakably that the flowed surface layer is covering over and masking the irregularities below, just as it did in the case of antimony.

The final stage of polishing is reached when all the pits have been covered over. At this stage there is no further structure to photograph.

The emery used in these experiments was prepared by shaking up 15 grams of levigated emery flour with half a litre of water. After

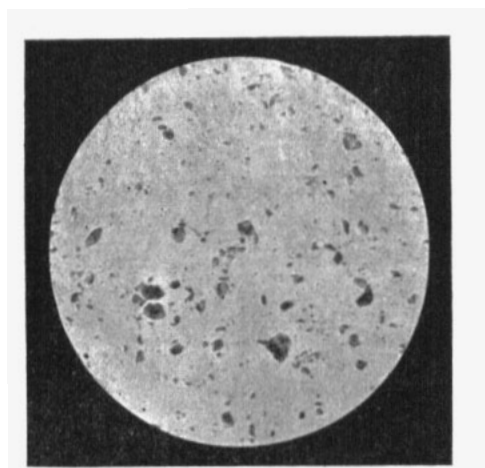


FIG. 41, $\times 700$.

settling for four minutes in a cylindrical vessel the top half of the liquid was run off and settled by itself—the product was set aside as “four minute emery.” The residue in the vessel was filled up with water to the original volume, shaken up and settled for seven minutes, when the top half was decanted and settled, the product being set aside as “seven minute emery.” This set of operations was twice repeated, and the products were set aside as “12 minute and

20 minute emery." A thin film of the 12 minute emery smeared on glass and dried, showed that it contained crystalline transparent masses up to .04 mm. in diameter. After this emery had been ground between two pieces of glass till its cutting action became very feeble, it was smeared on a glass slip and allowed to dry, the larger angular masses had completely disappeared, giving place to much smaller rounded, gravel-like particles, the larger of which measured about .001 mm. Mixed with these was a considerable quantity of glass which, so far as its structure could be resolved by the microscope, appeared to be in fine film-like particles.

Attempts have been made to study the structure of fine rouge. It was found that the rouge left in suspension in water after 10 to 15 minutes, chiefly consists of particles small enough to possess pedetic movement. Some of these particles examined by an objective of the highest resolving power appear as transparent red particles of rather irregular shape. Owing to the extreme activity of their movements in water it is difficult to estimate their dimensions with accuracy, but their average diameter may be taken as from 500 to 800 micro-millimeters. The pedetic movements are not confined to single granules of this size, but groups containing a number of these particles possess activity though of a lower order than that of the single units. The result of numerous observations, the detailed description of which would be out of place on the present occasion, go to show that these visible microscopic particles are really aggregates of very much smaller invisible units, and that the special qualities of rouge, as a polishing substance, largely depend on the hardness of the minuteness of these ultimate particles. The *visible* aggregates are more or less casual associations of these finer units under the cohesive forces; they are not, therefore, really hard in their collected form, if they were

they would act like emery or other rough powders, and produce furrows and scratches. The researches which we are discussing this evening show that the flow which is necessarily involved in all true polishing is a molecular operation, the layers of the substance which are involved are in some cases known to be only a few molecules in thickness. It is due to the almost molecular fineness of rouge that the necessary molecular contact over comparatively large areas simultaneously can occur. The seizure of the surface layer of metal or glass in rouge polishing is something altogether different from the ploughing action of the coarser abrasives.

In the ploughing by emery, or by the point or edge of a steel tool, molecular movement and mobility often of a considerable mass of the substance always occurs in the immediate neighbourhood of the moving point, but the essential feature in these cases is that the disturbance is more or less convulsive, the material being turned up from considerable depths judged by the molecular standard. As the moving point passes on, the disturbed material subsides as a thick liquid would do into ridges and furrows of smooth outlines, at least in detail.

The complete obliteration of the furrows by the liquid surface layer only occurs when a sufficiently large number of points on the polishing agent and the surface are simultaneously in contact, in other words, if something like a continuous sheet of molecules of the polishing and the polished surfaces are in contact. In polishing the furrowed surface of antimony across rouged leather by hand there is a perfectly definite feeling of "grip" as the surface of the metal is seized by the rouged surface. This feeling is quite distinct from that produced when the rouged leather is replaced by the finest emery paper, even though in the latter case more actual force is expended in pushing the metal across the rougher surface.

In the polishing of glass, figs. 36-41 show very

plainly the distinction between the surface flow caused by emery and that caused by rouge. While the finest emery particles undoubtedly cause flow as they plough through the surface layer, yet the depth to which they penetrate disturbs the under surface and impairs the smoothness of the final surface layer. The rouge particles, it may be supposed, hardly penetrate below the surface, but coming into almost molecular contact with the sheet of molecules on the surface, drag it off like a skin. The fresh molecular layer left by the removal of the skin retains its mobility for an instant, and before solidification is smoothed over by the action of surface tension, thus producing the liquid-like surface which is the necessary condition of a perfect polish.
