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THE STRUCTURE OF ABRADED GLASS SURFACES

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SUMMARY. The physical nature of the processes involved in the workshop operations of cutting and grinding are but little understood, such attention as these operations have received being mainly of an empirical nature. In the present paper some preliminary observations are recorded on the tooling of hard brittle substances where the phenomena may be expected to be simplest. Even here they are sufficiently complex. The primary object is to substitute the conception of a flaw- or fissure-complex for the current view of a hill-and-hollow structure, as characterising a ground surface in brittle materials.

PART I. *Section I* describes observations on the flaws produced in glass by stationary, rolling and sliding spheres, and by glazier's diamonds and wheels.

Section II deals with the structure of ground glass surfaces, applying the results of the previous section, and showing the surface to be a fissure-complex.

Section III explains the double refraction observed by Twyman near the surface of these pieces of ground glass.

PART II. *Section I* shows the enhanced solubility of ground surfaces in hydrofluoric acid, and suggests a value for the upper limit of the thickness of the flowed, or surface-tension, layer on polished glass.

Section II describes the structure of polished surfaces of glass and similar materials as developed by etching, showing that mechanical abrasion is still active during polishing, and also confirming a low value for the thickness of the surface tension film.

PART I

SECTION I. THE CUTTING, ABRADING, AND POLISHING OF BRITTLE MATERIALS, WITH ESPECIAL REFERENCE TO GLASS

THE behaviour of a material when stressed beyond the elastic limit is a matter which appears to defy all attempts at mathematical analysis, and this is true not only of materials which enter on a ductile stage after the elastic limit is passed, but also of brittle materials which are elastic up to the instant of fracture. The failure of the mathematical treatment in the simplest cases is much more complete than is generally realised. The brilliant analysis of Hertz on the contact of elastic solids has been shown by Auerbach to fail entirely to predict when failure will occur; it does not indicate with any exactness *where* failure will occur, and it is of course quite unable to indicate what the progress of events will be once an initial fracture has been produced. Where the particular analysis of Hertz fails, the much more general principle of similitude fares no better. There is, in fact, a complete discordance between theory and experiment which is overlooked by several recent writers.

In the present paper the experimental argument only will be pursued, and the theoretical treatment dealt with in a later paper.

The nature of the cracks produced when two spheres of a brittle substance are pressed into contact has been described by many writers. Most of them, with the exception of C. V. Raman, refer to the fracture as a cone, which, strictly speaking, it is not. The formation of the flaw (Fig. 1) is readily observed in the case of glass through a polished side of a specimen against the plane upper surface of which a steel bicycle ball is pressed. In the photograph, *AA* is the surface of the glass, the flaw being seen in elevation. The part above *AA* is, of course, the image of the flaw reflected in the polished surface of the glass.

As the load is increased, the contact circle increases until, at a certain critical value, the glass fractures near the edge of the area of contact. Without appreciable further increase of load the flaw spreads rapidly round the characteristic hyperbolic part of its course and then extends under a slowly increasing load along a sensibly conical sheet. It is seldom that the initial flaw forms with perfect symmetry round the axis of thrust. Frequently one side forms first and the flaw then, instead of conforming to the asymptotic cone, extends on one side only and becomes concave towards the thrust axis. This curling in may proceed to extraordinary lengths and will be discussed later in connection with rolling ball flaws.

The Progress of a Chattering Needle or Ball which does not rotate.

W. B. Hardy has found that, whenever two chemically clean surfaces are in contact and an attempt is made to slide one past the other, the material seizes. This, however, does not occur if the surfaces are not chemically clean. If the thrust be sufficient a flaw is formed, outcropping in an incomplete circle on the side of the ball in the acute angle between the direction of the thrust and the plane surface. The flaw penetrates into the glass in an incomplete hyperboloid sheet which has the same general form as that already mentioned. If the thrust be sufficiently oblique the ball or needle end moves across the surface, producing a sequence of such flaws. Fig. 2 shows a plan view of these flaws which will be described as chatter flaws*. The sequence of flaws regarded as an individual whole we shall describe as a chatter cut or chatter sleek. The appearance of these flaws in side elevation is shown in Fig. 3, where the upper half of the picture is the reflection of the lower half in the surface of the glass. The flaws are seen to have

* Similar photographs have been given by many writers.

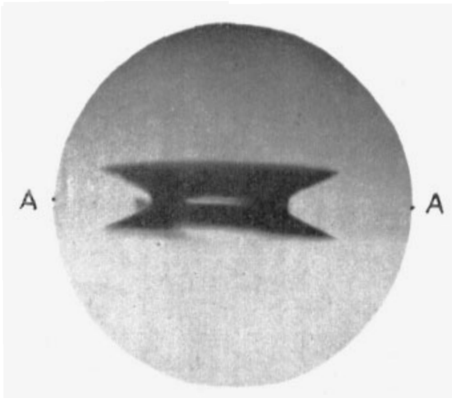

Fig. 1

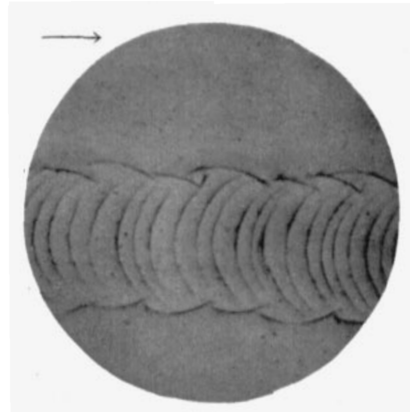

Fig. 2

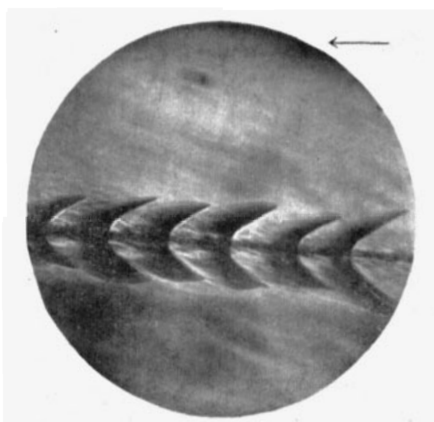

Fig. 3

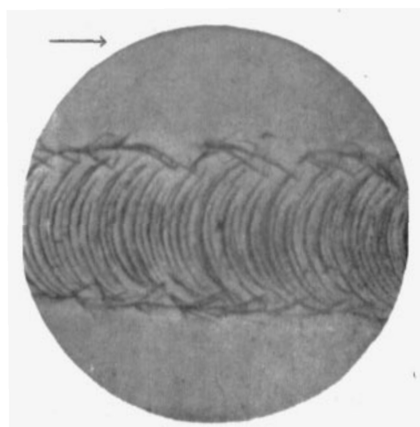

Fig. 4

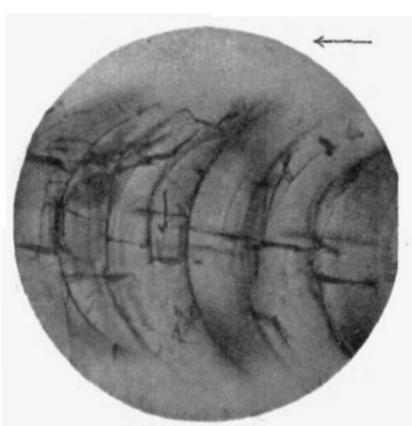

Fig. 5

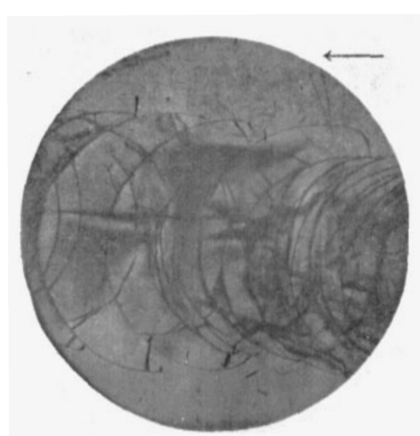

Fig. 6

a distinctly hyperbolic outline and occur at fairly regular intervals in the rear of the travelling particle. It will be noticed that though the glass has been much fractured by the passage of the needle no sensible amount of material has been actually detached.

The following points must be noted here:

(1) The complete sleek consists of three parts as seen in plan (Fig. 2), namely, the central series of arcuate chatter flaws and two lateral series of flaws arranged in cascades down the sides. The diameter across the cascades is the full width of the sleek, but it may happen that the cascades are not produced, or again the cascade flaws may appear without the central chatter flaws proper. The sleek, therefore, is capable of being dissected under circumstances which are not yet understood and the various parts of it may exist independently.

(2) A given ball cannot produce a sleek of less than a certain critical width. This critical width is practically the same as the diameter of the initial flaw-circle in the static example. The width of the sleek may be increased slightly by increasing the load, but the increase of width is limited to about 30 per cent. and is accompanied by a change in the character of the sleek. At the lower critical load the chatter flaws are at a relatively great distance apart and the cascade flaws approximate to straight lines representing the envelope of the chatter flaw sequence. An increased pressure widens the sleek, reduces the pitch of the chatter flaws, and develops cascades which are more arcuate and less continuous in character (Fig. 4).

For steel balls on glass the ratio of the breadth of the sleek to the pitch of the chatter flaws under critical loading is generally about 6. By using excessive loads this ratio may be increased to 12 or 13, but with still greater loads the glass begins to splinter and break away in fragments and the character of the sleek is then entirely lost.

Sleeks Produced by a Rolling Ball.

The sleek produced by a rolling ball resembles superficially that produced by a ball which does not rotate. It consists in plan view of a sequence of arcuate fractures but the arcs are reversed in direction; their concave sides face the direction from which the ball came. With a non-rotating ball the reverse is the case.

If the pressure is appreciably greater than the critical pressure there is a pronounced tendency to develop longitudinal flaws penetrating vertically into the glass near the median line (Fig. 5). No tendency to form these longitudinal flaws was observed in the case of non-rotating balls or spherical points. The rotating ball also differs from the sliding needle point in producing a less marked formation of cascade flaws (Figs. 5 and 6); the cascade flaws in fact are generally not visible without etching. After etching they appear to be merely continuations of the chatter flaws and do not seem to be capable of existing independently. Etching also not infrequently shows arcuate flaws facing in the same direction as those produced by a chattering needle. These flaws are not always present and are apparently of secondary importance. They stop sharply where they meet one of the primary "reversed" fractures (Fig. 7).

The asymmetric character of the flaw produced by a rolling ball under a heavy load is so marked that the flaw curls round and begins to approach the surface. Fig. 8 gives an idea of the outline of these flaws, but the complete outline can rarely be obtained in a photograph. The drawings in Fig. 9 give some idea of the shape of the complete flaw.

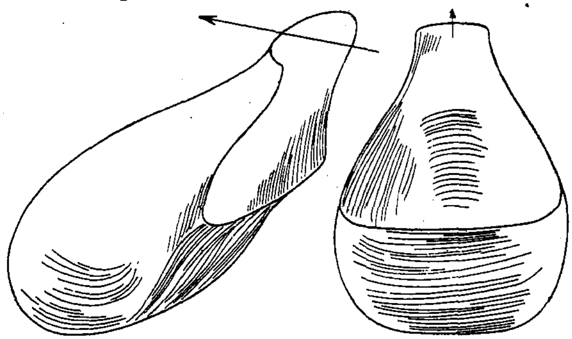

Fig. 9

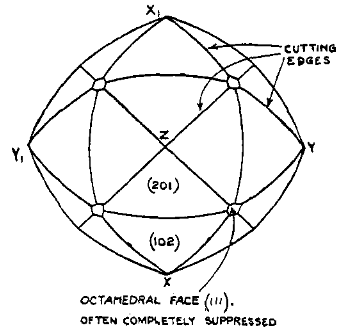

Fig. 10

The Action of the Glazier's Cutting Diamond.

The technical importance of the glazier's diamond is considerable, but so far as I have been able to ascertain its action has not been studied in detail. The diamond crystal belongs to the cubic system and the primary form seems to be the octahedron or possibly the tetrahedron. Fortunately the primary form is uncommon and generally secondary faces, such as those of the icositetrahedron are developed, these faces being generally curved*. The intersection of these faces gives an edge which has the profile of an axe, though of course it is very obtuse in cross section (Fig. 10). In use the diamond is so held that the pressure comes on this curved edge and care must be taken that it does not come on the point.

The structure of a glazier's cut consists of three longitudinal flaws, a median one and two lateral "subcutaneous" ones. These are shown in cross section in Fig. 11. Here *AA* is the original surface of the glass; *O* is the path of the diamond, *OB*, *OB* are the two lateral flaws and *OC* is the median flaw. This median flaw originally terminated at *C*, but the specimen was afterwards broken through. It will be noticed that the surface at *O* is hardly disturbed at all, but the glass above the right-hand flaw *OB* has flaked away.

Fig. 12 shows the appearance of the median flaw in elevation after the glass has been broken through. The direction of passage of the diamond was from left to right as shown and the curved marks on the surface have the same general outline as the profile of the chatter flaws in cross section. An interesting point is a second set of marks orthogonal to the first.

A plan view of a glazier's cut is shown in Fig. 13. It shows the narrow and shallow central groove made by the diamond and a number of fine cracks pointing backwards, which may be true chatter flaws analogous to those made by a sliding

* The curvature of the faces almost reduces the icositetrahedron to a rhombic dodecahedron in many of the examples which I have examined.

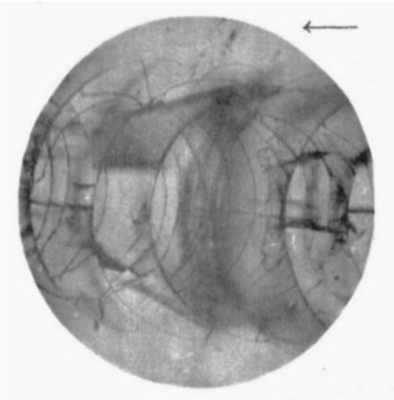

Fig. 7

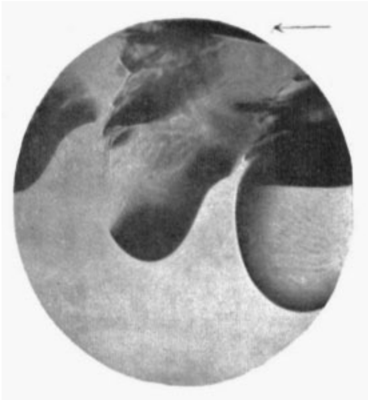

Fig. 8

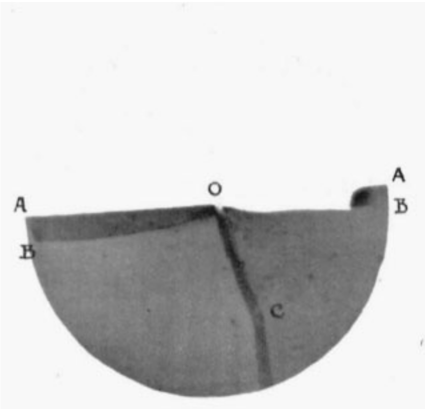

Fig. 11

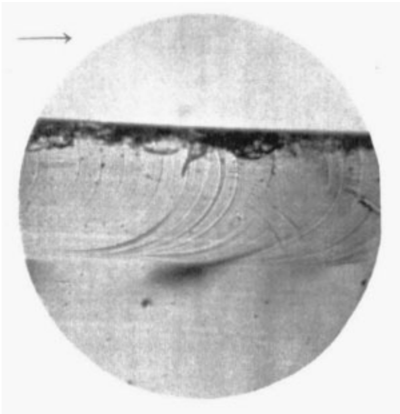

Fig. 12

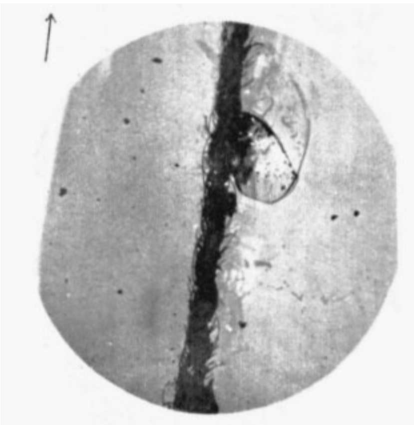

Fig. 13

Fig. 14

needle. The edges of the lateral flaws extend beyond the boundaries of the photograph, but on the extreme right there can be seen a number of parallel interference bands indicating the existence of the right-hand flaw.

Glazier's wheel cuts are in all respects similar but are not so perfect in formation. Fig. 14 shows the three flaws in cross section, the surface having flaked up on both sides. Fig. 15 is the elevation of the median flaw and shows the orthogonals very clearly.

The glazier, who of course requires the median flaw to be produced, uses a diamond which, by reason of its extreme hardness, maintains its keel edge and does not wear rapidly to a spherical form, or he uses a wheel which produces a median flaw partly by reason of its keel-shape and partly by virtue of its rotation.

It will be noticed that the types of flaws which can be produced in the glass are very varied but that, in general, the passage of a cutting or a flawing agent causes very little disturbance at the surface and removes very little material. The amount of material pushed away in front of the abrasive is extremely small and the main action is to produce a complex flaw structure beneath the surface of the glass.

In the light of these results we are able to discuss some of the properties of ground and polished surfaces of glass and other brittle materials.

SECTION II. STRUCTURE OF "GREY" SURFACES

The traditional method of grinding glass and similar materials and the one which is invariably used to-day when the finest surfaces are required, is to lap them with a loose abrasive (e.g. sand or emery) trapped between a metal plate called the "tool" and the glass surface to be ground; as successively finer grades of abrasives are used the coarse irregularities are reduced step by step to a very fine stage. A limit is set to the degree of fineness obtainable by the tendency to seize and "cut" which becomes manifest in the later stages, and this limit unfortunately is such that the irregularities remaining are still somewhat greater than the wave length of visible light. It is generally held that the surface would appear polished if it were possible to grind a little finer, in which case there would be no need for the final polishing operation*. As it is, the object of good smoothing is to leave as little work as possible to be done in polishing, which is a relatively slow, difficult, and somewhat uncertain business.

A ground surface is technically known as a "greyed" one, and the grinding operation, when a fine finish is required, is known as "smoothing."

It has hitherto been the universal view that a grey surface consists essentially of hills and pits. This is the natural workshop view and it is also the view tacitly endorsed by the late Lord Rayleigh, by Dr J. W. French†, and other writers on the subject. It is the purpose of the present section to show that this does not give a complete interpretation of the true structure of the surface layers, in that it ignores entirely the condition of the glass immediately below the pitted surface.

The earliest experimenters (Hooke and Herschel) held the view that *polishing* (a subject with which we are not here so directly concerned, though it will come up for consideration in the section on Etch Patterns) was simply a continuation

* Lord Rayleigh, *Proc. Roy. Inst.* (1901), p. 563; *Proc. Opt. Conv.* (1905); *Collected Works*, vol. 4, p. 542.

† *Trans. Opt. Soc.* (Nov. 1916), etc.

of the grinding process; Lord Rayleigh (*loc. cit.*), however, indicated in 1901 that he suspected polishing of being a molecular or "nearly molecular" process, and in the next few years G. T. Beilby developed the view that a polished surface is essentially one which, having attained for an instant a liquid-like mobility, has come to rest under the action of surface-tension forces. Beilby shows that, though surface-tension and plastic flow effects were especially characteristic of ductile materials such as the metals, yet even in brittle substances (including glass) surface-tension effects were to be observed. Other experimenters, notably Osmond, have helped to illustrate this theory; but the concentration of attention during the last decade or so on surface-tension effects and plastic flow has tended to result in neglect of the phenomena of mechanical abrasion, whether in the case of ordinary grinding or in the case of polishing, where, although obscured by surface-tension effects, the forces of mechanical abrasion are still active.

We are here concerned, in the first instance, with "grey" surfaces in which surface-tension effects are not prominent. The depth of "grey" left to be removed in polishing may be estimated by several methods, which agree in making it very small in comparison with the usual dimensions used by the engineer.

The late Lord Rayleigh described two methods. The first consisted in observing the loss of weight during the polishing of a large flat disc. The surface was greyed fairly finely, and it was estimated that there was removed a depth of about six wave lengths for an incomplete polishing, "...but this would probably have to be increased to 10 or 12 wave lengths to get to the bottom of the deepest pits." The second method, which consists in smoothing a disc to a flat surface and polishing a hollow in it until the centre of the hollow is free from grey specks, gave a value of about three wave lengths for an incomplete polish.

This second test we have repeated on a number of occasions, and, though the values obtained are somewhat variable, it appears that a complete polish may generally be reached in about six wave lengths and a very fair polish in three or four. These values agree fairly well with Lord Rayleigh's. Direct microscopical examination carried out at the British Scientific Instrument Research Association has been found to give a value of about three wave lengths for the deepest pits left by fine smoothing.

There are two or three other methods, such as the observation of the limiting angle of specular reflection, which however give only a statistical average for the probable depth of the grey. These methods, though of a rather unsatisfactory character, agree in suggesting a value not much greater than one wave length as the depth of an average representative pit.

The general trend of the evidence, therefore, is to show that methods which involve the actual removal of the grey indicate that there is more work to be done than the methods involving mere inspection would suggest. The evidence is perhaps not sufficiently precise to do more than raise suspicions as to the nature of a ground glass surface.

We have reason to suspect, in view of what has been said in the previous section, that penetrating flaws may play a large part in the structure of abraded

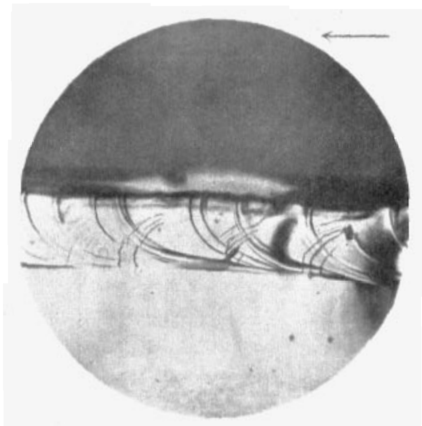

Fig. 15

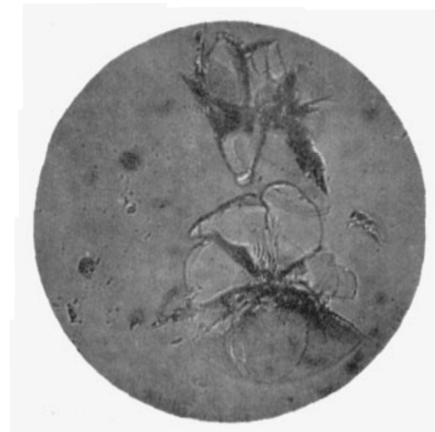

Fig. 16

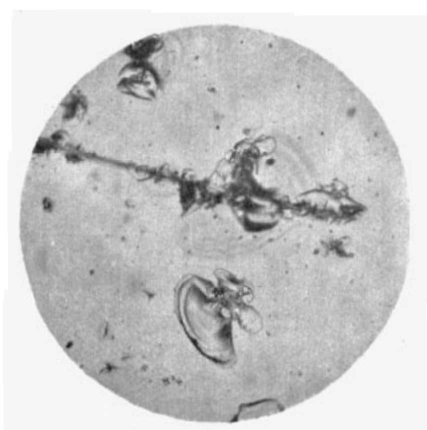

Fig. 17

Fig. 18

Fig. 19

Fig. 20

glass. We have in fact seen that when conditions are at their simplest the passage of an abrading grain breaks up the surface layer of the glass to a considerable depth, though relatively little material is actually removed.

It is commonly supposed that an abrading grain acts by pushing away material that obstructs its passage, either by digging its nose into the glass and flaking out a conchoidal splinter, or by shearing away the top of an existing prominence. Without denying the possibility of such a method of action we can say that we have failed to observe evidence of its playing any part in the grinding process.

It has been shown in the previous section that the passage of a rounded grain produces a series of penetrating flaws (chatter-flaws) in its rear, unless it be a rolling grain, when it produces them in front. In either case it removes practically no material. An angular abrasive, such as a diamond, tends to produce penetrating flaws to the sides of its track; this results from the action of a moderately sharp *edge*. Similar cuts penetrating less deeply would be produced by a fine abrasive with clean crystal edges; the smaller penetration produced in this case is due to the smaller pressure exerted on each individual edge. In the case of an abrasive possessing sharp *points* we may have the nose digging into the glass and producing a percussion flaw somewhat similar to the flaws produced by a static load. If the abrasive is fixed in the tool it will then inevitably shatter the glass in front of it. If, however, the abrasive is loose, it will, in accordance with the principle of least work, swing round into some other position where its passage will meet with less resistance. We shall thus have a number of percussion flaws, but it is quite likely that even in such cases very little material will be removed. Removal of material in any large quantity will only begin when the various flaws have begun to intersect in a number of directions at the same part of the surface.

Fig. 16 shows what happens when a polished surface of glass is submitted to a new grinding operation with loose abrasive, or, as the workshops will term it, when the glass is "re-greyed." The figure shows an early stage in re-greying with sharp carborundum. We have a number of irregular percussion flaws made by points of the abrasive. The glass is badly shattered around the point of impact and then the grain of abrasive seems to have gone out of action for a time, later making another flaw further along. With this abrasive the tracks of the grains consist almost entirely of disconnected percussion flaws, and anything approaching a scratch or a "cut"* is rare.

Fig. 17, however, shows a cut made on the same specimen by the same abrasive. Here the glass has been flawed to each side of the track of the grain, recalling the action of the glazier's diamond, though, of course, the regularity is wanting. Fig. 18 shows the commencement of a re-grey with an abrasive prepared by the British Scientific Instrument Research Association (D_3). Here we get quite characteristic chatter cuts, and little else of importance. With some abrasives we have in addition cuts consisting essentially of a series of cascade flaws, and cuts occasionally approximating to the glazier's diamond type. Some examples of these various types will be seen in Figs. 2 and 16 to 19.

* Workshop term for an irregular scratch.

When a surface has been completely reground, so that no trace of the original polished surface is left, or when it is obtained by smoothing down from a more coarsely ground state, the direct microscopical examination is more difficult to carry out. There is a great deal of scattered light, and it is difficult to obtain at one and the same time a sufficient resolving power and a sufficient depth of focus to deal with so irregular a surface.

Photographs of grey surfaces, and of grey surfaces partly polished, have been given by many writers, but are quite uninstructive. Much more can be seen visually by continually changing the focus than can be photographed successfully, but even in visual work the structure is not of the clearest.

On etching the surface with hydrofluoric acid, however, the true nature of the surface is disclosed. The method was used by Lord Rayleigh*, but unfortunately he etched his specimens too much before examining them. A photograph of a long-etched grey surface is given in Fig. 23, which may be compared with Lord Rayleigh's in the paper mentioned. The genesis of this structure will be readily understood from Figs. 20 to 23, showing a 15-minute emery surface after etching for various lengths of time, and demonstrating that, contrary to Lord Rayleigh's interpretation, the hollows of Fig. 23 do not originate in pits but in *flaws*.

The elongated shape of the pits in the early stages of the etching shows that the original grey surface is dominated by a linear and not a point structure—by long narrow valleys and not by pits. But if these were simply valleys between more or less pyramidal hills, then the junctions of such valleys would virtually be pits, and after etching the identity of the hollows would be quite lost at the junctions. Actually we see that the hollows preserve their individuality very distinctly, and their ends are rounded off around the end of the original line-structure. Thus it is clear that we are not dealing with an ordinary valley structure at all, but the appearance of the etched surface is perfectly explained if the elongated hollows are regarded as widened flaws, developed by the acid according to the method of envelopes explained by Lord Rayleigh (*loc. cit.*).

It is clear from these observations that in a grey surface there are deep flaws extending far below the surface irregularities, but further evidence can be obtained by polishing a greyed surface with very fine abrasives.

It is not difficult to prepare chromic oxide whose effective grains are too small to produce any etch-pattern of sleeks; when a lens polished with such an abrasive is etched and examined with the dark ground condenser, the pattern is a remnant of the chatter grey from smoothing, resembling that of Fig. 37 in Section II of Part II of the paper, and consists of a chaos of unconnected penetrating flaws†.

* *Proc. Roy. Soc.* (1901); *Proc. Opt. Conv.* (1905); *Trans. Opt. Soc.* (1908); *Collected Works*, vol. 4, p. 542.

† It can be shown that the pattern is not due to the chromic oxide by first polishing the specimen with a good rouge and then following with the chromic oxide. The rouge polishes out the pattern left in the smoothing, cutting down to the bottom of the flaws produced in this process. When the rouge-polished surface is further polished with chromic oxide for varying periods the characteristic rouge-pattern is brought up on etching but it becomes less and less prominent according as the chromic oxide polishing is continued for longer and longer periods. After very long polishing with the chromic oxide the subsequent etching shows little of the rouge-pattern but under no conditions is there any reappearance of the chatter grey.

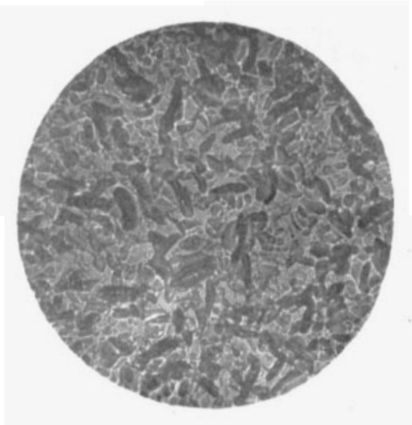

Fig. 21

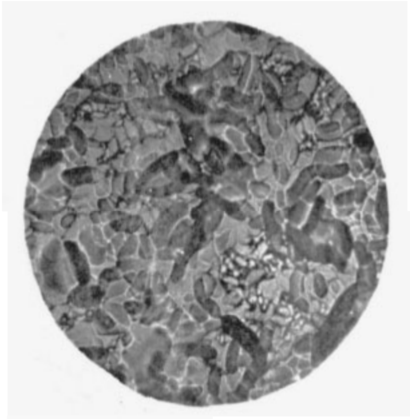

Fig. 22

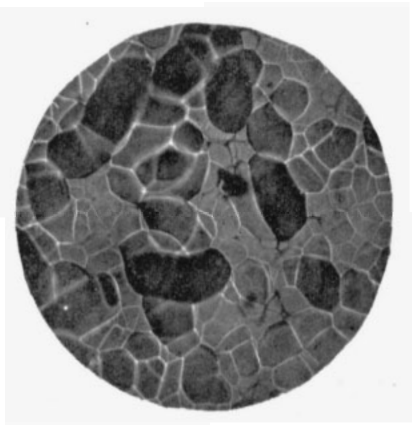

Fig. 23

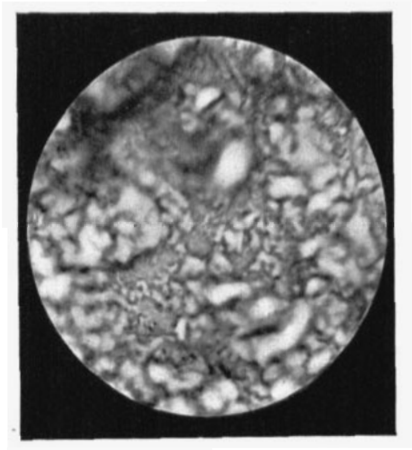

Fig. 24

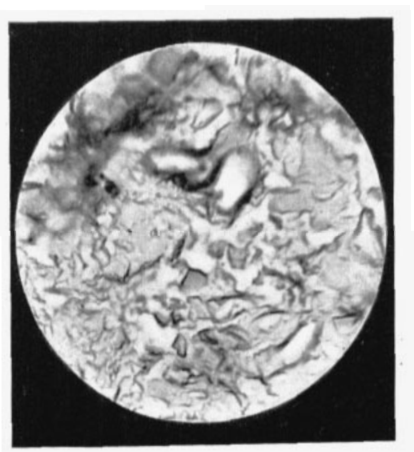

Fig. 25

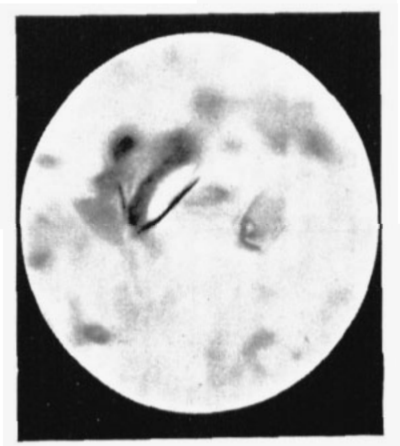

Fig. 26

Confirmation by direct observation and measurement of the penetrating flaws and with the glass in its original ground state has been found possible by the staff of the British Scientific Instrument Research Association at Russell Square. For this purpose microscope cover-slips were ground on one side and examined with a 3 mm. apochromat oil-immersion lens of n.a. 1·4; the flaws were observed both through the grey surface and from the back, through the polished surface. Figs. 24 to 26 show at a magnification of 960 the appearance, as seen from the rear, of the same field focussed at various depths below the hill tops of the grey. It was found that the deepest pits extended to a depth of about three wave lengths, but the flaws to a depth three times as great. Something like a million flaws per square inch could be detected in some fields, but calculation from the indirect methods previously described shows that there are very many more than this in a finely ground surface.

The surface layer of a smoothed piece of glass consists, therefore, of a chatter flaw complex extending to a considerable distance below the actual surface; a grey surface, indeed, might be more accurately described as a "grey *layer*."

The mechanism of the ordinary process of smoothing, then, appears to be somewhat as follows:

The grains of abrasive are dragged about by the tool over the surface of the glass, producing chatter cuts or cuts approaching the diamond type, percussion flaws, cascade cuts, or intermediate forms of markings according to the character of the abrasive and the nature of its support.

Whatever the nature of the flaws so produced, practically no material is removed until several abrasive grains have passed over, or very nearly over, any given spot. When the flaws due to the several passages begin to intersect, material is removed, but only from the upper parts of the flaw complex; the flaws remain, extending much below the surface proper.

The flaws may be either of the diamond-cut type or may be chatter cuts such as are produced by a blunt needle passing over the surface. When the abrasive produces a flawing of the diamond-cut type it is probable that two or three passages will be sufficient to start the removal of material. On the other hand, in some observations made with a blunt needle in a shaping machine it was found that no material was removed until after four or five passages of the needle. The load here was rather more than critical; if it had been a minimum needed to produce a flaw at all, then probably ten or a dozen passages would have been required. (There is reason to believe that this is most often the condition obtaining in the polishing operation.)

When the material has been removed in this way and the surface is completely "grey," the surface irregularities—the hills and hollows—do not represent the full depth of the fractured layer. Below them a large number of flaws extend to a depth apparently two or three times as great. These flaws will in general be continuations of the sides of the "pits."

Since the greyed surface is thus broken up and full of narrow fissures, it will be easier to continue grinding on a surface already ground than it is to start a grinding process on a polished surface. It is commonly observed in the workshop that a polished surface appears to have a tough "skin" and it has sometimes been thought that this is due to a surface layer tougher than the general body of the glass. It will be shown later that any such surface layer is too thin to affect a grinding operation with a coarse abrasive, and it appears more probable that the toughness is the true toughness of the massive glass and is due to the absence of large fissures such as are found in every "grey" surface.

The object of the smoothing process is not to splinter out fragments of glass by the frontal attack of the abrasive. It may happen at times that glass is sheared away in front of an advancing particle having a sharp edge or point, but such a process is difficult to keep under control and no evidence has been found of it in our observations. It is the nature of glass to fail in tension behind or to the side of the moving grain, and we rely on the intersection of flaws so produced to work down our brittle substances to the required form.

Section III. Structure of Glass Surfaces. The Twyman Effect

"If a very thin piece of glass, grey* on both sides, be polished so that it can be examined through its thickness and polarised light be applied, stress can distinctly be seen near each surface; if now one side be polished strain disappears from that surface, and the glass blows up; on polishing the remaining grey side, the glass becomes parallel again, and strain entirely disappears†."

The appearance of the glass as observed between crossed nicols is shown in Fig. 27, the appearance when examined through a Babinet compensator being as shown in Fig. 28. So far as the writer is aware, no explanation has hitherto been given of this phenomenon, but the simple stresses suggested in the foregoing paragraph represent a system which is not in equilibrium. The conditions that the strain may be self-contained in the body of the material are (1) that the total thrust across any complete plane section should be zero, and (2) that there shall be no resultant moment about any axis.

If we imagine that the fissures which have been shown to exist in a ground surface are slightly open at their mouths and are held open by minute fragments of glass or other materials, the system of stresses thus set up in the glass can be satisfactorily visualised. The surface would be in very severe compression for a depth of a few wave lengths, the material just below the grey layer would be in tension and this tension would diminish as we proceed away from the greyed surface, changing into a slight compression again as the other side of the glass is approached. The sum of the compressions in the greyed surface and in the other face of the glass will be equal to the tension existing in the material immediately below the grey layer and the system would be mechanically stable.

This view of the stresses is quite compatible with the appearance of the glass as shown between crossed nicols. The compression in the greyed surface itself cannot be detected visually on account of the minute depth of the chatter flaws.

* A glass surface which has been ground with a loose abrasive is technically known as a "grey" surface.

† F. Twyman, *Proc. Opt. Conv.* (1905), p. 78.

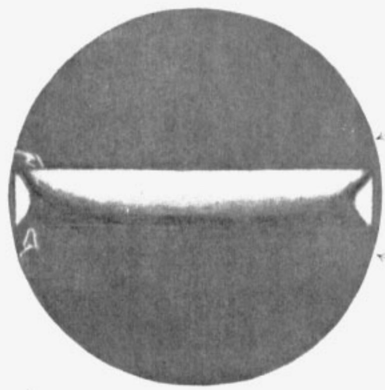

Fig. 27

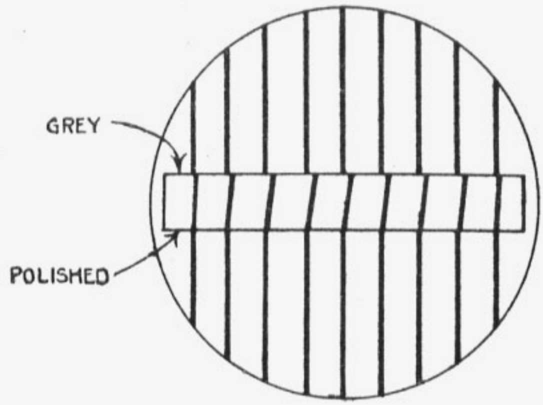

Fig. 28

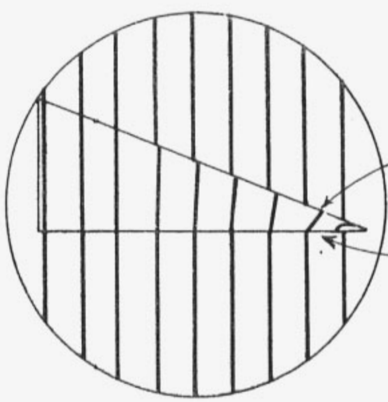

Fig. 29

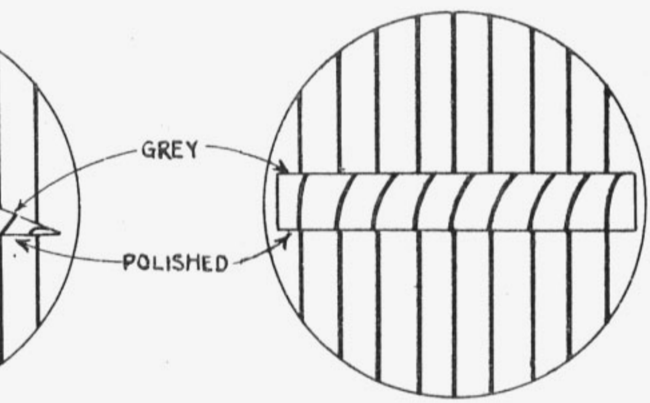

Fig. 30

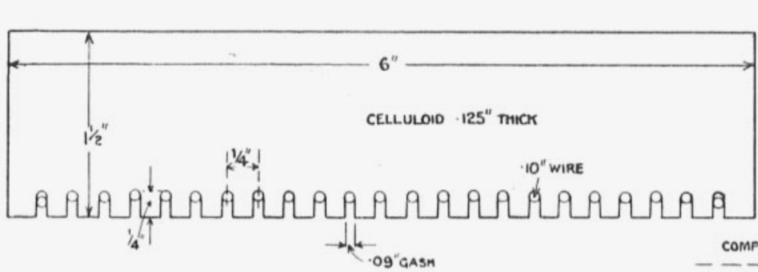

Fig. 31

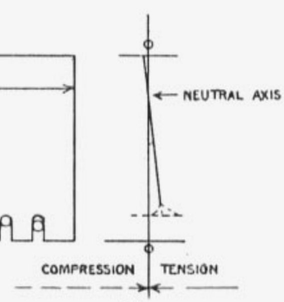

Fig. 32

By means of a Babinet compensator it may be shown that the strain in the material below the grey layer is a tension, and this is the only strain producing a visible double refraction. The compression in the greyed surface and the tension immediately below the grey layer act along directions which are separated by a very small distance and the forces themselves are very nearly equal. The result of this is that these two forces constitute an almost perfect couple, but the moment of this couple is very small. The force required to keep the glass in equilibrium is the compression exerted on the polished side of the slab. This is distributed over an appreciable depth and acts at a considerable distance from the greyed surface. To produce equilibrium, therefore, this compression need only be quite small and its existence may easily be overlooked when the glass is examined in polarised light.

Confirmation of this view is obtained if a wedge-shaped specimen of glass be used, one side of the wedge being greyed and the other side polished. When this is examined in polarised light with a Babinet compensator the appearance is that shown in Fig. 29. (The specimen is an inch thick in the direction of the light path.) No effect can be observed until the specimen thins down to about ·15″ and the canting of the lines increases rapidly as the knife edge is approached. At the extreme limit the slope of the line becomes 90°. This would seem to imply that the action of the greyed surface is to impress a bending moment of constant amount on the material at each section, but as the section decreases in thickness the extreme stress produced by this constant bending moment increases, becoming infinite when the thickness of the material becomes infinitesimal.

The fact that the stress increases with increased coarseness of grey also confirms the view described above. To test the hypothesis experimentally an attempt was made to aggravate the Twyman effect as much as possible. One surface of a specimen of thickness ·15″ was greyed with the coarsest possible grey and the light was allowed to travel through three or four inches parallel to the greyed surface. When this specimen was examined in the Babinet compensator the appearance was that given in Fig. 30. The distribution of the strain parallel to the greyed surface and at right angles to the light path is one of a constant bending moment except near the ends where a slight modification takes place. This also is in agreement with theory.

The Twyman effect may be imitated by taking a piece of celluloid and cutting gashes along one side (see Fig. 31). Wires of slightly greater diameter than the width of the gashes are then pressed into the material as far as they will comfortably go. The resulting distribution of stress is found to be exactly analogous to that found in the Twyman effect, while the distortion of the Babinet bands is as in Fig. 32.

If then, in actuality, the Twyman effect be caused by minute particles of glass wedging open the mouths of the chatter flaws, it may be expected that a very little polishing will be enough to remove the effect, for the particles cannot enter far into the flaws. It is, in fact, found that the merest trace of polishing, consisting only of a surface gloss, removes the effect entirely. The grey is scarcely touched before the Twyman effect has completely disappeared. It may also be anticipated that immersing a specimen in a solution of hydrofluoric acid for a short time would likewise cause the disappearance of stress; for the small particles that wedge open the flaws must be under very considerable compression, and strained materials are, in general, very much more susceptible to chemical action than material not so strained; also these particles are very small in comparison with their surface area. Experimentally it is found, in fact, that a very few moments' etching in a very dilute solution of hydrofluoric acid is enough to remove the effect almost completely. Some further observations relating to the etching away of the Twyman effect are given in Part II.

PART II

Section I. Observations on Etch Attack

Rate of Solution of various surfaces in hydrofluoric acid.

The experiments described in this section were undertaken in the first instance to provide further evidence on the Twyman effect, and also in some measure with a view to estimating the thickness of the flowed (surface-tension) layer on polished glass.

After a glass surface has been ground in the manner previously described, it is still necessary to polish it. This is done by means of a fairly fine abrasive* with a supporting material, capable of giving way to excessive pressures by elastic or plastic deformation. Materials commonly used in the elastic category are wood, cloth, felt, and in the plastic group, pitch and wax. The details of the process cannot be considered here. Brewster† nearly a hundred years ago gave an outline of methods which do not differ essentially from those in general use to-day, and no very important contributions to the literature of the subject, from the point of view of workshop practice, appear to have been made since. The best recent accounts are probably those of J. W. French in papers read to the Optical Society. Unless otherwise stated, the mention below of polished surfaces will refer to specimens polished on pitch.

As previously stated, Beilby‡ has demonstrated the existence on all polished surfaces of a flowed layer. On crystalline substances this layer is amorphous; on amorphous substances it is, of course, still amorphous, but somewhat different in its properties from the massive material below. Beilby showed that the flowed layer on calcite was practically confined to the region within 100 $\mu\mu$ ($\frac{1}{5}\lambda$) of the surface, though traces of mechanical disturbance made by the coarser particles could be detected to a depth of one to two wave lengths. On metals the flow is greater, but on glass and quartz we may reasonably expect that it will be less.

French§, however, has suggested that on glass there is a flowed ("beta") layer about eight wave lengths thick; the evidence is derived from a study of fire cracks. Polished specimens of glass were placed in a furnace at a temperature somewhat below the softening point; the surfaces developed a "crazed" appearance with

* The abrasives used for polishing glass may be much coarser than those employed with metals (*v.* below).

† *Edinburgh Encyclopædia* (1830), vol. 15, p. 660. Article on Optics.

‡ *Proc. Roy. Soc.* 82 A (1909), 599, etc.

§ *Trans. Opt. Soc.* (Nov. 1916).

numerous fine grooves or cracks on the surface. These cracks were rather uniformly about eight wave lengths deep; French assumes that this is the extent of the flowed layer, which has softened and contracted, while the massive material has not been permanently affected by the heat.

It seemed possible that some additional evidence might be obtained on this point by etching with hydrofluoric acid, and determining the rate of solution for material in the surface layer and for the material below the critical depth. If a change in the rate of attack were noticed when some eight wave lengths had been removed, this would strongly confirm the views of Dr French. If, however, no such change were found, this could not of itself be taken as negativing his views, because there may be no very great difference in the properties of the two materials. It has, we believe, been suggested that the flowed layer is more susceptible to attack by acid than the underlying material; we have therefore to look for a *decrease* in the rate of solution on passing below a depth of 8λ.

The value for the rate of solution of the massive material might also be obtained from observations of specimens obtained by fracture, if the area of their surfaces could be accurately determined; or from observations on specimens *ground* but not *polished*, if we did not suspect, in view of the Twyman effect, that there is something very abnormal about a ground surface.

In the section on the Twyman effect it was suggested that, if a greyed surface consisted of numerous minute flaws wedged open by particles of glass, attack by acid would be very rapid. We should expect this initial rapidity to fall off, however, within a short time, and to approach the value for the massive material as the Twyman effect disappeared. By observations of the progress of the acid attack on *polished* surfaces we may therefore hope to obtain some information on the depth of the flowed layer; and by observing the progress of the attack on *greyed* surfaces we may confirm our interpretation of the Twyman effect. The rate of attack will in each case ultimately approach that for the massive glass.

The specimens used were discs or cylinders of glass cut from the slab by the disc-cutting machine of British Patent 15,376/1915 (W. Taylor). In all the specimens a certain small proportion of the area exposed to the acid was a surface left by the machine, and it was therefore necessary also to determine the susceptibility of disc-cut surfaces to the attack of the acid.

(A) *Comparison of etch attack on disc-cut and greyed surfaces.*

The specimens were on the one hand a flat disc of 2″ diameter and ·05″ thick, and on the other two cylinders ·36″ in diameter and 1·46″ long, of the same glass (medium flint $\mu_D = 1{\cdot}604$, $\nu = 37{\cdot}8$, $\rho = 3{\cdot}47$). The grey surface was obtained by a moderate 15 min. emery smooth. They were etched for 25 seconds in a solution of HF with the following results:

	Area sq. cm.		Loss of weight gr.
Flat disc	grey	40·4	·0081
	disc-cut	2·0	
First cylinder	grey	1·33	·0010
	disc-cut	10·7	
Second cylinder	Same		·0008

These figures indicate that the susceptibility of the disc-cut surface is about ·3 of that of the greyed surface. Other independent experiments have given the ratio as about ·4.

(B) *Comparison of etch attack on greyed and polished surfaces.*

The specimens in this case were both discs of 2″ diameter. The greyed one was ·04″ thick, the polished one ·08″.

They were etched for 15 seconds in a dilute solution of hydrofluoric acid, with the results below:

	Area sq. cm.		Loss of weight gr.
First disc	disc-cut	1·6	·0088
	grey	40·4	
Second disc	disc-cut	3·2	·0010
	polished	40·4	

Using the value ·3 found in (A) above for the grey equivalent of a disc-cut surface, the figures here given indicate that the grey surface is attacked 11 times as quickly as the polished one. Other and independent experiments have given the ratio as about 12 or 13 to 1.

(C) The discs used in (B) were now alternately etched and weighed until the polished disc had lost about 15 wave lengths from each surface. The results are tabulated below.

Grey Disc				*Polished Disc*			
Time of etching	Weight gr.	Loss between weighings gr.	Loss per 15 secs. gr.	Time of etching	Weight gr.	Loss between weighings gr.	Loss per 15 secs. gr.
	8·2986				16·4430		
15 secs.		·0088	·0088	15 secs.		·0011	·0011
	8·2898				16·4419		
15 ,,		·0056	·0056	15 ,,		·0011	·0011
	8·2842				16·4408		
30 ,,		·0075	·0037	30 ,,		·0023	·0011
	8·2767				16·4385		
90 ,,		·0116	·0019*	90 ,,		·0055	·0009
	8·2651				16·4330		
15 ,,		·0022	·0022	15 ,,		·0008	·0008
	8·2629				16·4322		
15 ,,		·0019	·0019	15 ,,		·0008	·0008
	8·2610				16·4314		
Prolonged etching in another bath		—	—	Prolonged		—	—
	8·1977				16·3886		
15 secs		·0014	·0014	15 secs.		·0008	·0008
	8·1963				16·3878		
Long etching in another bath		—	—	Prolonged		—	—
	8·0943				16·3038		
15 secs.		·0008	·0008	15 secs.		·0009	·0009
	8·0935				16·3029		

* Owing to the two or three seconds that elapse before the acid can be washed off the specimen, a 90 seconds etching is not equal to six 15 seconds etching, so that this value is rather too low.

From these figures it would appear that the rapidity of the acid attack on the grey surface quickly declines, becoming ultimately the same as that on a polished surface. The rate of attack on the polished surface remains constant, the slight decline observed being probably due to a change of temperature.

It seems that, if there is a layer of "beta" material extending to a depth of eight wave lengths, it does not differ in its solubility from the massive or "alpha" material.

The high initial values for the rate of attack on the grey surface can only be explained on the assumption that there is a relatively enormous surface area, 10 or 12 times that of the polished disc, or that the material in the surface differs radically from the massive material. The first alternative seems by itself to require altogether too high a figure, while we know from the Twyman effect that the surface material *is* in a radically different state, namely one of excessive strain. It seems probable that both effects may be present—a largely increased area due to chatter flaws, and a greatly enhanced solubility due to the strain. In etching, the strain rapidly disappears, reducing the acid attack to perhaps one-fourth or one-fifth of its initial value within two or three minutes, while the remaining excess of the rate above that on a polished surface may then be due to the greater area of the pitted surface.

(D) *Comparison of etch attack on coarse and fine greys.*

It has been found that the rates of attack on surfaces prepared by smoothing with 15-minute emery give very consistent results. In a comparison of the rates of attack on 15-minute and 60-minute emery smooths it was found that the latter was sensibly less affected at first—at roughly two-thirds of the rate of the coarser grey. This seems to agree with the polariscopic evidence that the Twyman.effect is less with finer smoothing.

(E) *The depth of etching in the development of etch patterns.*

The specimens used for microscopic examination, as described in the section on Etch Patterns, were discs of the same glass as that of the above experiments, and ·65″ in diameter by ·1″ thick. A number of examples were etched and the loss of weight determined. It was found that the pattern was well developed in the matter of fine detail when the loss was ·0002 gramme, while the coarser structure could be best seen when the loss was about twice this. The area polished was 4·3 sq. cm., and the disc-cut area 1·32 sq. cm., equivalent to about 5 sq. cm. of polished surface. The loss per square centimetre of polished surface when the finer detail is best exposed is therefore ·00002 gramme or ·000006 cm. in depth (·0000023 inch—about one-tenth of a wave length).

It will be shown in the section referred to that in the etch patterns thus developed there is probably detail of the order of a few millionths of an inch, and beyond the limits of resolution of the microscope. This detail could hardly exist in a flowed (surface tension) layer, and it would therefore appear that the latter in the case of glass is only, at the most, some two or three millionths of an inch in thickness.

Section II. Etch Patterns

A surface which has been brought to a state of liquid-like mobility* and then, as it were, petrified in that condition, may be expected to be microscopically structureless; and as a matter of fact when a glass surface has been polished in the ordinary way and finished by dry polishing†, practically nothing can be seen of it in the microscope. But if the surface be lightly etched with dilute hydrofluoric acid‡, and suitable forms of illumination used, there is rendered visible quite a variety of etch patterns which we shall be able to interpret with the aid of what has been said in the previous sections.

Figs. 33, 34 and 38 show examples of the three chief types of polished surfaces. Fig. 33 represents the structure of a lens polished with rouge, the surface being covered with a great number of very fine sleeks of considerable length. The sleeks actually run in every direction indiscriminately and cover a very large part of the surface, but their structure is so fine that no illumination has been found that will enable all to be seen at once. It is necessary to use oblique illumination (in the present case transmitted by a dark ground condenser) and then those sleeks whose direction is at right angles to the light are rendered visible. Consequently the complete pattern with a dark ground condenser is a concentric one, somewhat as in Fig. 35, which we shall describe as a spider-web pattern.

Fig. 36 shows the same field as Fig. 33 with an illumination which shows that the heavier sleeks occur equally all over the field and run indiscriminately in all directions. But it is only in the illumination of Fig. 33 that the closeness of the web marks is really appreciated. It is a matter of great difficulty to photograph the web sleeks in a manner which shall satisfactorily bring out their extraordinary development, but Fig. 35 gives the best impression we have been able to obtain.

Fig. 34 shows a second type of pattern—extreme development of chatter sleeks. This specimen was worked on coarse manganese dioxide. Chatter sleeks are characteristic of polishing abrasives which contain large rounded particles; many commercial rouges fall in this category. If not too heavy, such sleeks are not harmful, as they are quite invisible before etching; but in the present example the chatter sleeks were so numerous and so pronounced that complete polishing was impossible.

Figs. 37 and 38 show examples of the third type of etch pattern, the "chatter grey" pattern. Chatter grey is the characteristic pattern left by fine chromic oxide, and other abrasives whose effective grains are very small, say of the order of $\frac{1}{2}\lambda$ in diameter. The three types of pattern are not mutually exclusive, and web sleeks, chatter sleeks, and grey may occur together in the same specimen.

The *chatter sleek* in its simplest form consists of a regular series of arc-shaped flaws; the sleek is therefore incomplete in the light of the section on the Abrading of Glass, in that the lateral "cascades" are missing. Many fairly regular chatter

* "The particles of rouge seem to have the power of seizing the surface so as to set the molecules gliding." Beilby, *Proc. Roy. Soc.* 72A (1903), 218.

† Technically known as "drying up the wet."

‡ A convenient strength is 2N.

Fig. 33

Fig. 34

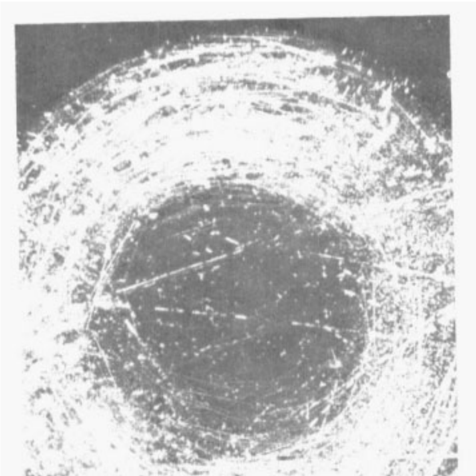

Fig. 35

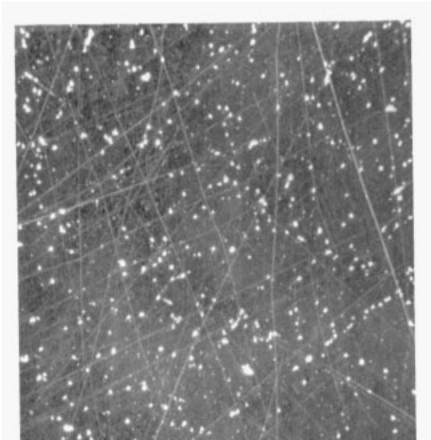

Fig. 36

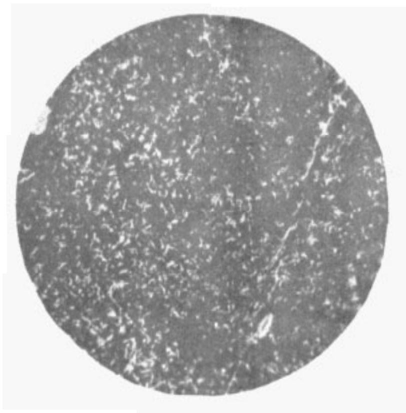

Fig. 37

Fig. 38

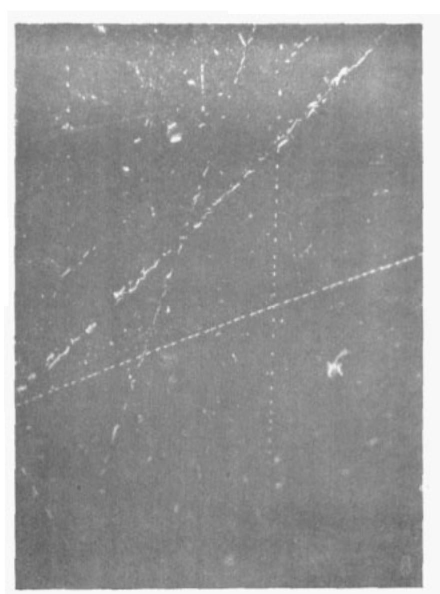

Fig. 39

sleeks are shown in Fig. 34 (manganese dioxide polish), but chatter sleeks are more often interrupted, so that blank spaces are left in the track of the grain (cf. Fig. 39). Occasionally there is a periodic and rapid increase and decrease of the width of the sleek without complete discontinuity, but more often a sleek which shows a periodic fluctuation of width is interrupted at the narrow points.

Web sleeks also are a product of the polishing operation. Examined by reflected light or with insufficient resolving power, they appear to be fine grooves in the surface of the glass. With transmitted dark ground illumination and sufficient power many such sleeks can, however, be resolved into chatter sleeks; they differ from the larger sleeks mainly in being less interrupted. Down to the limits of resolution of the microscope, that is, until the chatter flaws are closer together than a hundred thousand or so to the inch, it is possible to find chatter sleeks in increasing numbers. It seems very probable that web sleeks which are not thus resolvable are nevertheless chatter sleeks in constitution, but with detail of ultramicroscopic dimensions*.

In the ordinary way of polishing, as stated above, the sleeks run indiscriminately in all directions, but it is possible to prepare specimens in which the particles of abrasive have all passed across the surface in one direction only. When this is done it is found that in all resolvable sleeks the convex side of the flaw faces the direction from which the particle came. It follows, as shown in the first part of the paper, that all the effective particles in the polisher are *sliding* and not *rolling*.

Chatter grey is not a product of the polishing operation at all, but a remnant of the smoothing structure.

Besides the three main types above described we get asymmetric or twisted sleeks, of which examples can be seen in Fig. 39, and a few in Fig. 34. These are clearly the *cascade* flaws occurring without the chatter flaws.

There is a good deal of variety in the patterns falling under each of the above categories, and especially in those of the chatter sleek group. It is often possible to recognise a certain individuality in the sleeks and to detect several passages of the same grain across the surface. There may also be observed at times the evidence of the gradual breaking down of a large grain into two or three smaller ones, but as this process requires more than the width of the field of the microscope, it cannot readily be photographed.

The pitch of the chatter flaws in a very coarse chatter sleek made by rouge or other workable abrasive on ordinary glass is from 1/10,000 to 1/20,000 of an inch. A typical example (made by a commercial workshop rouge) was found to have chatters 24,000 to the inch. The width of the sleek was $1\frac{1}{2}$ ten-thousandths of an inch (7λ).

The detail of most web sleeks is beyond the limits of resolution of the microscope†, but by the aid of the diffraction pattern it has been possible on many occasions to assure ourselves that sleeks which were at first classed as web sleeks,

* This interpretation is of interest, inasmuch as it has hitherto been supposed that sleeks are fine grooves in the glass.

† It is a difficulty that the highest power objectives, being immersion lenses, are useless for this work.

and supposed to be no more than continuous fine grooves in the surface of the glass, were in reality chatter sleeks composed of a very regular sequence of chatter flaws at the rate of a hundred thousand or more to the inch.

There remain, however, the great body of true web sleeks in which no structure whatever can be made out; the width of many of these sleeks is undoubtedly below $\frac{1}{2}\lambda$, possibly considerably below, and only intense oblique illumination on a dark field renders them visible at all. The conclusion, however, seems to be irresistible that these also are chatter sleeks, and that their detail is of the order 10^{-6} of an inch. Now the atoms themselves are of the order 10^{-8} and if we can speak of molecules of glass, these must be approaching the order 10^{-7}, so that the chatter flaws of a web sleek may be said to occur at intervals of a few molecules. It seems to follow that any flowing of the surface layer (under the action of surface-tension, etc.) must, in the case of such materials as glass and quartz, be of extremely limited extent. Indeed, it seems very apparent that liquefaction of the surface layer to a depth of a few millionths of an inch would destroy all the detail of the finer sleeks.

Now the chatter flaw character of sleeks has been shown to obtain from the coarsest dimensions down to the limits of resolution of the microscope. It will be shown later* that the sleeks whose flaws are of the order 10^{-5} or 10^{-6} apart are caused typically by grains of diameter about 12 to 16×10^{-5} of an inch. But some abrasives that will polish, though extremely slowly, seem to have no grains of a stable nature above 10^{-5} of an inch. These abrasives leave no sleeks at all, so far as the microscopic evidence goes, though it is conceivable that they really produce chatter flaws of completely ultramicroscopic character (presumably of the order 10^{-7} of an inch apart by analogy with the larger grains). But the atoms themselves are not much smaller than this, and if we are to allow any thickness at all for the Beilby layer, it seems probable that the flaws of these smaller ultramicroscopic sleeks must be flowed together.

If we confine our attention to polishing abrasives and polished surfaces of a workshop character, it appears that the best abrasives are those that produce a good web pattern, the detail of the sleeks being just on the limits of resolution of the microscope (10^{-5} of an inch).

It remains to decide whether, under workshop conditions, the removal of glass is a truly molecular or merely a "nearly molecular" process. It is possible to induce a polish on glass without the help of any abrasive. In such a case the action is presumably molecular; glass is removed and may be detected later in the surface of the polisher†. The progress of the polishing in such conditions is very slow, and much greater rapidity may be attained by the use of abrasives. The speed of polishing in general increases with the coarseness of the abrasive, until the sleeks produced thereby become altogether too prominent. It seems difficult to regard the sleeks as a purely accidental feature, having no direct influence on the polishing of the glass; for we have seen that the best polishing abrasives are those that produce

* Paper to follow.
† J. W. French, *Trans. Opt. Soc.* 21 (1919–20), 81.

the finest pattern of sleeks, and the surface of the glass under these conditions is a mass of tiny flaws.

The process of polishing (on pitch polishers) seems therefore to be carried out in this way:

When the abrasive is first applied to the work, the particles are carried in a thin film over the whole surface of the glass, producing (in the case of a fine-grained spherical abrasive) innumerable chatter sleeks whose chatters are of ultramicroscopic, or nearly ultramicroscopic, dimensions. These sleeks, owing to the more spherical shape of the polishing abrasive, are more regular than those produced in "smoothing." Intersecting in all directions they break up the surface into a chatter flaw complex, and then in the dry polishing stage the polisher comes into intimate contact with the work and incipient cohesion takes place between polisher and work. At this stage the effort required to drive the polisher increases enormously, and the whole flaw-complex is broken away by the roots*. At the same time a slight molecular rearrangement of the new surface takes place, as observed by Beilby and others.

In the case of our own workshops, it is known that there is commonly removed in the polishing process from three to six wave lengths of thickness. It is found that with automatic polishing and when the polisher is working at its best, this amount is removed in some 50 or 60 "wets" (alternations of wet and dry polishing); consequently the average amount removed per wet is in the neighbourhood of one or two millionths of an inch. This it will be noted agrees with the general postulate, that the detail of an average spider-web is of the order of a few millionths of an inch. This interpretation, though in no way contradicting the experiments of Beilby, represents in some measure a return to the views of Hooke and Herschel; it raises a number of questions, some of which are capable of formulation in quantitative terms, and it is hoped to deal with some of them in a further communication. A considerable amount of experimental data has been collected, but its discussion involves a more detailed consideration of workshop practice and technique, which would increase unduly the length of the present paper.

It could not be observed that various types of glass differed at all in their etch patterns, while the structure of polished examples of quartz and of felspar was also very similar to that of polished glass. The crystal specimens (cut parallel to the long axis) show no influence, on the pattern, of the anisotropic character of the crystals. This is equivalent of course to saying that the crystals break equally well in any direction, or are devoid of any signs of cleavage. It was observed that felspar and quartz were much more resistant to hydrofluoric acid than glass. The structure of a glass surface was well developed by etching for 15 seconds in 2N hydrofluoric acid at 15° C. The felspar required five minutes to bring out the pattern, while the quartz required seven minutes with acid of 5N strength†.

* The same thing happens in time and in a more gradual manner even if the polisher is not allowed to dry.

† It is to be expected that various types of glass will etch at various rates, but no great difference was observed. The types used included Dense Flints, Hard Crowns, Barium Crowns, and plate glass.

The structure on apatite and fluorite appeared to be quite different. The etching agent was sulphuric acid, and the sleeks when developed did not resemble chatter sleeks, but rather the grooves produced on metals by polishing powders. This would suggest a certain plasticity in these crystals, which are of a mineralogically lower hardness (fluorite 4, apatite 5, felspar 6, quartz 7 on Moh's scale).

A Further Note on the Extent of Surface Flow in Glass

Beilby* has described the covering over of minute pits in metals by the smeared surface-tension layer. His observations relate more particularly to very ductile materials (copper) and the covering film is estimated to be 10 to 20 micro-millimetres in thickness (less than a millionth of an inch). French was unable to obtain any covered over cavities in glass; he experimented with a special glass containing many minute air-bells, which, once broken into, could not be smeared over. He also deposited a fine layer of silver on a grey surface and found that the silver was never covered in during the polishing process. He therefore concludes that the surface flow in glass is much less than in metals, and that it differs therefrom in the fact that the material must be ploughed away to the level of the bottom of the deepest pits.

The workman nevertheless believes that "grey" can be covered over, the curious workshop expression being that grey can be "*blinded in*." The workshop view is confirmed by the microscopic examination of etched surfaces, where chatter grey (a remnant of the smoothing structure) can be observed on polished surfaces of glass and quartz, which previously to etching showed no such structure. The workshop view does not contradict that of Dr French, when we interpret grey to mean "chatter grey," that is fissures rather than pits. The surface irregularities must be ploughed down to the level of the deepest pits in the polishing operation, but the whole surface is not necessarily ploughed away to the level of the deepest fissures.

A fine layer of silver can be deposited on the surface of the glass, but is quite unable to penetrate into the chatter flaws. Consequently the silver is all removed in the earlier stages of polishing, but the deep flaws still remain. If the surface layer be not too much broken up, these fractures may be covered in, but there is apparently a tendency for the severe tangential drag of the polisher to dislodge fragments that have been rendered insecure but not actually broken out in smoothing, so that it is also quite possible to "open-up" grey in polishing as one works downwards. The experiment with a silver deposit has been repeated, and a similar one made with iodeosin. Both the silver and the iodeosin stain disappeared at a very early stage, long before the grey. It seems clear that they only affected the surface irregularities and never penetrated the chatter flaws at all.

The results of a number of experiments seem to indicate further that but little covering over of the "grey" occurs with those coarse abrasives which are suitable for ordinary workshop practice; with such materials the tangential drag or "bite"

* *Proc. Roy. Soc.* 89 A (1914), 593; also 72 A (1903), 218.

is very considerable and the rouge grinds its way down till the bottoms of the deepest flaws are removed. On the other hand, with certain abrasives of very fine texture where the drag is negligible, a flowing of the surface layer seems to take place which results in covering over the last traces of the grey-complex.

I wish to acknowledge the valuable criticism of Sir Herbert Jackson and his staff of the British Scientific Instrument Research Association in the preparation of this paper.

DISCUSSION

Mr H. Moore said that the papers which the author submitted to the British Scientific Instrument Research Association had been passed on to him for criticism. A number of experiments had been made to test Mr Preston's rather startling conclusions. By using an oil immersion objective it had been possible to obtain photographic evidence of the presence of fissures well below the deepest holes left in abraded glass surfaces. The maximum depth to which the fissures extended was about 12λ. The general idea that an abrasive appeared to act like a plane over wood, the plane iron being loose, seemed to be entirely inadequate to explain the structure of the greyed surface obtained. The fissures under the greyed surface could only be explained on the lines suggested by the author.

It was Sir Herbert Jackson's view that the present paper constituted a marked advance in the subject. Apart from its scientific value, it should be of great assistance to manufacturers.

Dr J. S. Anderson asked if an interference method had been used to determine the depths of the fissures in terms of wave length.

Mr Moore explained that the microscope was fitted with a fine adjustment which had been checked in various ways; the results could be relied on to $\frac{1}{2}\lambda$.

Mr J. Guild said that the author's results appeared to give a reasonable explanation of the fact that the surface of a lens or prism, no matter how well polished it is, always scatters a good deal of light. The subcutaneous fissures, though too small to be seen, might be quite effective as scatterers of light.

Mr J. Rheinberg thought that the paper threw light on other problems. In platinising glass by heat processes the platinum seemed to penetrate only to a small extent—about $\frac{1}{2}$ or $\frac{1}{3}\lambda$ according to Beilby. The author had used deposits of silver. He suggested that platinum and palladium should be tried, as they were the only metals which he could get to enter the glass.

He had found that various types of glass etch at different rates.

Mr H. S. Ryland said that the existence below a polished glass surface of chatter sleeks and flaws seems to suggest an explanation of the "film" or "scum" which was so troublesome in enclosed optical instruments during the war. Grease, oil from pitch, etc., might be absorbed in minute quantities by these flaws, etc., and afterwards exude, forming the scum. This would appear to be borne out by the method of preventing scum which he had advocated before the Society; this briefly consisted in heating the lens or prism in hot water, and afterwards using suitable precautions to prevent foreign matter from reaching the surface.

He asked whether the extent of the chatter sleeks varied with the speed and pressure of the rolling or sliding ball. It was possible that they would increase with speed and pressure up to a point, falling off with any further increase. If this is so it would seem that in lens manufacture there is a critical speed and pressure at which the time needed for polishing and smoothing is a minimum.

It would be of interest to observe the structure, if any, of a "fire polished" surface after etching and to compare the structure, after etching, of surfaces ground on a wheel with that of those ground in the usual way with loose abrasive.

Mr P. F. Everitt thought that there was not a single phenomenon in connection with the process of grinding and polishing that the author had not explained.

In cutting glass with a diamond it was important to finish the process right out. In one case an operator had been told to cut 100 specimens and then break the edges, with the result that they all went to pieces. He suggested that the author might investigate the time factor.

Mr F. C. Bullock said that the effect of varying the speed of the rolling or sliding ball had not been tried, but with varying pressure the width of the sleek had been found to be a function of the diameter of the ball.

Author's reply (communicated): I am afraid that, notwithstanding Mr Everitt's kind remarks, we are still very far from understanding everything that goes on in the workshop in abrading glass. Workshop processes are in general most complex, and the tooling of any material, brittle or otherwise, is a matter not yet brought within the frontiers of Science.

With regard to Mr Guild's remarks, I had not thought of the ultra-microscopic fissure-complex as a possible cause of scattering of light; I have no observations on this point.

In reply to Mr Ryland, the structure of the "fire polished" surfaces is, in all the cases I have examined, radically different from that of a mechanically polished one. The structure of surfaces ground with wheels is generally fundamentally the same as that of one ground with loose abrasive, but wheel-ground surfaces present many features of special interest that are best reserved for a separate paper. The effect of varying the pressure on the appearance of the chatter sleeks is outlined in the paper; the speeds were not varied a great deal, but when expressed as diameters per second were of course very low compared with the speeds obtaining with rough grains in polishing. Expressed as an ordinary velocity (e.g. cm./sec.) the speeds used for the needle and ball would be comparable with the speeds commonly used in polishing optical glass.

In reply to Mr Everitt, I am aware that the glazier who is cutting glass with a diamond regards it as important to break the glass "while the cut is hot." If the cut is allowed to become cold the glazier says that it degenerates into a scratch.

The material above the subcutaneous (lateral) flaws flakes away in the interval, but what happens to the central flaw to prevent its extension on bending the glass. I am unable at present to say.

No particular importance is attached to the experiments in depositing silver on greyed surfaces, and it scarcely seems worth while to pursue the matter further for the present purpose. Mr Rheinberg's suggestion that in other problems the point may be of direct importance is interesting, and had not occurred to me previously. I am afraid that at present I shall not be able to investigate these matters, but hope that Mr Rheinberg may perhaps be able to do so.

DESCRIPTION OF FIGURES

Fig. 1. The hyperbolic (static) flaw in elevation. The upper part is a reflection of the lower, seen in the totally reflecting surface *AA* of the glass. ×48.

Fig. 2. The chatter sleek of a sliding needle, in plan. Needle end part of a 1-inch sphere. Load just critical. ×9.

Fig. 3. A similar sleek in longitudinal elevation, showing the chatter flaws. The upper half is again a reflexion of the lower. ×60.

Fig. 4. A sliding-needle sleek with excessive load, in plan. ×9.

Fig. 5. Plan view of a rolling ball's track. (Diameter of ball ⅜-inch.) ×60.

Fig. 6. A similar track after etching with HF. ×60.

Fig. 7. A similar track, showing secondary flaws. ×60.

Fig. 8. Side elevation of a rolling-ball track with heavy load. ×60.

Fig. 9. Apparent form of rolling-ball fractures, when complete.

Fig. 10. Form of the glazier's diamond crystal.

Fig. 11. Cross section of a glazier's diamond cut. ×36.

Fig. 12. Longitudinal section of same, broken through the central flaw. ×60.

Fig. 13. Plan view of a diamond cut, etched with HF. ×60.

Fig. 14. Cross section of a glazier's wheel cut. ×36.

Fig. 15. Longitudinal section of same. Note the orthogonal systems of markings, as in Fig. 12. ×36.

Fig. 16. Percussion flaws at commencement of a re-grey with coarse carborundum. (The focus is slightly below the surface of the glass and small surface markings appear as spots over the field.) ×250.

Fig. 17. A splinter cut and percussion flaws made by carborundum at commencement of a re-grey. The important flaws are to the *sides* of the cut; there are none at either *end*. The most important flaws are well below the surface and may be detected by the interference bands. ×60.

Fig. 18. Chatter cuts formed at the commencement of a re-grey with a soft variety of corundum (D_3). ×250.

Fig. 19. A very complex family of chatter cuts from (D_3) corundum. ×250.

Fig. 20. A plate glass surface smoothed with "15-minute" emery and etched for one minute with 3N hydrofluoric acid. ×250.

Fig. 21. The same after etching for 2 minutes. ×250.

Fig. 22. The same after etching for 7 minutes. ×250.

Fig. 23. The same after etching for 25 minutes. ×250.

The photographs in Figs. 24 to 26 were obtained by the staff of the British Scientific Instrument Research Association, Russell Square, from a cover glass ground on one surface with (C_3) corundum and photographed through the polished side using a 3 mm. apochromatic object glass of 1·4 n.a. ×960.

Fig. 24. Top of ground surface in focus.

Fig. 25. Bottom of pits in focus 3 wave lengths below 14.

Fig. 26. Shows flaw 10 wave lengths below 14.

It will be noticed in Fig. 25 that a number of flaws are also visible, some, of course, out of focus.

Fig. 27. Twyman effect between crossed nicols.

Fig. 28. Twyman effect in Babinet polariscope.

Fig. 29. Twyman effect on wedge of glass.

Fig. 30. Twyman effect with high resolution.

Fig. 31. "Artificial" Twyman effect specimen.

Fig. 32. Distribution of stress in above.

Fig. 33. The "spider-web" pattern, the fine sleeks developed by etching with HF.

Fig. 34. Chatter sleek pattern of coarse manganese dioxide.

Fig. 35. The complete web pattern.

Fig. 36. The same field as Fig. 33 in a different illumination, showing that the sleeks run in all directions.

Fig. 37. Chatter grey left, showing ground-mass of chatter flaw complex.

Fig. 38. Chatter grey from coarse emery, after partial polishing. Also a heavy chatter cut.

Fig. 39. Specimen polished with chromic oxide with help of rouge in polisher. Note the interrupted and twisted (cascade) sleeks. There is also a good spider-web and some chatter grey not visible in this lighting.

Magnification in Figs. 33–39, approximately 80 diameters.