T H E W O R K I N G

of

O P T I C A L P A R T S.

by

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THE
WORKING OF OPTICAL PARTS.

by

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The Balsam Problem	"	"	"	1918.
The Unaided Eye, Part I	"	"	"	1919.
The Unaided Eye, Part II	"	"	"	1919.
The Unaided Eye, Part III	"	"	"	1920.
The Surface Layer of an Optical Polishing Tool	"	"	"	1920.
The Properties and Production of Optical Glass.	Opthalmic Soc.			1920.

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Modern Power Generators, Vols I and II	1908.
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Machine Tools, Vols I and II	1911.
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Contributor of Two Sections of the Dictionary of Applied Science, edited by Sir Richard Glazebrook.	(In the press).

During the War.

A member of various standing committees of the Department of Scientific and Industrial Research, particularly the Panel of Standardisation and the Editorial Committee for Optical Works, such as the "Formation of Images in Optical Instruments" by von Rohr, and the "Theory of Modern Optical Instruments, by Gleichen".

A member of the Glass Delegacy, and

A member of the Councils of Optical and Glass Technology Societies.

PATENTS GRANTED TO J.W. FRENCH.

British Patent No. 28125 of 1913.	Reversing Switch Transmitter.
Corresponding Foreign: United States	No. 1147359 of 1915.
France	No. 47[illegible]11 of 1914.
Italy	No. [illegible]159 of 1914.
British Patent No. 7854 of 1915, Secret Patent	Fire Control apparatus
British Patent No. [illegible] of 1917.	Instrument Facepieces.
British Patent No. 127[illegible]5 of 1917.	Eyepiece prism combinations.
Corresponding Foreign: United States	No. 1322780 of 1919.
British Patent No. 120644 of 1917.	Periscope casings.
Corresponding Foreign: United States.	No. 1298632 of 1919.
British Patent No. 129692 of 1917.	Periscope. Head reflector.
Corresponding Foreign: United States.	No. 1316438 of 1919.
France.	No. 505121 of 1918.
British Patent No. 129124 of 1918.	Transmitting motion. Spring accumulator.
British Patent No. 144118 of 1919.	Kinematograph. Sprocket-drum and shutter adjustment.

The Working of Optical Parts.

For the production of an optical instrument the collaboration of the designer, the computer and the optical worker is essential. Particulars of the function of the proposed instrument and the conditions to be fulfilled having been determined, the designer is able to prepare a general scheme of the mechanical and optical arrangement. So far as the optical portion is concerned, this involves a general knowledge of the limitations of computations, and the accuracy attainable in the practical working of the parts.

Where possible the designer avoids the introduction of extreme angular apertures that might necessitate the use of very special types of glass or increase the computational difficulties. But the tendency must always be towards the imposition of increasingly drastic demands, and frequently for one or more details of the optical system the designer must finally rely upon the utmost skill of the computor. Close collaboration between the computor and the work shop is also essential. Thus, for example, it may be desirable to use particular types of glass that happen to be in stock or standard test plates and tools.

It is the function of the optical worker with whom this chapter is mostly concerned to form the parts to the specified dimensions, to polish the surfaces, to examine the performances of the finished work, and when possible, to compensate the defects whether of surface or substance.

As to the methods employed in the workshop, each depends upon the character of the work. Large astronomical objectives for which the demand is extremely small are invariably produced singly and involve the exercise of very special craftsmanship.

One renowned manufacturer[(1)] has stated that object glasses cannot be made on paper. The hand method of producing such parts consists in the computation of the objective by means of the simplest formulae with a view

(1). H.Grubb. The production and testing of telescope objectives and mirrors. Nature v.34, 1886, p. 85.

to the elimination of chromatism principally, and the determination of the desired focal length, and then in the removal of residual aberrations, and more particularly spherical aberration, by mechanical local retouching based upon optical examinations of the images formed by different zones and portions of the objective. From the point of view of the perfection of the objective this empirical method appears to be justified by the excellence of the results attained. Other makers of large astronomical object glasses[1] advocate the alternative method. By rigid computation they determine the curves, thicknesses, separations and apertures of the parts, and in the workshop they endeavour to attain the desired degrees of freedom from the several aberrations by the least possible departures from the calculated data. Local retouching can hardly be avoided in the production of large optical parts. Peripheral or central zones of one or more of the surfaces may have to be retouched in order to produce an aspherical surface for the compensation of spherical aberration. Regular cylindrical

(1) S.Czapski. Zeits. f. Instk. 7,p 101, 1887.

retouching may be necessary for the correction of astigmatism. Surface imperfections, defects of homogeneity, defective annealing, constraint during working processes, and thermal effects may all involve irregular retouching.

But the organisation of most optical workshops is arranged principally for the production of ~~comparatively~~ small lenses and prisms, of which comparatively large quantities have usually to be produced, as for example in the manufacture of binoculars and cameras. For reasons of cost, retouching of such parts is not permissible, and indeed rarely necessary, if the materials are well selected. They must be produced within limits specified by the designer and computor, and defective elements are rejected. Trial and error methods play but little part in such an organisation. Each step is based upon precise measurements.

There is an intermediate class of multiple work involving parts the size and cost of which are such as to make a certain amount of retouching necessary, although such retouching must always be regarded as undesirable. At the present time the technique of the optician is in advance of that of the glass maker. By machinery it is possible to produce surfaces that may be regarded as optically perfect.

A prism such as is used at the ends of a rangefinder having perfect optical surfaces will not necessarily give a well defined image, owing to small imperfections of the glass, such as defective annealing or homogeneity. The larger the piece the greater is the difficulty in obtaining glass that is sufficiently homogeneous to suit the requirements of the optician.

In such work it is customary to form and polish the pieces by machine, to test the perfection of the definition of the parts, and if necessary, of their individual surfaces. Those that fail to pass and that exhibit certain types of imperfect definition may be saved by retouching by hand, or in the more regular cases, by machine. Of the remaining defective pieces, some may require re-annealing. The others must be finally rejected unless they can be utilised in instruments of lower power or inferior quality.

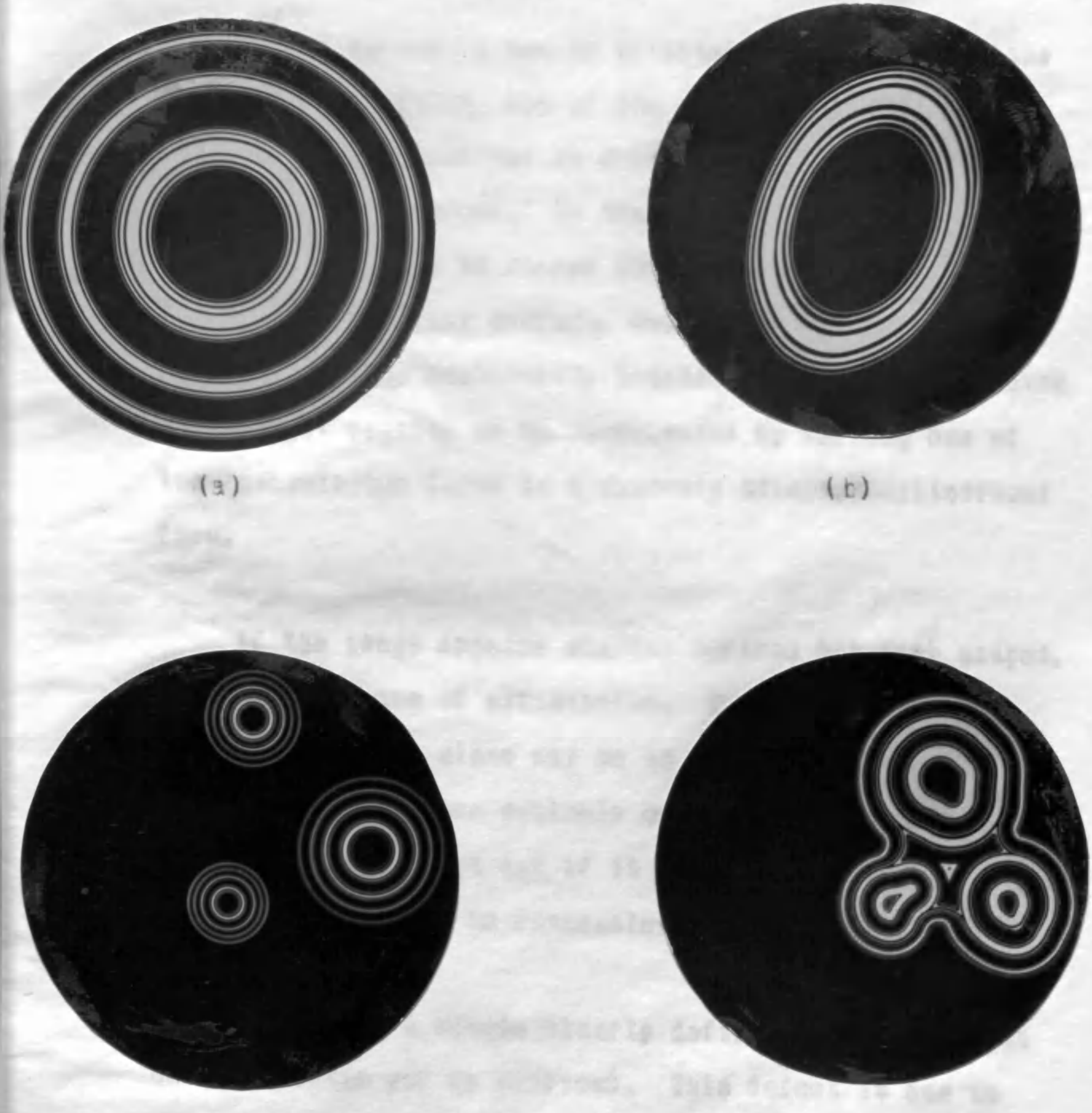
There is another class of work, such for example, as condenser lenses and to some extent spectacle lenses, in which no great accuracy either of form or surface is required, and which will not be further considered.

It will be evident from the above general remarks that the production of high quality optical parts cannot be reduced entirely to purely mechanical operations. A certain amount of hand work is involved, not only because of the need for the irregular retouching of surfaces, but also for the production of certain delicate and accurate details for which suitable machinery has not yet been elaborated.

In the most highly organised workshops there may therefore still be seen in operation the early hand processes elaborated by such pioneer workers as Huyghens, Hooke, Newton, Father Cherubin, Herschel, and Molyneux.

Whether for the purpose of final or work-in-progress inspection, or for retouching, it is necessary to analyse the definition of the image produced by the optical part or system in question, and to diagnose the probable defects with a view to their possible correction.

It is not sufficient to make the broad statement that the definition is bad, because it may be possible to compensate the defect in the case of large and costly parts without much additional expense. Suppose the optical part to be examined is a thick parallel plate of glass whose transmission surfaces have been optically worked and may be regarded as being unquestionably true, and suppose the part is placed in the parallel beam before the objective of a telescope which is directed upon a collimator or test image comprising small holes or lines. If the glass is perfect its insertion in the path of the light should not affect the appearance of the collimator image. If, to obtain a sharp image, a readjustment of the telescope eyepiece is necessary, the parallel plate has a focus error. It is equivalent in its action to a very weak lens. Examination by means of the interferometer may reveal a regular change of optical density from the centre outwards as represented by the circular bands of Fig. 1a. The defect in question may be due to imperfect annealing, or a regular defect of homogeneity. Double refraction resulting from imperfect annealing of the glass may be tested by inserting a half wave plate and observing the extent to which the bands are displaced as the half wave plate is rotated.



(a) (b) (c) (d)

Fig. 1.

If the defect is due to internal stresses, the glass should be reannealed, but if the substance itself is at fault the definition may be corrected by making one of the surfaces spherical. In the case of a prism a transmission face would be chosen for the operation in preference to a reflecting surface, since oblique reflection at a curved surface necessarily introduces astigmatism, which again might require to be compensated by working one of the transmission faces to a suitably oriented cylindrical form.

If the image appears sharply defined but oval shaped, the defect is one of astigmatism. The interferometer appearance of the glass may be as indicated in Fig. 1 b. A cylindrical surface suitably oriented will suffice to compensate the defect but if it is the glass that is strained, it should be reannealed.

Instead of a singèe clearly defindd image a complex multiple image may be produced. This defect is due to heterogeneity of the glass, the structure of which when viewed by means of the interferometer may appear as ån Fig. 1 c. Such a structure might result from imperfect solution of the constituents, the nucleus of a sphere, for example in a soda lime glass for instance, being quartz, having an ordinary refractive index of 1.54, and the various layers being silicates of gradually diminishing refractive index, approximating to about 1.5 which is the index for sodium silicate. Each sphere acts as a small aperture lens and forms a separate part of the multiple image.

Local retouching may sometimes suffice for the compensation of these multiple image defects.

If the spheres are distorted and merge into one another as indicated by the interferometer appearance in Fig.1 d, the image produced will be indefinite or "fuzzy". Retouching in such a case is usually impracticable and the part must accordingly be finally rejected.

These several defects may appear singly or in combination and in various degrees. Thus, for example, in practice pure astigmatism is seldom found in optically parallel plates of thick glass. Usually the appearance of the image is attributable to lenticular and astigmatic defects which may be compensated by working one surface to a suitable cylindrical and the other to a spherical form.

It should be remembered that in the estimation of the various types of definition it is necessary that the inspector should know to what extent the errors are attributable to the defects of his eye, or to the apparatus employed, which should involve the smallest possible number of optical parts.

Veins if not numerous, and if unaccompanied by other defects, have no serious effect upon the definition. A vein is usually an extremely fine thread of glass richer in silicate of alumina than the surrounding substance. Each vein is equivalent to a long astigmatic lens of extremely short focus, and the separate image formed by it is usually so diffused as to be invisible. But if the test object is a fine line, then by a movement of the eye the image may be momentarily occulted by the passage of the vein in front of it. A number of parallel veins may give rise to a rippling appearance of the image, and be sufficient cause for the rejection of the part. Often however, the veins in glass are an indication of defective homogeneity, and in the best work the use of such glass should be avoided.

For the investigation of spherical aberration errors Foucault's[1] original knife edge method is still frequently

(1) Foucault's method is discussed in the handbook on the adjustment and testing of telescope objectives by T. Cooke & Sons. 1896.

employed especially in the case of large object glasses. If the eye of the observer is placed close to the focal point of the object glass and receives all the rays falling upon it from a star or its equivalent, the whole a aperture of the object glass will appear illuminated. If then the focus is cut transversely by means of a knife edge which should be mounted upon a fine operating screw, the whole aperture will become dark at the instant the knife edge reaches the axis, if the objective is ideally perfect. If all the rays from the objective do not pass through the ideal focus, a number of rays will escape past the edge and still reach the eye, and the aperture will be partially illuminated, the distribution of the light affording an indication of the extent and distribution of the aberration. In the direct focussing method(1) the eye receives the focal image formed by the objective of a natural or artificial star, which appears as a system of diffraction rings surrounding a central spot of light. By examining the image out of focus on the near and far

(1) On the Adjustment and Testing of Telescope Objectives. Thos. Cooke & Sons, 1896.

sides, the nature of the spherical aberration either over the whole surface or over zones may be deduced from the change in the distribution and character of the rings. Irregular defects of the surfaces or of the glass may be indicated by distortion of the rings. Thus an oval shaped system would denote astigmatism. Chromatic aberrations may also be investigated by using homogeneous light of various wave lengths. These two methods, and particularly the former, give qualitative results rather than quantitative. The latter method in the hands of a skilled observer is more precise and the appearances may be more directly interpreted.

Special forms of Michelson's Interferometer[1] are now frequently employed for the examination of prisms and lenses, and even of complex optical systems, although the interpretation of the results is then difficult. When a

(1) F. Twyman. On the Use of the Interferometer for Testing Optical Systems, Traill Taylor Lecture, Roy. Phot. Soc. 1918.
F. Twyman. Phil. Mag. Vol.XXXV, Jan.1918.
F. Twyman. Correction of Optical Surfaces. Astro-Phys. Journal, Vol. 48, No.4, 1918.
Michelson. Astro-Phys. Journal, June, 1918.

simple prism or object glass is examined in this way the surface will appear uniformly illuminated if the piece under test causes no relative retardation of any portion of a plane wave front, assuming of course, that the optical parts of the interferometer itself have been accurately compensated.

A concentric ring appearance would indicate curvature of one or more of the surfaces or a regular variation of the material. Irregularities of surfaces or substance would be indicated by a distortion of the system of rings.

The interferometer does not discriminate between retardations attributable to the glass and to the surfaces, except those due to defective annealing, which may be detected by observing the shift of the rings as a half wave plate inserted before the eye is rotated. It is the resultant retardation that is indicated by the interferometer, and by the use of the interferometer alone it is not possible to allocate the component defects to the particular elements. But in practice it is sufficient to compensate the resultant defect by retouching one of the surfaces and for this purpose a contour of the ring system as seen by the observer is painted upon the surface selected for the retouching operation. By polishing away the high portions, and repeating the observations a comparatively uniform distribution may ultimately be obtained, and the definition be thereby greatly improved. Only large prisms and objectives can be subjected to an expensive process of this kind. For the production of aspherical surfaces the method is particularly valuable.

Chromatic aberrations may be investigated by the Vogel[(1)] method, provided the aperture is not so small that a large shift of the eyepiece is necessary to detect a difference of focus. It is also essential that the chromatic effects due to the eye and the eyepiece or other parts involved should be previously determined.

In the eyepiece there is mounted a direct vision prism which forms a spectrum of the star image formed in the field of view through the intermediary of the part to

(1) H.C. Vogel. Monats Berichte d, Berl. Ak. 1880.

be tested. If the correction is perfect, the spectrum, when the eyepiece is focussed, will appear as a thin line of uniform width, but if there is any chromatic aberration of particular colours the corresponding portions of the spectrum will be broader than the remaining parts. A measurement of the aberrational defects may be obtained by observing the shift of the eyepiece necessary to reduce the various widths to a minimum amount. This method indicates only the general chromatic defect. It can hardly discriminate between zones and as the aperture is reduced by stopping out the peripheral portions, the usefulness of the method is diminished.

Precise measurements of the various aberrations are obtainable even in the case of objectives of small aperture by the Abbe Focimeter method.(1)

But probably the most complete and precise investigation of the spherical and chromatic aberrations of any optical

(1) S. Czapski. Methode und Apparate zur Bestimmung von Brennweiten nach Abbe. Zeitsch. f. Instrk. 12, p 185. 1892.

part, is obtainable by the Hartmann method[1] by means of which the final positions of particular rays are located in a manner comparable with the trigonometrical computation of the paths of rays. Symmetrically arranged holes in a diaphragm determine the portions of the optical part to be traversed by the fine bundles of rays which are finally received upon photographic plates situated at symmetrical positions before and after the focal plane. From the spacing of the images on the photographic plates in comparison with the spacing of the holes in the diaphragm the aberrations can be determined. Separate observations with light of different colours are made for the determination of chromatic aberration. The original method of examining the optical performance of an objective by means of selected rays is described by Father Cherubin[2] who also demonstrates the effects of defective centering and emphasises the importance of accuracy in this respect.

From a consideration of the light intensity at a focal point Lord Rayleigh[3] has stated that "in general we may

(1) J. Hartmann. Objektivuntersuchungen. Zeitsch. f. Instrk. 24, 1904.
H. Fassbender. Zeitsch. f. Instrk. 38, p.377. 1918.

(2) Père Cherubin. Vision Parfaite, Vol. II, p.108, also p.25.
William Molyneux. Dioptrics, 1692. Part II, Chap.IV, p.222.

(3) Lord Rayleigh. Scientific Papers, Vol.III, p.100 and p.104. Also L. Silberstein, Light Distribution round the Focus of a Lens, Phil. Mag. Vol.XXIV, p. 35, 1918.

say that aberration is unimportant when it nowhere, (or at any rate, over a relatively small area only) exceeds a small fraction of the wave length (λ). Thus in estimating the intensity at a focal point where in the absence of aberrations all the secondary waves would have exactly the same phase, we see that an aberration nowhere exceeding $\frac{1}{4}\lambda$ can have but little effect", and again, "An important practical question is the amount of error admissible in optical surfaces. In the case of a mirror reflecting at nearly perpendicular incidence there should be no deviation from truth (over an appreciable area) of more than $\frac{1}{4}\lambda$. For glass, $\mu - 1 = \frac{1}{2}$ nearly; and hence the admissible error in a refracting surface of that material is four times as great." This estimated value of Lord Rayleigh of the permissible phase difference is generally confirmed by practical experience.

Test plates are very commonly used for the examination of the surfaces not only during the progress of the work, but also in the final testing, with a view to the allocation of any observed defects of definition.

Sir Isaac Newton[1] has dealt very exhaustively with the colours of thin plates, which had previously been observed, but not completely described by other workers. Although it is evident from Newton's description that he realised that these colours afforded an indication of minute irregularities of thickness of the intervening layer, it is not so clear that it was his practice to test the surface being operated upon in comparison with a test plate having a very perfect optically flat surface.

These test plates which are the most valuable of the practical optician's appliances are usually made of quartz. But for reasons of economy glass test plates which from time to time must be compared with the standard quartz plates are employed. Quartz has the primary advantage of hardness. The frequent cleaning of the test surface that is essential, soon impairs the definition in the case of a glass plate, and even in the case of quartz a good worker handles the surfaces with the greatest came.

(1) Sir Isaac Newton - Opticks. 1704. Book II, part I.

For flat work the parallel quartz plate, having an approximate thickness of about one fifth its diameter is polished on both sides and worked as perfectly flat as possible on at least one side. When the test plate surface is placed upon the surface to be tested if the latter is the larger and the more rigid, a thin layer of air is enclosed between them. Diffused white light which is reflected from the two surfaces of the air film gives rise to interference colours which may be viewed by a suitably placed eye. If monochromatic light is used numerous fine interference lines are visible, indicating minute variations that cannot be detected when using white light. Since the temperatures of the work and of the test plate will most probably be unequal, several systems of Newton's rings more or less distinct will be visible. As the temperatures equalise, the rings will broaden and in the course of 5 to 30 minutes, or more according to the volume of the parts, if the surface is perfect, a uniform straw yellow appearance may be obtained by skilful manipulation of the plate. If the surface is regularly curved, concentric rings will be seen, and the greater the curvature the closer will be the spacing of the rings, provided the surfaces are clean and dry and the test plate is properly handled. Distorted rings or bands indicate irregularity of the surface relatively to the test plate. If when the test plate is gently pressed eccentrically by means of a pointed piece of wood, and not the finger, the centre of the rings moves towards the point of application, the surface under test is convex. It is very important that the adjacent surfaces of the work and the test plate should not only be thoroughly clean and free from the minutest specks of dust, but that they should also be free from any trace of moisture, the capillary action of which would locally distort the pieces and give a false indication.

For the best quality of work great skill is necessary in the use of a test plate, the indications of which require careful interpretation. Flat surfaces may be finally tested by an analysis of the reflected image in the manner already described. The reflection test is the more reliable, but the test plate has the merit of great convenience and for the greater part of the work the optician is called upon to perform, it is thoroughly reliable and invaluable. For curved work, one surface of the test plate is worked to the appropriate curve and the other surface is made flat. The radius of the curved test surface is measured by means of a spherometer or the focus may be determined optically. It will be understood that the primary function of the test plate is not to obtain absolute measurements, but to determine the extent and nature of the difference between the worked surface and the test plate. To indicate the permissible amount of irregular distortion is hardly possible. If there is any noticeable irregularity the surface should be reworked. Slight angular ellipticity may be permissible especially when the astigmatisms of two transmission faces are normal to one another. Curvature to the extent of one and a half to two complete rings is generally regarded as being just permissible. It might be thought that such a statement would require extensive qualification according to the size of the part, its function, and its position in the optical system, particularly as regards its distance from a focal plane. Practical experience however shows that this limit of two rings, which accords with the practice of at least one large German firm,[1]

(1) W. Zschokke. Festschrift. Firma C.P. Goerz, p.240

covers a very wide range of work. Factory conditions render it practically impossible to adjust the limits to suit the requirements of individual parts. The tendency is towards the adoption of approximately one general and high standard, of optical quality.

For practical reasons it is customary to divide the process of working optical surfaces into three stages. (1) The forming stage in which the size and shape of the part is accurately determined. (2) The smoothing stage and (3) the polishing stage.

Stages (1) and (2) involve the use of abrasives and these operations are accordingly performed in rooms quite separate from the polishing departments where fine media only are employed. But it must not be assumed that the polished appearance of the surface as distinct from regularity of surface is a phenomenon that only takes place as a result of the polishing process. Actually a certain amount of polish is associated with the use of the roughest abrasive.

It is only within comparatively recent years that the molecular regularity of polished surfaces has received recognition. The earlier conception is very clearly expressed by Sir Isaac Newton[1] in the following words:-

"For in polishing glass with sand, putty or tripoly, it is not to be imagined that these substances can, by grating and fretting the glass, bring all its least particles to an accurate polish, so that all their surfaces shall be truly plain or truly spherical and look all the same way so as together to compose one even surface. The smaller the particles of those substances are, the smaller will be the scratches by which they continually fret and wear away the glass until it be polished, but be they never so small they can wear away the glass no otherwise than by grating and scratching it and breaking the protuberances and therefore polish it no otherwise than by bringing its roughness to a very fine grain so that the scratches and frettings of the surface become too small to be visible."

There is no indication here that Newton regarded the

(1) Newton's Optiks. (1704). Second book, page 68.

surfaces as being molecularly regular or comparable with the surface of a liquid.

Subsequent writers have not hesitated to accept without question and to repeat the statement of so authoritative an observer as Newton. Thus, for example, Coddington,[1] Sir J.F.W. Herschel,[2] and Sir David Brewster[3] use practically the words of Newton when describing a polished surface.

If polishing were merely a continuation of the grating and fretting of the surface protuberances it should be possible to observe a continuous sequence of appearances from coarse conchoidal fractures to a grain of ultra-microscopic character. But if the operation of polishing a smoothed surface is performed under the microscope, it will be seen that numerous patches of perfect polish akin to

1 Coddington's Optics (1825) p. 32.
2 Sir J.F.W. Herschel, Encyclopoedia Metropolitan (1830) Optics, p. 447.
3 Sir David Brewster, Optics, p. 159.

the still surface of a liquid are formed almost instantly and that these patches exhibit no intermediate structure other than accidental scratches and kindred defects.

Lord Rayleigh[1] in a lecture on "Polish" appears to have been the first to describe their appearance. He states that, "in view of these phenomena we recognise it is something of an accident that polishing processes as distinct from grinding are needed at all and we may be tempted to infer that there is no essential difference between the operations. This appears to have been the opinion of Herschel (as expressed in the Enc. Met. Art. Light,[2] pp.447 to 330) whom we may regard as one of the first authorities on such a subject. But although perhaps no sure conclusion can be demonstrated, the balance of evidence appears to point in the opposite direction."....
"Under those conditions which preclude more than a

(1) Lord Rayleigh, "Polish", Royal Institution, March 29, 1901. See also Lord Rayleigh, "Interference Bands and their Applications", Royal Institution, March 24, 1903. Also "Polishing of Glass Surfaces", Proc. Opt. Convention, No.1. 1905, p.73.

(2) Herschel's description is practically a repetition of Newton's earlier observations.

moderate pressure it seems probable that no grits are formed by the breaking out of fragments but that the material is worn away almost molecularly."....... And later he states, "But so much discontinuity as compared with the grinding action has to be admitted in any case that one is inevitably led to the conclusion that in all probability the operation is a molecular one and that no coherent fragments containing a large number of molecules are broken out. If this were so there would be much less difference than Herschel thought between the surfaces of a polished solid and of a liquid."

Although the molecular character of the polishing operation and the similarity of the surface produced to that of a liquid are quite definitely expressed, and, although Lord Rayleigh has referred in other of his papers to the remarkable pool-like appearance of elementary polished patches of a glass surface, it is not quite clear whether he regarded the result as being due to the removal of the substance molecule by molecule as distinct from the removal of minute aggregates of molecules or as being due to a molecular rearrangement or flow of the surface molecules as in the case of a liquid.

This latter conception is attributable very largely if not entirely, to Sir George Beilby, who has developed it in a series of papers[1] dealing principally with metal surfaces, the tenacity of which is such that the surface amorphous layer is capable of bridging over surface cavities even when these are not completely filled with debris. It is very doubtful if any such bridging over of even minute cavities occurs in glass owing to the small cohesion of the silicates as compared with that of the metals.[2]

According to the molecular flow theory of polishing, the forces exercised by the polisher upon the surface

1 Papers, G.T. Beilby.
Surface Flow in Crystalline Solids under Mechanical Disturbances. Proc. Roy.Soc. Vol. 72, 1903.
The Effects of Heat and of Solvents on Thin Films of Metal. Procs. Roy.Soc. Vol. 72, 1903.
The Hard and Soft States in Metals. Phil. Mag. Aug. 1904.
The Influence of Phase Changes On Tenacity of Ductile Metals, etc. Procs. Roy. Soc. Vol. A76, 1905.
The Hard and Soft States in Ductile Metals. Vol. A79, 1907
Surface Flow in Calcite. Procs. Roy. Soc. Vol. A82, 1907.
Transparence or Translucence of the Surface Film produced in Polished Metals. Procs. Roy. Soc. Vol. A89, 1914.

2 Some Notes on Glass Grinding and Polishing, J.W. French, Opt. Soc. Vol. XVII No. 2, 1916

molecules of the glass suffice to overcome the cohesive forces binding them together, with the result that the molecules rearrange themselves uniformly under the action of their surface tension forces. Thus it would appear that the grain of a polished surface, being molecular, is much finer than is actually required for the regular reflection of even the shortest visual rays at normal incidence.

Polished layers may be produced in several ways although in all cases the action is fundamentally the same. Fire glazed surfaces result from the thermal agitation and consequent flow of the surface molecules. Chemical forces produce a similar result. Provided precautions are taken to prevent the accumulation of fluoride crystals, very perfect light reflecting glass surfaces may be produced by the action of Hydrofluoric acid.[1]

1 Lord Rayleigh "Polish" Royal Inst. March 29, 1901.

The writer has confirmed Lord Rayleigh's experiments and has reduced by means of Hydrofluoric acid the surface of a polished plate to the extent of about 50 μ without adversely affecting its optical perfection.

When a piece of glass is fractured the forces at the cleavage edge so profoundly disturb the molecules that they are able to flow and form the characteristic polished appearance of a fractured surface.

It is hardly possible to fracture a piece of glass so suddenly that its surface is not polished. Under the microscope a rough.ground surface is seen to consist of numerous conchoidal depressions the surfaces of which are all light reflecting, and which may indeed be made to act as so many separate lenses of poor quality.[(1)] Closer examination will disclose a rounding of all the ridges where the conchoidal surfaces intersect that can only be attributable to viscous flow. The ridges have a characteristic yellow green colour whether the glass is flint or crown. Where these ridges intersect elementary polished patches are found and if an attempt were made to polish a rough ground surface of this type, it would be seen that

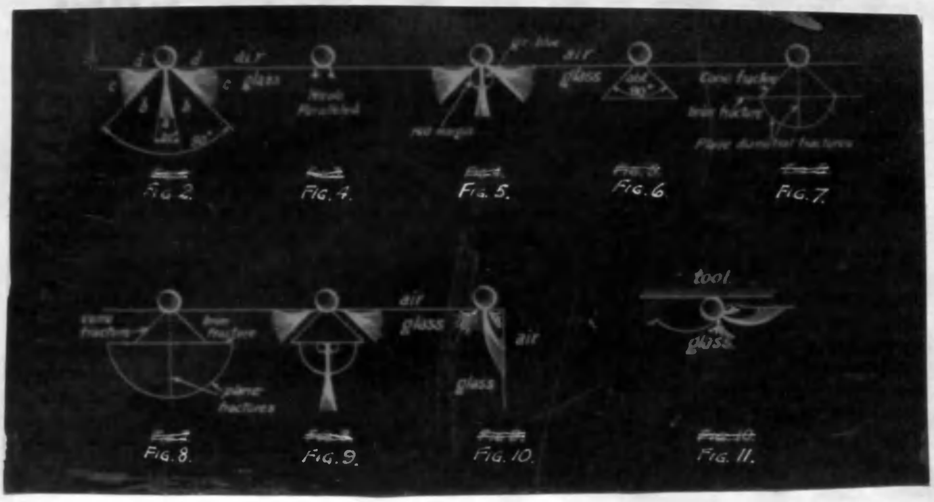
1 Lord Rayleigh. Interference bands and their applications. Royal Inst. March 24, 1893.

these elementary patches would be extended until they joined one another with the ultimate formation of a continuous polished surface.

In order that the workshop processes may be more fully understood the features characteristic of abrasion and polishing must be considered in detail.

Suppose a small steel ball is pressed upon the polished surface of a glass cube the transverse faces of which are also polished so that the stresses introduced may be viewed by means of a polariscope.[1] When the pressure is very light, the appearance between the crossed Nicols is as in Fig. 2. The central black cone has an angle of about 20° which appears to be practically independent of the pressure. The cone of strain b,b, has an angle of about 90°. Some surface light is visible at d,d. At low pressures the dark cones c and a merge softly into b. As the pressure is increased the interfaces become more intensely

1 J.W. French. Percussion Figures in Isotropic Solids. Nature, Nov. 20, 1919, p.312.



Figs.2, and 4 - 11.

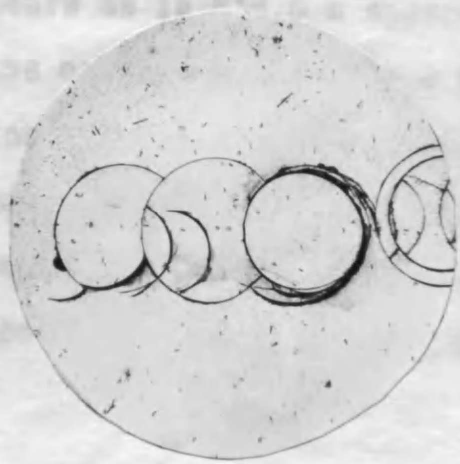


Fig.3.

Magn. 42 diameters.

defined, but the angles do not alter appreciably. Further gentle increase of pressure causes the surface layer to rupture as in Fig.3 which is a photo-micrograph of an etched polished surface repeatedly ruptured by gentle impact. If the Nicols are paralleled black rays will be seen proceeding from the edge of the crack as in Fig.4, their direction indicating that the crack is normal to the surface and not merely superficial. The character of Fig.2 is not appreciably altered.

A new phenomenon makes its appearance when the pressure is again increased. Immediately under the ball there appears as in Fig.5 a sphere pierced by the filament of the cone a, and having a black outline tinged with red on the outside. The interior is filled with green blue light; otherwise the general appearance of Fig.2 is unaltered. If now the Nicols are paralleled, it will be seen that the well known type of conical fracture[1] has

1 L'Eclatement. Ch. de Freminville, Revue de Métallurgie Sept. 1914, Sect. VII, p. 66

been produced as indicated in Fig.6. The coloured sphere of Fig.5 is a certain indication of the existence of a cone fracture. Examination with the Nicols in an intermediate position shows that the cone fracture which follows the surface of b is tangential to the sphere which it encloses. If the pressure is again increased the crushing point is soon reached. The glass under the ball collapses almost explosively, a distinct click being audible, and the ball sinks deeply through the surface. At the moment of this collapse, the cone of light t broadens out owing to the extension of the area of pressure. The cone fracture also may extend horizontally like the brim of a hat, thus definitely terminating the depth below the surface, and the space within the cone becomes cleft by one or by two fracture planes normal to one another and having their line of intersection on the axis of the dark cone a, as in Fig.7. The diametral planes may be extended to the brim as in Fig.8. Under crossed Nicols two new small coloured spheres indicative of subsidiary cracks may be observed as in Fig.9.

Now the grains of an abrasive such as carborundum are nodular and hard and akin to the steel balls used in the experiment. But a rough ground or smoothed glass plate exhibits no cone fractures, notwithstanding the vast number of impacts that must have occurred in the operation. Only if the tool carrying the abrasive is lowered sharply on to the glass surface will a number of cone fractures probably be formed.

From this it seems evident that the grinding of glass is not the result of any such normal pressure of the grains, and another explanation must be obtained. In the experiments with the steel ball as described above, the forces were symmetrical about the vertical axis. When the pressure is applied near the edge of the surface, the new appearance corresponding with the stage illustrated in Fig.2 will be as illustrated in Fig.10, from which it will be seen that the central cone is now deviated towards the side. Its axis along which fracture finally takes place follows the characteristic conchoidal section. It is presumably the impact of the abrasive grains on the edges of cavities that produces the conchoidal splintering of a ground surface as indicated in Fig.11.

As it is the transverse movement of the tool relatively to the glass that forces the hard grains against the edges of the cavities, it is to be expected that the rate of grinding will depend upon the speed of movement of the tool relatively to the work, and also upon the pressure exerted by the grains. This is confirmed, so far as the effect of relative speed is concerned, by the results of carborundum abrasive tests which indicate that the weight of glass removed is directly proportional to the relative speed,[1] the other conditions being maintained constant. To eliminate the effect of loss of cut fresh abrasive must be applied at intervals of about one minute, and precautions must be taken to ensure constancy of the general conditions throughout the tests.

From an examination of the previous Fig.11, it will be seen that the larger the grain the deeper, in general, will be the point of impact and the larger the splinters removed. The rate of grinding is therefore dependent also upon the size of the grain. Thus by reducing the coarseness of the abrasive at each stage of the grinding operation, a surface

1 More Notes on Glass Grinding and Polishing. J.W. French, Trans. Opt. Socy. Vol. XVIII, Jan. 1917.

of any desired degree of fineness may be obtained, and indeed the surface may be highly polished by means of the same material as is used for the rough grinding, provided a sufficiently fine grain of a suitable character is obtainable. Prior to the time of Antheaulme[1] it was the practice of the earlier opticians[2] to make the polishing process merely a continuation of the grinding stage, the sand first used being ground down sufficiently in the operation to serve as a polishing medium in the later stages.

Highly polished optical surfaces have also been produced by the use of very fine grades of carborundum. As much more suitable polishing media than fine carborundum are available, this experiment is mainly of interest as emphasising that there is no strict line of demarcation

1 Histoire des Mathématiques. Montucla, Vol.III, Part V, Livre II, p. 498.

2 Renati Descartes, Opera Philosophica, Dioptricis, Cap X, 1656.
Johannes Zahn, Oculus Artificialis Teledioptricus, 1702.

between abrasion and polishing. The removal of material and the production of the amorphous polished layer occur simultaneously although to different extents. Thus in the coarsest grinding there is removal of material and only very slight surface flow along the ridges between the concavities of the surface, since the cleavage flow over the depressed surfaces of the conchoidal fractures do not contribute except in the last stage, to the final surface.[1] As the abrasive becomes finer the splinters decrease in size and the material removed diminishes, while the amount of surface flow over the network of ridges increases.

If in the grinding process the flat grinding tool is so hard that it rides over the grains, the impacts would be more normal to the surface and undesirable cone fracturing would occur.

The finer the abrasive the harder may be the polishing tool. Lead, zinc, copper, aluminium, brass and cast iron

1 Some Notes on Glass Grinding and Polishing. J.W. French, Trans. Opt. Socy. Vol.XVII, No.2, Nov. 1916.

have all been used for various kinds of work and various abrasives, but fine grained cast iron and brass, free from surface defects are most generally, and indeed almost universally, employed. Steel is too hard for even the finest grades of abrasive. After the surface has been ground to the necessary degree of fineness, polishing may be commenced, the purpose of the process being to promote the greatest possible amount of surface flow while avoiding the conchoidal splintering characteristic of the grinding process.

A very small amount of material is removed during the polishing action, but the nature of the abrasion, if it can be so termed, is characteristically different from that during the grinding. Minute grooves are ploughed through the amorphous surface layer and small portions of the amorphous substance become disengaged by the action of the polisher and are removed. These fragments may be recovered by dissolving away the rouge and resinous substances. The residue has a sparkling snow-like appearance consisting of extremely minute unresolvable particles cemented loosely together possibly by surface fusion along their edges.

A clear distinction must be drawn between a polished surface and one that is at the same time optically regular. This will be more easily understood by considering the action of a cloth polisher as compared with that of a pitch polisher.

Suppose in Fig.12, A is the fine ground surface greatly magnified composed of flat elementary areas with numerous conchoidal depressions. A surface of this kind is said to be grey, the appearance being due to the irregular reflection or scattering of the light. B is a layer of soft cloth or felt cemented to the regular surface of the metal runner C, which may be of aluminium, brass or iron. Over the flat areas of A the drag, and consequently the reduction of the general level will be greatest. Over the surfaces of the depressed areas into which the felt partially sinks there will be a certain amount of drag and polishing action, combined with the removal of material not only from the flat portions but to some extent from the depressions also. There will be a general rounding off of the irregularities, but as is confirmed by practice, the irregularities cannot be eliminated

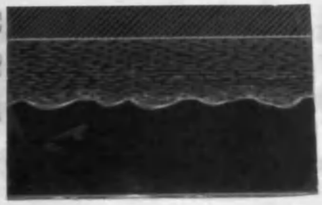


Fig.12.

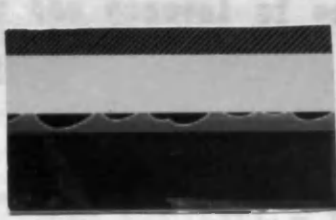


Fig.13.

Fig.14.

by the use of a soft polisher, although a small amount of original greyness is rendered less conspicuous to ordinary vision, and a false appearance of complete uniformity and polish may be produced more quickly by means of a soft polisher. Suppose a harder type of polisher such as a pitch polisher is used. When using the same polishing medium such as rouge, the amount of drag and polishing action over the flat portions will be greater than when using cloth, but the pitch will not sink into the depressions to the same extent and the rounding and particularly the removal of material from the depressed portions will be less.

When using a hard polisher a uniform polished surface free from all greyness is obtained by the removal of the surface material stage by stage until the surface is reduced below the level of the deepest conchoidal depression.(1)

Under the action of the polisher the disturbance of the surface molecules is such that they are able to rearrange themselves or flow with the consequent formation of a polished amorphous layer. Minute aggregations of the rouge or other medium plough away the surface layer, and it is

(1) Polishing of Glass Surfaces. Lord Rayleigh, Proc. Opt. Convention, Vol.I, 1905, p.75.

possible that there may be also some swaging action, material being removed from the higher portions and welded upon the adjacent depressed areas. As the amorphous material is removed in this way the underlying molecules are acted upon by the polisher and the process is repeated layer by layer, as indicated in Fig.18.

If rouge is employed in the last stage it is generally possible by special illumination of the surface to detect an open network of these fine grooves, but if no medium other than a very fine film of water is used for the final polishing operation, the presence of grooves will hardly be observable. When a surface of this kind is etched with hydrofluoric acid a network of grooves will reappear[1] and it has been assumed that just as in the case of metals the original grooves have been bridged over by the amorphous layer and are uncovered when the surface layer is dissolved away. Numerous experiments, however, seem to indicate

1 Interference bands and their applications. Lord Rayleigh, Royal Inst. March 24, 1893.

that the cohesion of the amorphous silicates is too small to permit of the bridging of the finest surface cracks that can be produced.[1] That the grooves produced during the rouge polishing stage become filled up during the final water polishing stage may be accepted without question. Thus it is probable that the groove A in the surface layer becomes filled up possibly in stages at each stroke in the manner indicated in Fig.14. On the assumption that the expenditure of energy upon a substance tends in general to reduce its chemical stability, it is to be expected that the material filling the grooves would be rapidly acted upon and that the grooves produced by etching are really reproductions of the original grooves. The course of the original grooves will in any case be indicated by a very fine groove B, which would be extended by the acid to form a deeper groove occupying the place of the original one.

The various stages in the grinding and polishing

1 Some Notes on Glass Grinding and Polishing. J.W. French, Trans. Opt. Soy. Vol. XVII, No.2, Nov. 1916.

of a glass surface may be summarised briefly as follows:-

1. The removal of material by the breaking away of splinters, the size of which is reduced in stages by the use of finer grades of abrasive.
2. The production of an amorphous or surface flow layer and the gradual removal of these layers by grooving as distinct from the splintering of the first stage, the removal of material being effected by means of a very fine abrasive or polishing material such as minute aggregates of particles of rouge.
3. The elimination of the grooves produced in stage 2 by the use of a continuous medium such as a film of water in place of the discontinuous medium such as rouge, there being during this stage the maximum production of surface flow and practically no removal of the surface layer material and no splintering action whatever.

An abrasive to be effective must possess several well defined characteristics. The grains which must be hard should have an irregular form presenting many strong edges or rounded points that will transmit the impact forces to the glass to be abraded. When the grains break down the fragments should be of the original form in order that the action on a finer scale may be continued. An abrasive that breaks down into lamellar fragments is said to lose its cut. Diamond, fragments of which are illustrated in Fig.15, is the most effective of abrasives, but owing to its cost it can only be used for special operations such as the slitting of glass where the quantities are small.

Carborundum (SiC) is a compound of Carbon and Silica, resulting from the fusion of carbonaceous materials such as coke or charcoal with sand in the electric furnace at a temperature of about 2000°C. Its hardness on Mohs scale is about 9, diamond being 10. From Fig.16 it will be seen that the grains are of the desired shape which is retained as they break down.

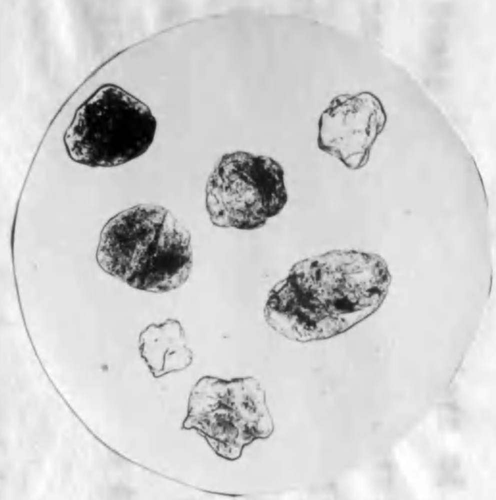
Other important abrasives are obtained by the combination of alumina and silica in the electric furnace, such for example, as Corundum, Alundum and Aloxite. They are most commonly employed in the form of grinding wheels. As loose abrasives they are not so effective as Carborundum.

Diamond
Magn. 16 diameters

Fig. 15.

Carborundum
Magn. 48 diameters

Fig. 16.



Sand
Magn. 48 diameters

Fig. 17.

Emery is a natural form of artificial Corundum, being a silicate of alumina containing, however, oxides of iron and other impurities irregularly distributed. It breaks down more readily than Carborundum and loses its cut. The loss of cut is only temporary, however, as after washing, the material can be used as a finer grade of emery.

Sand is frequently used for rough abrasion more particularly in establishments where no facilities exist for the washing and recovery of the more expensive types of abrasive. Its grains are frequently rounded and water-worn as indicated in Fig.17 and it readily breaks down and loses its cut.

Separation of an abrasive into the various grades of fineness is generally done by a process of settling and levigation. Thus three minute emery is the material obtained from the liquid that is decanted after a settling period of three minutes. For Carborundum it is necessary to use sieves of various finenesses in conjunction with settling except in the finest stages for which sufficiently fine sieves are unprocurable.[1]

1 The Grading of Carborundum for Optical Purposes. J.W. French, Trans. Opt. Socy. Oct. 1917.

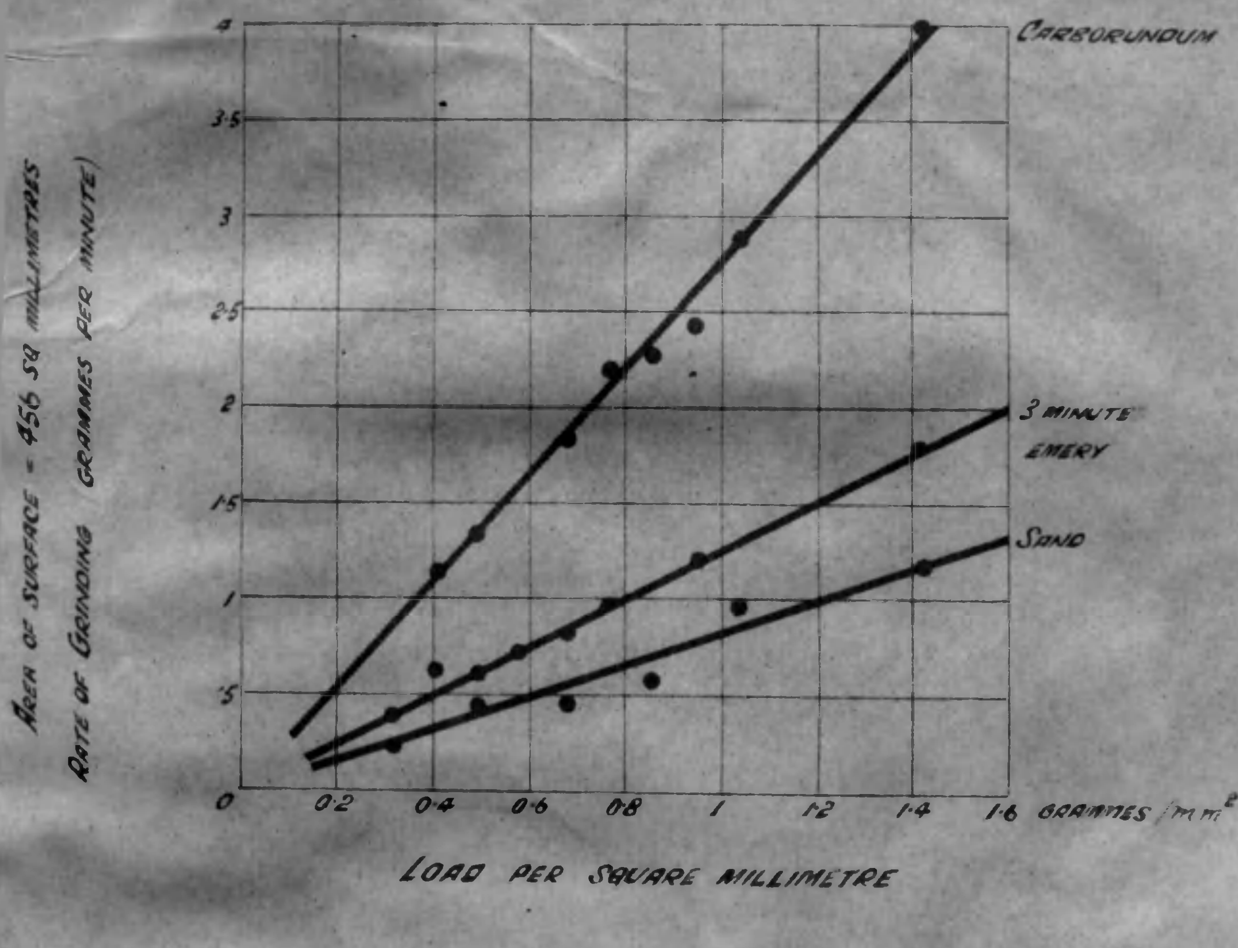

CARBORUNDUM
3 MINUTE EMERY
SAND
AREA OF SURFACE = 456 SQ MILLIMETRES
RATE OF GRINDING (GRAMMES PER MINUTE)
LOAD PER SQUARE MILLIMETRE
GRAMMES /mm²
0
0·2
0·4
0·6
0·8
1
1·2
1·4
1·6
·5
1
1·5
2
2·5
3
3·5
4

FIG. 18

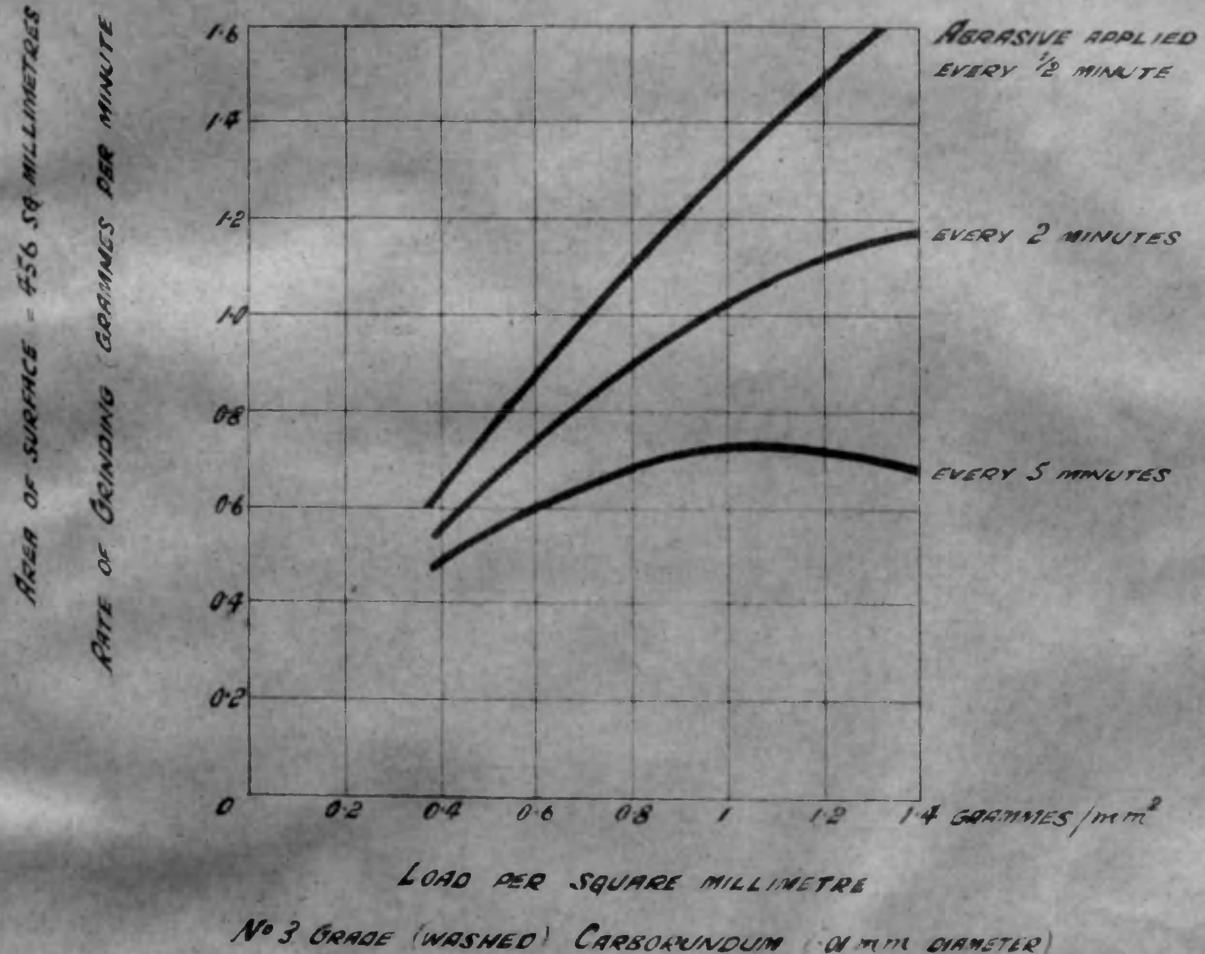

AREA OF SURFACE = 456 SQ MILLIMETRES
RATE OF GRINDING (GRAMMES PER MINUTE
1·6
1·4
1·2
1·0
0·8
0·6
0·4
0·2
0
0·2
0·4
0·6
0·8
1
1·2
1·4 GRAMMES/mm²
ABRASIVE APPLIED EVERY ½ MINUTE
EVERY 2 MINUTES
EVERY 5 MINUTES
LOAD PER SQUARE MILLIMETRE
No 3 GRADE (WASHED) CARBORUNDUM (·01 mm DIAMETER)

FIG 19.

A comparison of the abrasive powers of Carborundum, Emery and Sand of approximately equal size of grain is obtainable from Fig.18, which also shows how in the case of each abrasive the rate of abrasion is directly proportional to the pressure when fresh abrasive is supplied continuously.

If the abrasive is not frequently renewed, the rate of grinding would not increase regularly with the load owing to the loss of cut and a certain clogging action, especially at the higher pressures. This is illustrated in Fig. 19, from which it will be seen that when using No.8 Carborundum having a grain diameter of 0.1 mm. the rate of abrasion is directly proportional to the load when fresh material is applied every half minute, whereas there is actually a reduction of the rate at high loads when the intervals between the applications are of five minutes duration.

The series of curves in Fig.20 show how the rate of abrasion varies with the size of the grains and the load on the tool. Fresh abrasive was applied every half minute and it will be seen that for the coarsest No.1 Carborundum

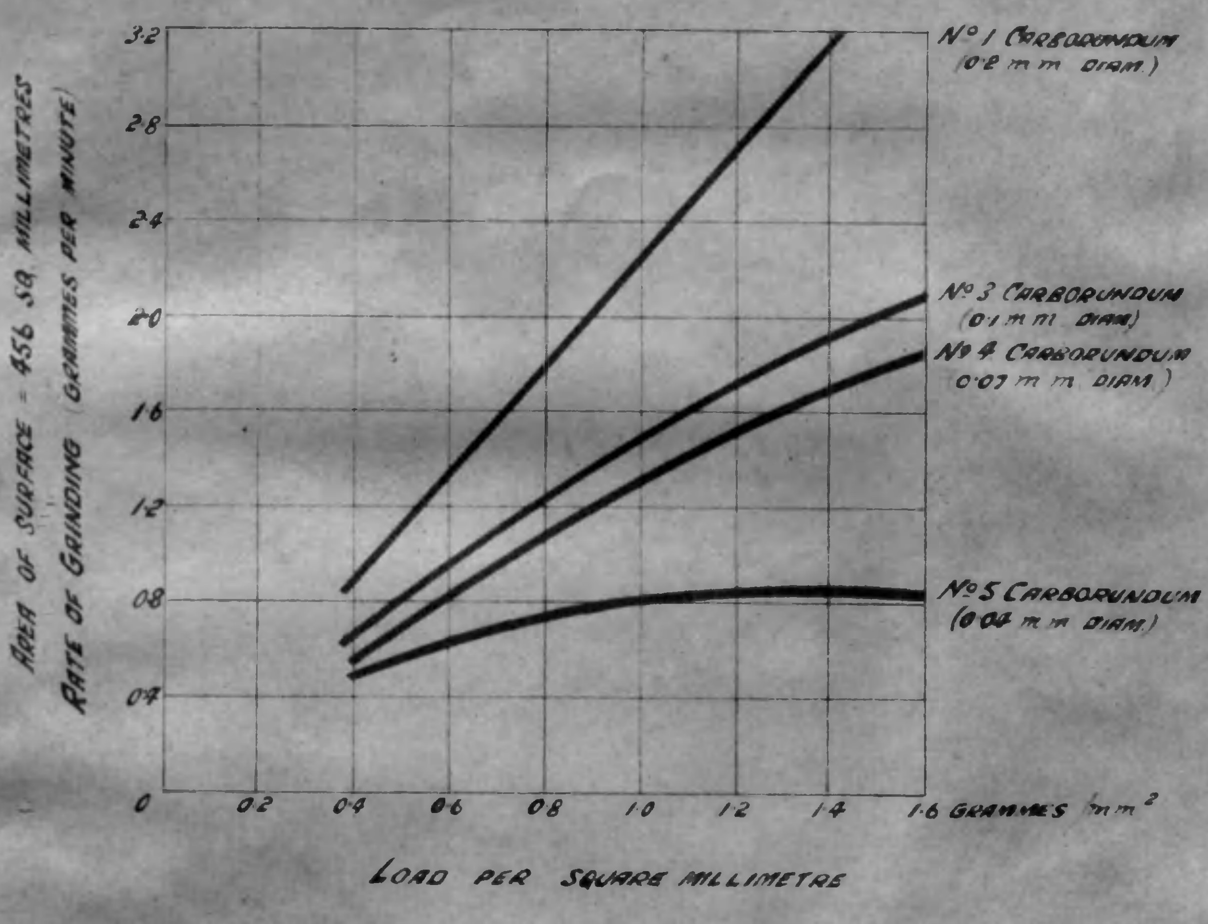

AREA OF SURFACE = 456 SQ. MILLIMETRES
RATE OF GRINDING (GRAMMES PER MINUTE)
3·2
2·8
2·4
2·0
1·6
1·2
0·8
0·4
0
0·2
0·4
0·6
0·8
1·0
1·2
1·4
1·6 GRAMMES/mm²
LOAD PER SQUARE MILLIMETRE
Nº 1 CARBORUNDUM (0·2 m m DIAM.)
Nº 3 CARBORUNDUM (0·1 m m DIAM.)
Nº 4 CARBORUNDUM (0·07 m m DIAM.)
Nº 5 CARBORUNDUM (0·04 m m DIAM.)

FIG. 20.

having a grain diameter of approximately 0.2 mm. the abrasion is directly proportional to the load. In the case of the Carborundum grades 3, 4 and 5 the curve bends at the higher loads suggesting the need for more frequent renewal of the abrasive, due possibly to clogging arising from an admixture of glass powder in these intermediate grades.

A similar series of abrasive curves for 3 minute, 15 minute and 40 minute emery is illustrated in Fig.21. Between the 8 and 15 minute curves there is a considerable interval which corresponds however, with the grain dimensions, which are 0.13 mm. and 0.01 mm. respectively.

From the various diagrams it will be evident that the rate of abrasion of a particular type of glass depends upon:

The nature of the abrasive.

Its grade of fineness.

The load upon the tool.

The relative speed and to some extent the frequency of renewal.

The material of the tool itself which has some bearing on the rate of abrasion is practically determined by the type

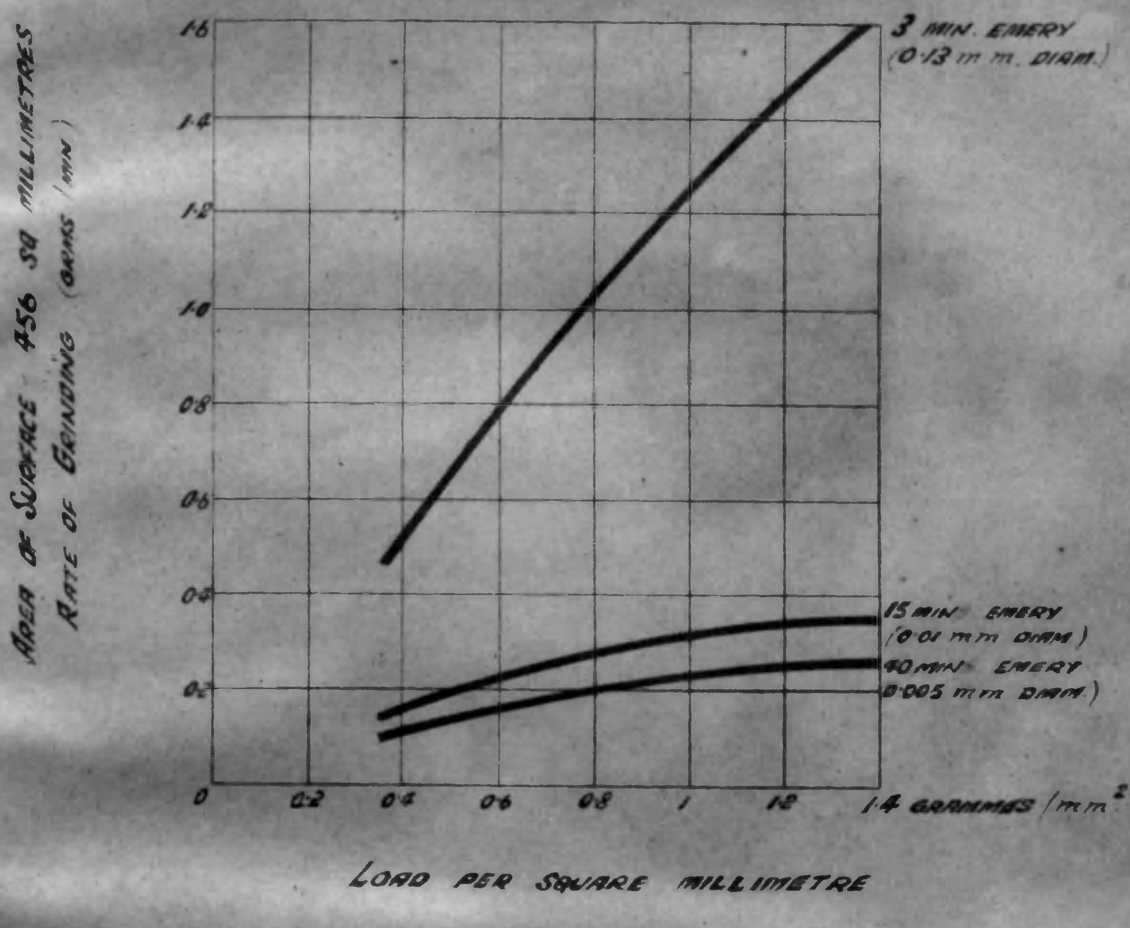

AREA OF SURFACE 456 SQ MILLIMETRES
RATE OF GRINDING (GRMS / MIN)
1·6
1·4
1·2
1·0
0·8
0·6
0·4
0·2
0
0·2
0·4
0·6
0·8
1
1·2
1·4 GRAMMES / mm²
3 MIN. EMERY
(0·13 m m. DIAM.)
15 MIN. EMERY
(0·01 m m DIAM)
40 MIN. EMERY
0·005 m m DIAM.)
LOAD PER SQUARE MILLIMETRE

FIG 21.

of abrasive, the materials of widest application being fine grained cast iron and brass.

Rates of abrasion afford a general but not definite idea of the quality of a ground surface, because the same weight of material may be removed by the production of large shallow splinters or by smaller and correspondingly deeper ones. In the grinding process it is sought to produce a surface of uniform texture free from isolated deep pits which often determine the thickness that must be finally removed. A record of the texture may be obtained by observing the reflecting power of the ground surface.[1] If the surface is viewed so obliquely that the irregularities are foreshortened to such an extent that even the largest red rays are reflected, a perfect white image of say, an incandescent filament may be seen reflected from the surface. The image may be as clear and distinct as if viewed by means of a polished silver mirror. As the

1 More Notes on Glass Grinding and Polishing. J.W. French, Trans Opt. Socy. Vol.XVIII, 1917.(Jan)

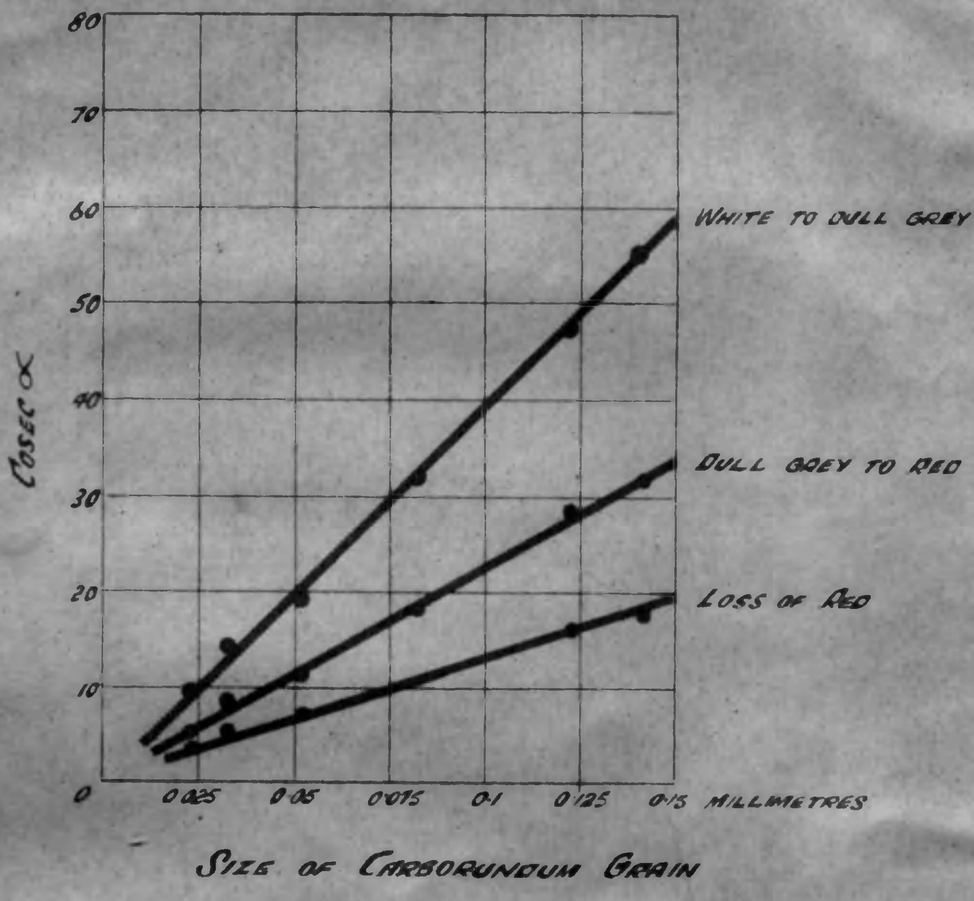

80
70
60
50
40
30
20
10
0
COSEC α
WHITE TO DULL GREY
DULL GREY TO RED
LOSS OF RED
0·025
0·05
0·075
0·1
0·125
0·15 MILLIMETRES
SIZE OF CARBORUNDUM GRAIN

FIG 22.

reflecting plate is rotated so as to decrease the angle of incidence, there will be observed an apparently abrupt change from bright white to dull grey, followed at a smaller incident angle by a change to red, which later suddenly disappears. These three changes take place sufficiently rapidly to provide a general record of the surface. Thus in the case of a piece of hard crown glass, ground with three minute emery, the respective angles of incidence , which can be repeated to within half a degree, were 80°, 78°, and 75°. For similar glass ground with an abrasive wheel, the corresponding figures were 66°, 61°, and 46°, thus indicating a much finer texture. In Fig.22 which gives a comparison of the surfaces produced by a series of carborundum abrasives, abscissae represent the size of the respective grains and ordinates the cosecants of the angle between the surface and the line of sight. This is equivalent to the projection of the texture in a plane normal to the line of sight, thus enabling the irregularities to be compared directly with the lengths of the waves regularly reflected. As it to be expected from the previous abrasion diagrams the curves are straight lines, the projected dimensions of the texture being directly proportional to the size of the grain when the other conditions such as load and speed are maintained constant throughout.

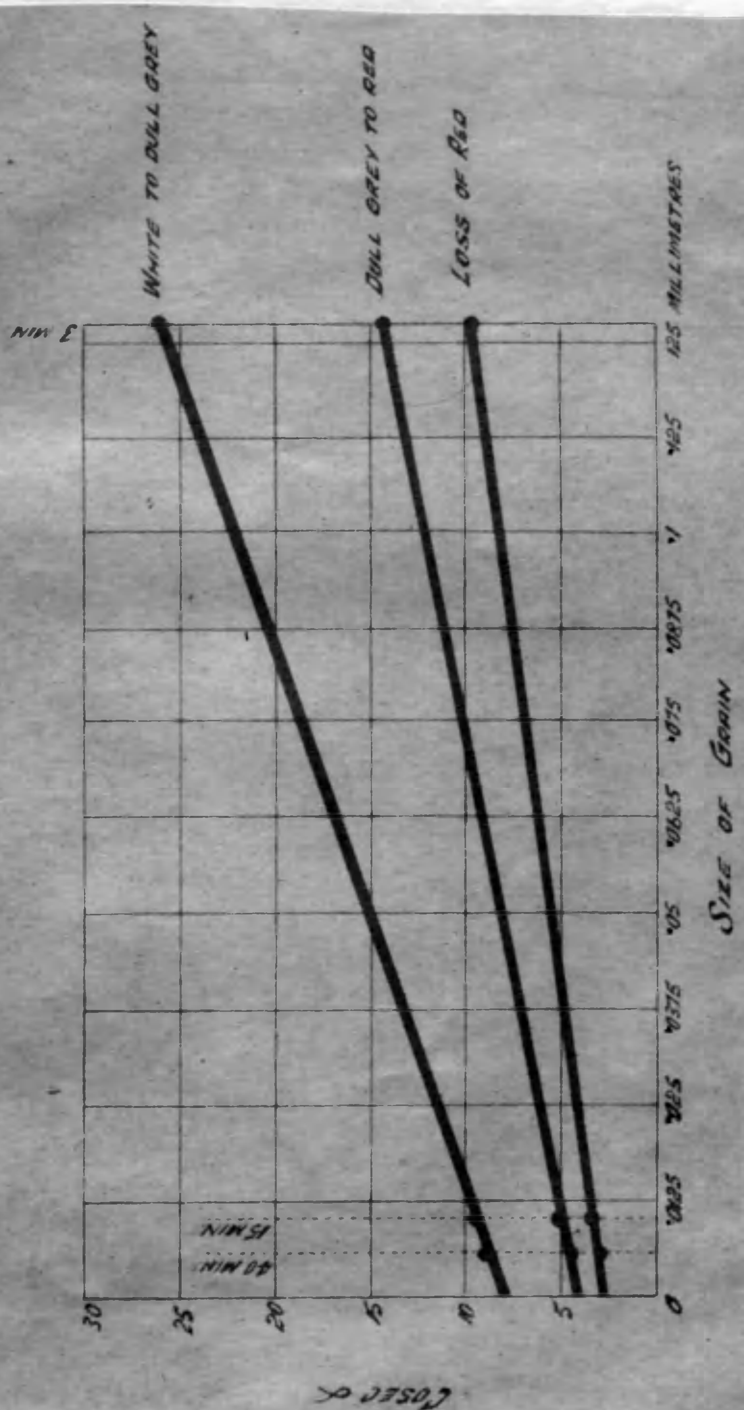


FIG 23

constant throughout.

Fig. 23 shows the corresponding results obtained when using the three grades of emery commonly employed, namely 8 minute, 15 minute and 40 minute emery. If the conditions can be controlled with sufficient accuracy similar straight line curves may be obtained for most abrasives, but in the case of such abrasives as powdered glass which break down readily and lose their cut, the conditions cannot be easily controlled and the curves generally fall away towards the coarser grades.

Smoothing operations in the case of a single piece may be regarded as a continuation of the rougher grinding processes, their purpose being to reduce as much as possible the amount of material that has to be removed in the polishing process, but when a number of pieces after being formed are mounted in one block so that they may be polished together, the smoothing process preparatory to polishing is necessary in order to reduce any irregularity of the surface levels due to slight errors in the laying down of the pieces.

Whether the surface desired is plane or curved the final form of the piece must be produced before the polishing operation is commenced. Any important alteration of the form is impracticable during the polishing process the functions of which are the formation of the brilliant amorphous light reflecting surface layer, and the production of a true figure, that is, the correction of minute errors of form not exceeding one or two wave lengths over the whole surface. Greater errors of form must be corrected by a repetition of the smoothing or fine grinding operation.

Almost any substance in a fine enough state of division and provided its grains are not lamellar in form or soluble in the liquid employed or liable to weld upon the surface of the glass, may be used as a polishing medium. Thus glass can be polished readily with fine charcoal but hardly at all with graphite.

But in practice the choice may be limited to a very few substances the principal of which is rouge, that is oxide of iron (Fe_2O_3). Many substances are slow in their polishing action. Putty powder, that is tin oxide (SnO_2), which at one time was extensively used, is now excluded for reasons of health.

Manganese dioxide (MnO_2), although an excellent medium is very black and is difficult to remove from the hands and clothing; from the point of view of general cleanliness its use is often avoided. Other media again cannot be obtained in a consistently uniform condition, and although the variety of substances is great, there are really few that have all the advantages of rouge which is so extensively used, except for the very cheapest kinds of optical work. Comparisons of the polishing media can only be made if the conditions are carefully standardised, and particularly if the texture of the original smoothed surface is the same in all cases. The rate of polishing, so far as polishing is determined by the removal of material until the bottoms of the deepest depressions are reached, depends upon:-

The original state of the smoothed surface.

The character of the polishing tool surface, which may be, for example, of cloth, pitch, wax or paper.

The polishing medium.

The lubricant.

The load.

The relative speed of the tool and the surface operated upon.

The typical chart, Fig.24, shows how the time of

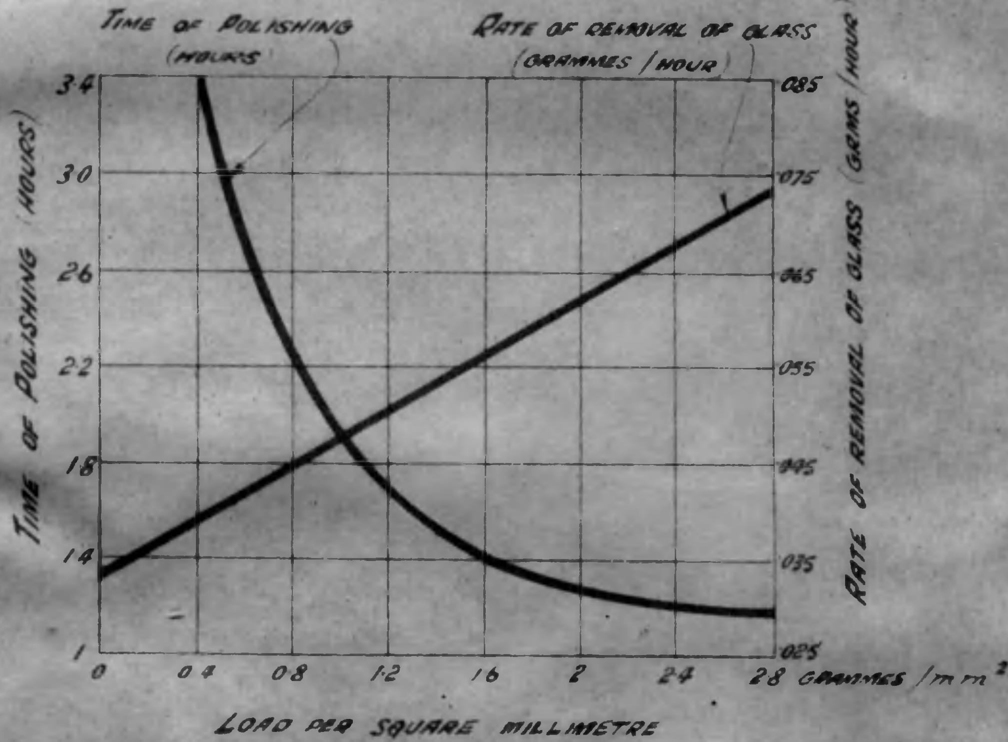


FIG. 24

The relative speed of the tool and the surface operated upon.

The typical chart, Fig.24, shows how the time of polishing and the rate of removal of glass are affected by the load on the tool. In this particular instance the rate of removal of material varied directly with the pressure, the tool being covered with a mixture of 95% of beeswax and resin and 5% pitch.

It is not possible to make any definite comparison of the numerous substances that may be used as polishing media because the results are greatly influenced by the conditions. Substances that are only moderately good when a pitch polisher is used may be much more effective when the polisher is of a different type, such as cloth.

To obtain consistent results it is also very necessary to control the conditions, the most important being the original state of the smoothed surface to be operated upon.

Table I shows the times of polishing when using a variety of typical polishing materials under the particular conditions specified. In all cases the original surface was smoothed with fine carborundum having an average grain diameter of about $^{1}/200$ mm., the reflection values of the surface being 10° grey, 16.5° red, and 26° loss of red. Pitch polishers were used throughout.

Table I.

Machine type - Reciprocating arm.

Revs. of spindle - 78 r.p.m.

Speed of arm - 190 strokes per minute.

Length of stroke - 1.25".

Diam. of worked surface - 8".

Diameter of polisher - 8".

Load on polisher - ½ lb. per sq. inch.

Medium	Polishing time	Quality
Precipitated rouge	8 hours	Good polish
Commercial rouge	4 "	" "
Glassite (MnO_2)	4.1 "	" "
Very fine carborundum	8 "	Fair
Putty Powder (SnO_2)	11 "	Surface cut and not good
Precipitated Silica (SiO_2)	12 "	Surface not good
Precipitated Chromium Oxide (Ch_2O_3)	14 "	" " "

Medium	Polishing time	Quality
Precipitated Alumina (Al_2O_3)	14 hours	Surface not good
Precipitated Ferrous Carbonate	16 "	Very slightly grey
Precipitated Hydrous MnO_2	22 "	" slightly grey

Putty Powder and the various precipitated media are better suited to cloth polishers than to pitch polishers, but the superiority of the first three media is still marked when used on cloth.

Very many substances have been used as a covering layer for the polishing tool to hold the polishing medium.

Huyghens[1] polished his glasses upon the metal tool itself, using a specially prepared mixture of Tripoli as a medium, which was reduced to a firmer and finer state by wiping away the marginal portions from time to time.

1 C. Hugenii, Opera Reliqua, Vol.99, p, 218, and Smith's Optics.

To Sir Isaac Newton[1] is attributable at least the suggestion that a pitch layer might be used for the polishing operation. In his Opticks he states that:- "An object glass of a fourteen foot telescope made by one of our London artificers I once mended considerably by grinding it on pitch with putty and leaning very easily on it in the grinding, lest the putty should scratch it. Whether this way may not do well enough for polishing these reflecting glasses I have not yet tried."

It is quite clear from a previous paragraph[2] that Newton actually used pitch for both the grinding and the polishing of metal reflectors for in the same work he states:- " Then I put fresh putty upon the pitch and ground it again till it had done making a noise, and afterwards ground the object metal upon it as before, and this work I repeated until the metal was polished, grinding it the last time with all my strength together for a good while,

1 Newton, Opticks p. 78
2 Newton, Opticks p. 77.

and frequently breathing upon the pitch to keep it moist without laying on any more fresh putty." The application of water alone in the final stage is of particular interest as being an important detail of present day practice.

Father Cherubin[1] lined his polishing tools with a variety of materials of fine and uniform texture. More particularly he refers to the use of very fine thin leather, fine English fustian, fine holland or any fine linen, silk taffety or satin. He describes at great length the process of lining the tools with paper and the method of removing little lumps or irregularities, but the previous use of paper is attributable to Antheaulme[2] who used the grinding tool itself when lined with paper as the polishing tool, the medium employed being Venetian Tripoli.

At the present day pitch, wax compounds and cloth are the materials most commonly used. Comparisons of a variety

1 Le Père Cherubin, La Dioptrique Oculaire, 1671. Part III, Chap. II.

2 Montucla, Histoire des Mathématiques, Vol. III, Part V, Book II, p. 498.

of materials when using a particular polishing medium can be obtained from Table II which shows the time required to polish a piece of crown glass smoothed in all cases to the same standard. For the purposes of comparison comparatively slow speeds and loads were employed. From the previous diagrams it will be understood that the time of polishing would be reduced by increasing these factors, and the relative positions of the various materials might be slightly modified by the use of another polishing medium such as putty powder.

Table II.

Surface layers of polishing tools

Material worked - Glass - Hard Crown.

Surface smoothed with - Fine Carborundum, diam. of grain about 1/200 mm.

Spindle speed - 124 to 130 r.p.m.

Arm speed - 100

Stroke 1.25"

Polishing medium - Rouge and water.

Polisher	Time of polishing Hours	Remarks
90% pitch with 10% beeswax and resin	1.5	Good surface
Very hard pitch	1.75	Fair surface, pitch hardness 0.5 at 37°C.
Beeswax and resin with 10% pitch	1.75	Good surface
Pitch 70% with 30% rubber compound	2	Good surface
Pitch 70% with 30% rouge	2	Fair surface
Soft pitch	2.75	Good surface, pitch hardness 16 at 36°C.
Ebonite with 10% pitch	3.5	Polished, but cut, contact obtained with difficulty.
New cloth	4.5	Good surface
Well singed cloth	6	Poor surface, cut.
Cork	6	Fair surface, slightly cut owing to bad contact.
Wood, deal	6	Cuts owing to difficulty of obtaining good contact
Brown paper, secured with beeswax and resin	6	Fair surface
Very thick felt	12	Surface grey and mottled.

Hand Polishing

Fig. 25.

Since the time of Newton over two hundred years ago, hand polishing methods as practised to some extent in most highclass workshops have remained unaltered, except possibly in so far as the materials employed are more uniform in quality.

Some idea of the essentials of the actual flat or prism surface polishing operations may be obtained from Fig.25. The pedestal (1) which must be rigid has at its upper end a standard nose piece upon which the tools may be screwed. Under the work bench there will be observed two flat tools (2) and (3) of close grained and well annealed cast iron, and on the bench another (5) lying face downwards and with a wooden operating knob screwed into the boss. On the pedestal is mounted the tool or runner (4) as it is called, which has a uniform flat surface layer of pitch, and on the bench there is a similar runner, (11) the pitch surface of which is exposed to view.

Three plane tools are necessary for the production of an optically flat surface; if two are ground together the respective surfaces will become convex and correspondingly concave, the tendency in practice being for the upper tool to become concave. If one of these tools, say the convex No.1 is then ground with No.3 tool, the latter will become correspondingly concave, more or less like No2. If then the two concave tools Nos.2 and 3 are ground together, their concavities will both be reduced. By grinding No.1 on No.2, then one on three, and two on three in this way, and repeating the sequence of operations as long as may be necessary, all three tools become optically flat and may be kept in this condition by an occasional repetition of the process.

Sir Joseph Witworth's name is generally associated with this method which he applied to the production of standard surface tables, but although the principle may not previously have been clearly expeessed, the method appears to have been known to the earlier opticians.

The work is ground or smoothed upon one of these metal tools, fine grades of carborundum or emery being used as the abrasive medium. It is essential that the surface should be ground and smoothed to the desired curvature or flatness as the time of polishing depends upon the perfection of the smoothing operations. Removal of material during the polishing process occurs very slowly and it is then impracticable to effect an alteration of the shape other than a change of the figure involving a removal of material to a depth of a few wave lengths.

For the polishing process the surface of the metal runner, which itself need only be approximately true, is covered with a layer of pitch about 1½ mm. thick, the runner being heated gently to ensure good adherence. The pitch surface is then moulded by one of the flat tools that has been heated just sufficiently to soften the pitch upon which it is pressed. When the pitch is cold, the whole surface is divided into small squares by deep grooves which may be cut more cleanly under water when the pitch is of a brittle type. Over the pitch surface there is then stretched a piece of open texture muslin which is squeezed into the pitch by means of the hot flat tool, and is then peeled off, leaving its network impeession on the surface.

While the deep grooves help to preserve the flatness by breaking the continuity of the layer and thus preventing the centre parts from being squeezed towards the periphery, their principal function as well as that of the fine network is to destroy the suction that would hinder the free movement of the work over the moist pitch surface.

The grooves also serve to retain any excess material that otherwise might collect and produce sleeks, that is, minute furrows on the surface of the work, or even cuts.

After the pitch surface has been prepared in the manner described, it is rubbed with one of the optically flat metal tools until it also is optically flat. Rouge and water are commonly used as the working medium, not only in the preparation of the pitch surface but also in the operation of polishing the work.

By means of the soft brush (7) fine well levigated rouge and water from the pot (9) are laid in streaks on the pitch surface of the tool (4), and the harder brush (6) is employed to spread the medium uniformly over the whole surface upon which the part to be worked is laid, the sponge (5) being used throughout the operations to wash away excess material from around the edge of the tool.

The operator whose attitude is illustrated in Fig.25 controls the work around its periphery by means of the fingers and thumbs and, while gently pressing it into contact with the pitch surface, he moves it to and fro. At frequent intervals after a few such repeated strokes the work is given a wide sweeping movement over the pitch surface and is occasionally rotated. At intervals the operator also steps round the pedestal, or alternatively the lower tool may be slowly rotated.

The purpose of these movements is to avoid any regular repetition of strokes that would tend to local wear of the tool or work, and the production of irregular surfaces. If the to and fro movements in one direction were repeated for too long a time, a broad depression would be formed on the tool surface, the optical flatness of which would accordingly be destroyed.

From time to time the pitch surface is reworked or formed by means of the metal tool (5), the flatness of which is preserved by occasional working with the tools 2 and 3. Towards the end of the process water only is used as a polishing medium and the operation is continued until the water is almost entirely dried up, which is evidenced by a characteristic squeaking noise. In this way the greatest possible viscous flow of the surface molecules is obtained owing to the close contact between the work and the polishing tool.

Surface defects such as sleeks are detected by examining the surface with a low power lens, the necessary illumination being obtained from the lamp (10). Defects of flatness are detected by means of the test plate (12) which is placed on the surface of the work lying upon a black cloth. It is essential that the temperature of the parts should be allowed to equalise before attempting to form a definite decision as to the character of the surface under test, and before using the test plate the parts should be thoroughly cleaned with a linen cloth or selvyt (13) and also freed from dust by means of the soft brush (14).

At night it is convenient to use Mercury Vapour lamp light which is approximately homogeneous and produces black interference rings that may be very readily observed.

Much skill is necessary to obtain the correct figure or form of the polished surface within the limits essential to the production of well defined images and each operator has his own particular method of controlling the figure. Two methods are frequently employed. In hand work with the tool below the glass if the surface becomes concave the stroke should be reduced within the limits of the polisher. If the surface becomes convex the stroke should be widened until the defect is corrected. On machine work with the tool above the work, these operations should be reversed, a wide stroke, and especially one that overlaps the polishing tool being employed to reduce any concavity of the surface.

In the case of large surfaces such as are usual in machine multiple work, the position of the polishing tool may be so altered that it acts more around the periphery or over the centre ar may be desired to correct the figure.

The second method consists in ringing the tool, that is, in broadening the furrows or scraping the surfaces, and thus reducing the effective polishing area at the centre or towards the edge according to the requirements.

Thus, suppose a block of concave lenses is too shallow. To correct the figure it is necessary to remove material from the centre. This may be done by lengthening the stroke of the block so that at the ends of the travel it overlaps the polishing tool with the result that for a portion of the time, the outer parts, as compared with the centre, are not acted upon and are not reduced to the same extent; or the outer portion of the polishing tool may be reduced by scraping, or the effective surface reduced by ringing so as to increase the relative effect of the centre parts.

A polisher that has been used for a considerable time often becomes glazed and loses its effect, so far as the removal of glass is concerned but not as regards the actual polishing action if the contact is good. It has been suggested that the glaze which may be readily scraped away is a more or less continuous layer of glass.(1)

Particular results are also obtained by a proper selection of the polishing layer.

In the case of pitch which should be a good quality of Burgundy pitch, the hardness must be varied by more or less prolonged boiling to suit the temperature and to some extent the nature of the glass and work.

(1) The Surface Layer of an Optical Polishing Tool.
J.W. French, Procs. Opt. Socy. Vol.XXV, No.5, 1920.

66A.

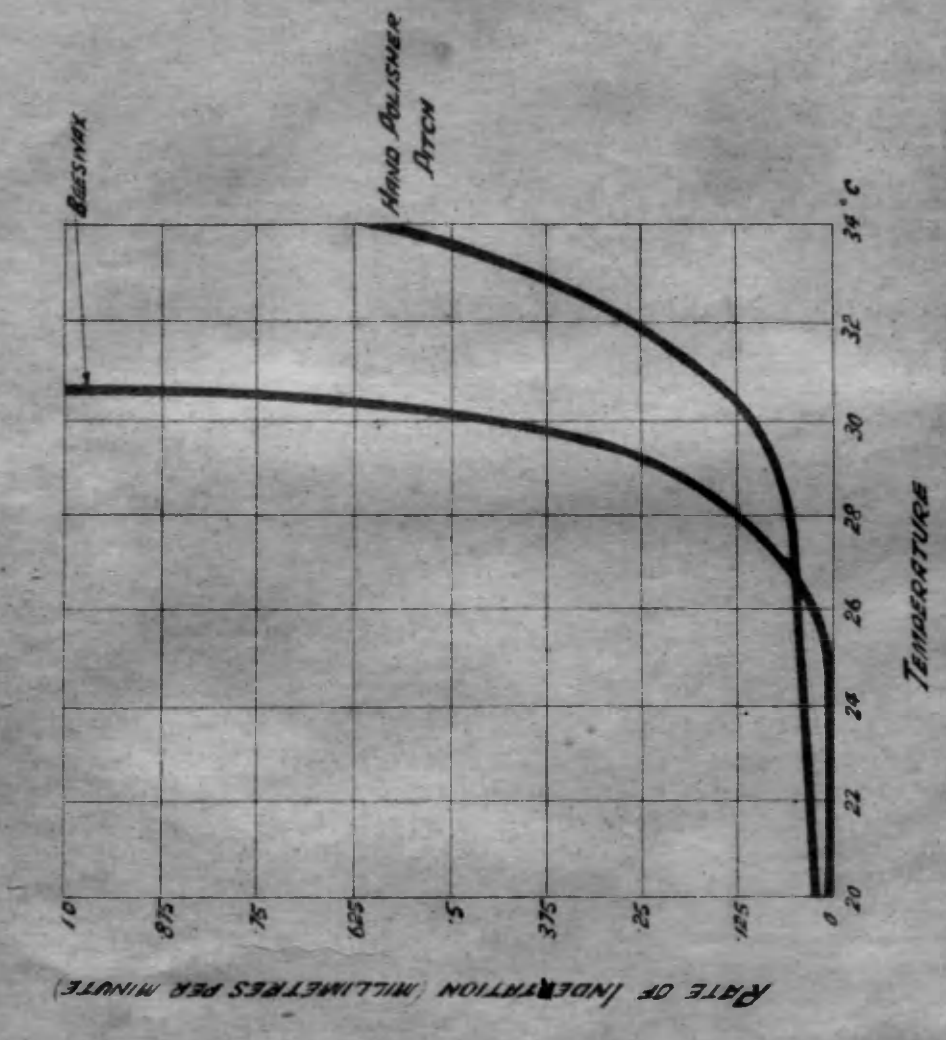
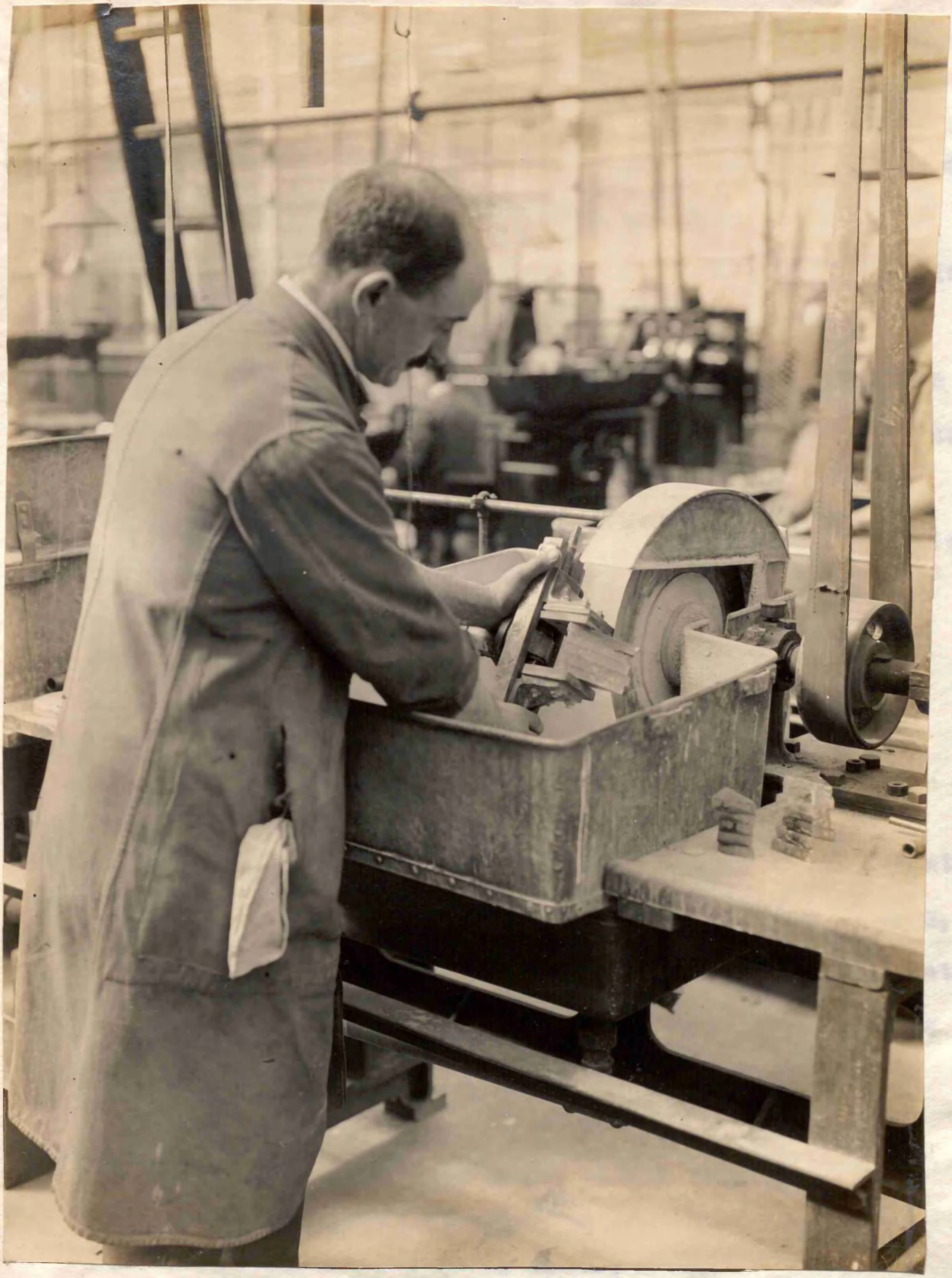

BEESWAX
HAND POLISHER PITCH
10
·875
·75
·625
·5
·375
·25
·125
0
20
22
24
26
28
30
32
34 °C
TEMPERATURE
RATE OF INDENTATION (MILLIMETRES PER MINUTE)

Fig 26.

Thus, unless the workshop temperature can be kept constant, which is not easy so far as the reduction of the maximum summer temperature is concerned, a hard well boiled pitch must be used in summer and a softer pitch in winter.

Some operators prefer the use of wax instead of pitch and particularly for the polishing of curved work.

From Fig. 26 it will be seen that there are character-istic differences attributable largely to differences in the viscosities of the materials. Abscissae represent temperatures and ordinates the rates of penetration of a steel disc under a constant load. Whereas the pitch yields even at the very low temperatures, very little change occurs in the beeswax-resin composition until a temperature of about 27°C is reached, when the viscosity rapidly changes. As the normal temperature of working rarely exceeds 22°C, it will be evident that wax layers are not so sus-ceptible to fluctuations of temperature as pitch layers. Wax therefore retains its shape better than pitch but its form is not so easily manipulated when a modification of the figure is desired, and the difficulty of obtaining good contact is greater.



Glass Saw.
Fig.27.

Only the very highest qualities of optical work or small quantities of individual parts are made by skilled hand methods. For the production of parts in large quantities considerations of cost make the use of machinery essential. Although highly specialised machinery has been evolved for the manufacture of particular products such as spectacle lenses,[(1)] there are certain well defined methods and types of machinery, a description of which alone will suffice to indicate the fundamental principles.

The processes may be divided into three groups:-

(a) Forming or Roughing

(b) Smoothing

(c) Polishing

Frequently the raw glass is supplied in the form of plates which are cut to the approximate shape by means of saws, as illustrated in Fig.27. These saws are thin sheet metal discs of a soft character. Iron armature stampings are very suitable for the purpose. The edge of the saw is

(1) Schule der Optik, Gleichen und Klein, 1914.
Praktischer Teil by Klein.

notched and charged with diamond dust mixed with olive oil to the consistency of a fine paste. In Germany it is common practice to cut deep radial peripheral slots about a millimetre broad and to fill these with lead which holds the diamond dust more effectively.

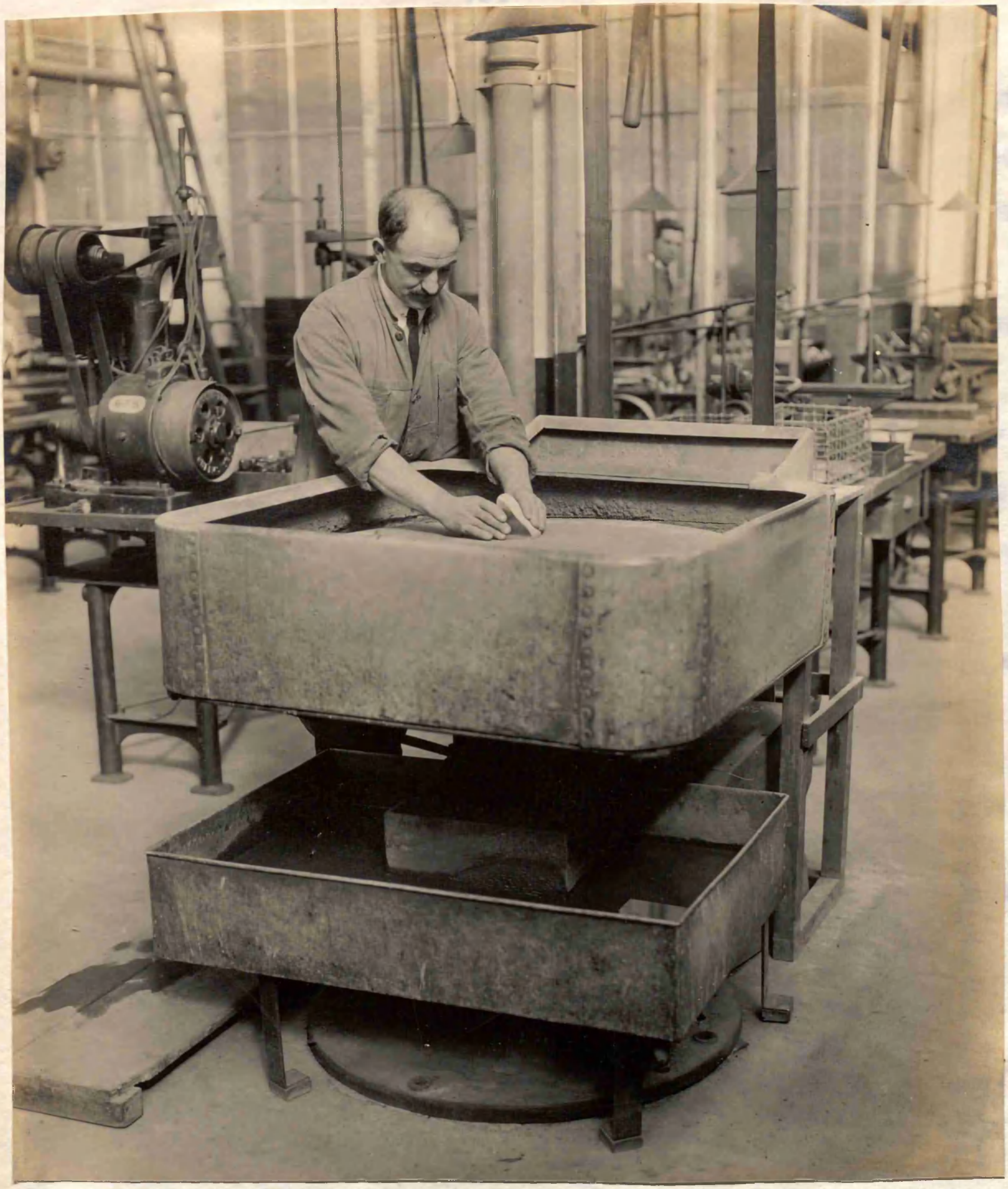
The work which may be a pile of plates held within the jaws of an adjustable holder is pulled by a weight against the cutting edge, the movement being controlled by the withdrawal of a screwed abutment.

Turpentine as a lubricant gives the best results, but it has the disadvantage of being costly. Petrol is very suitable. Water with a small admixture of soda to prevent rusting, although less effective, is commonly used.

An average peripheral speed of the saw is about 1200 feet per minute.

Labour and expense in cutting may be saved by the use of glass that has been moulded to approximately the correct shape and size, enough excess material only being allowed to ensure that when all the irregularities of the surface have been ground away the sizes will not be too small.

69 a



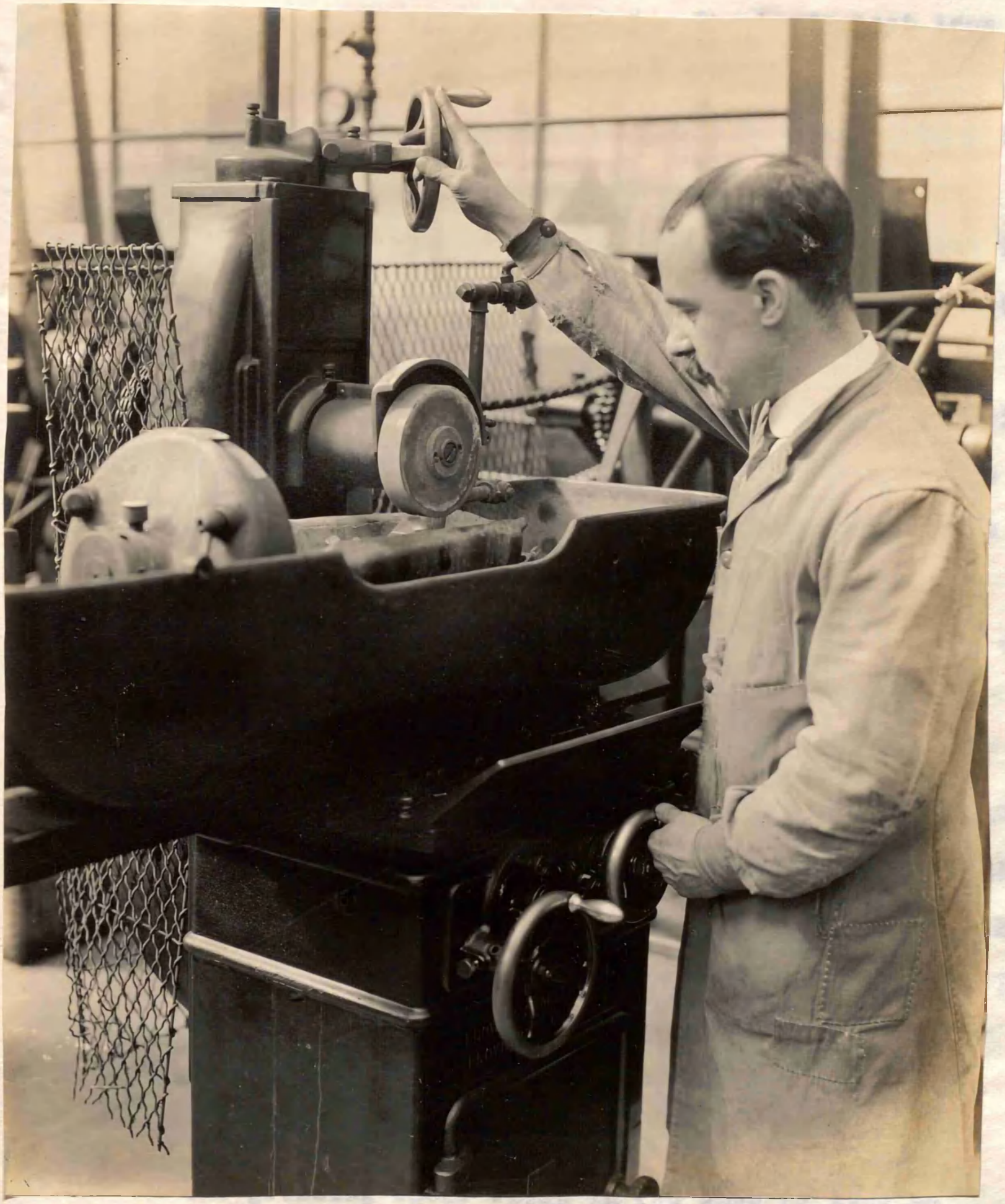
Rough Hand Grinding Disc
Fig. 28.

When the quantities involved are not large, the actual forming of the work to the required linear dimensions and shape within usually an angular limit of ± three minutes is sometimes done by hand, as indicated in Fig.25, the angles being tested by means of simple adjustable gauges,[1] or in the case of lenses, by disc gauges turned to the appropriate radius. For the roughest grinding, sand or coarse carborundum or emery may be used, the sand being cheapest but slowest in action. If a plant for the washing and grading of the abrasive is installed,[2] the use of a single type of abrasive such as carborundum, a coarse and cheap grade of which only need be purchased, is both economical and convenient.

When two abrasives such as carborundum and emery are employed for the coarser and finer grinding processes, great care must be exercised to avoid contamination of the

(1) Handbuch der praktischen Optik, by Halle, 1918.

(2) The Grading of Carborundum for Optical Purposes, Trans. Opt.Socy. Oct. 1917.



Carborundum Wheel Fine
Grinding Machine.
Fig. 29.

emery with the harder carborundum. The large cast iron grinding disc in Fig.28 which runs at a speed of about 250 revs. per minute serves the double purpose of breaking down the coarser abrasive preparatory to fine grading and of forming the heavier work. In the case of multiple work the cost of labour generally necessitates the adoption of grinding machinery, one type of which is illustrated in Fig.29. A number of parts are mounted upon an adjustable holder on the table of the machine, the holder being so arranged that it can be accurately angled in accordance with the indications of a scale. The table runs the work longitudinally under the grinding wheel and at the end of each stroke its motion is automatically reversed, the grinding being done during both strokes. At the end of each stroke the table is also fed transversely automatically or by hand. Either a heavy cut of about 1 mm. with a slow table speed, or a light cut of $\frac{1}{40}$ mm. with a fast cutting speed of 10 feet per minute may be used, but generally it is desirable to avoid the heavy forces incidental to a heavy cut.

The grinding wheel which is fed down by hand as required, is a fine grade carborundum type such as 220 J running at a peripheral speed of about 500 feet per minute.

An ample supply of lubricant such as water is essential to avoid all danger of the formation of minute heat cracks.

Milling cutters in the form of cylinders of copper, the surfaces of which are grooved longitudinally and charged with diamond dust, have been used by some of the more important German opticians, but such cutters appear to have been generally abandoned except for certain minor operations in favour of carborundum wheels.

Glass milling as compared with surface grinding has the disadvantage of being comparatively slow and therefore relatively costly. This will be evident when it is considered that there is only line contact between the wheel and the surface of the work which for the great part of the time is therefore not being acted upon, whereas in the case of surface grinding, material is being removed continuously from every part of the surface.

The grinding is usually done by means of a cast iron disc with loose abrasive, and the parts to be operated

Laying Down Process

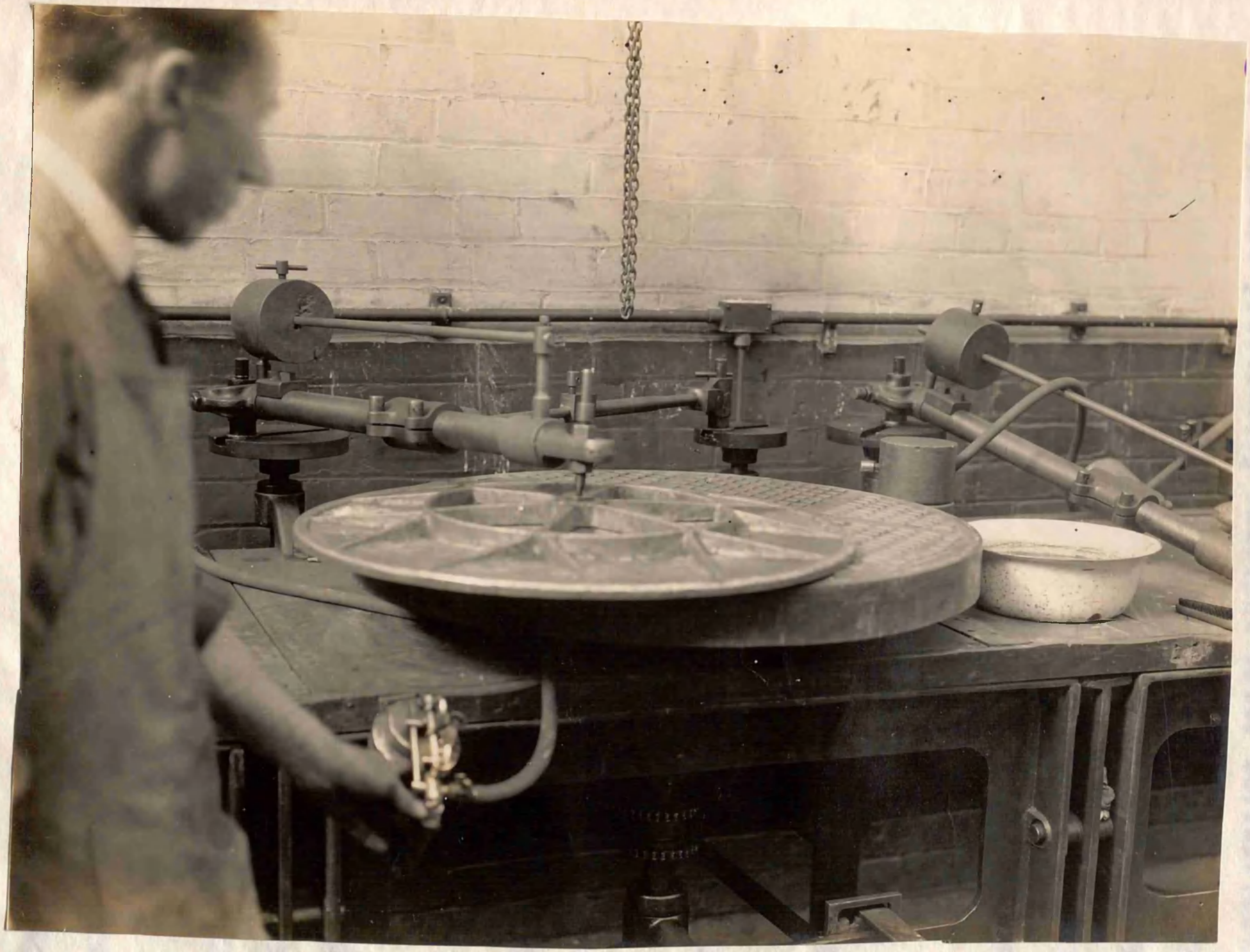
Fig. 80.

upon are mounted in accurate multiple jigs the expense of which can only be contemplated when the number of pieces to be manufactured is large.

As the work must be formed practically within the final inspection limits it is necessary that the machine should be capable of working to an angular limit of about 2 minutes and a dimensional limit of about $\frac{1}{10}$ mm. to $\frac{1}{40}$ mm.

After the individual parts have been formed to the exact shape they are submitted to the smoothing processes preparatory to being polished. For this purpose the faces to be polished are placed in contact with an optically worked tool, Fig.30, the surface of which has been thoroughly cleaned and slightly oiled. Care must be taken to ensure that the layer of oil between the surfaces of the work and the tool is uniformly thick. A very slight pressure on one end of the piece may suffice to introduce an angular error of a minute. With a little practice such errors even in the case of faces of a few centimetres length may be avoided.

Over the tool is then placed a circular frame work into which there is poured a layer of plaster of Paris of



Smoothing Machine

Fig.21.

about 8 mm. thickness. After the plaster has solidified the frame is filled with a special cement whose volume remains practically constant after solidification. Plaster of Paris and cements that contain free lime have the disadvantage that, owing to crystalline changes in the solid condition, the volume after solidification increases for many months, the growth being comparatively rapid during the first few weeks.

In such a case owing to this expansion, the smoothed surface of a cemented block of prisms tends to warp to an extent that may unduly prolong the polishing time, or even necessitate re-smoothing.

Plaster of Paris is suitable for blocks of 25 cm. diameter, and can be used for blocks of 50 cm. diameter if there is no delay between the smoothing and polishing processes and if the latter is completed rapidly and in one operation. For large blocks of 1 metre diameter such as is illustrated in Fig.81, special cements are essential.

The frame with the solidified cement containing the prisms is stripped from the oiled surface of the plate and when turned over the thin layer of plaster of Paris can be removed, leaving the surfaces of the prisms projecting from the layer of cement, the face of which is cleaned and varnished to make it thoroughly waterproof and to prevent fragments from breaking loose and interfering with the work of polishing. The thin layer of plaster of Paris has no appreciable ill effect as its thickness and time of action are both small.

For the actual smoothing operation a machine of the general type indicated in Fig.31 is employed, but although the principle involved is generally the same, the arrangements vary considerably.

In a machine tool for the working of metals or the forming of glass such as is indicated in Fig.29, the plane in which the work moves and the axis about which the tool rotates are both definitely fixed. The accuracy of the work is accordingly dependent upon the accuracy of the machine.

As the accuracy requisite for the polishing of an optically good surface is nearly ten times as great as is obtainable with the best type of machine tool, it is necessary for the manufacture of optical work to adopt the floating tool principle previously referred to in connection with the preparation of flat grinding tools.

In Fig.81 it will be seen that the flat grinding tool rests freely upon the surface of the work, the diameter of which is about 20% greater than that of the tool,(1) and that it is moved by a central pin resting in the hollow socket of the tool. For the actual movement of the tool various mechanisms have been introduced but that indicated in the illustration is the most common.

All the arrangements (2) are particularly designed to sweep the tool over the surface in a continually and widely varying path that only repeats itself after a great number of strokes, and further, to provide simple adjustments whereby the action of the tool may be distributed more or less over the central or outer zones of the work for the purpose of regulating the form or figure.

(1) Deutsche Mech. Zeit. Vol.9, 1909, p.81.

(2) Handbuch der praktischen Optik. Halle, 1918.

Behind the machine there are situated two vertical shafts each carrying at its head a crank pin the distance of which from the centre of rotation is adjustable. One crank drives the end of the main driving arm through the intermediary of a gimbal connection that enables the arm to be raised when necessary quite clear of the tool. The other crank similarly drives a radius bar coupled to the driving arm. As the throws of the crank are independently variable and as the point of connection of the radius bar with the driving arm is adjustable, a large variation in the path of the tool is obtainable. It is important that the revolutions of the crank spindles should not be a whole multiple of the work spindle revolutions. A hunting tooth should be introduced in the gearing, otherwise a portion of the surface will take longer to smooth or polish, thus increasing the time of the operation. By adjusting the length of the radius bar the tool may be made to act more over the periphery of the work, and the length of the stroke may be altered by a variation of the amount of throw of both cranks. These adjustments are necessary for the control of the form or figure of the work.

To determine by calculation the distribution of the grinding or polishing action over the surface of the work is very difficult and laborious. As was previously stated, the action is practically directly proportional to the relative speed of the tool and the work. When the tool is concentric with the rotating work, both rotate together and there is no relative movement or grinding action unless a partial brake is applied to the tool. As the tool passes from the centre towards the periphery its velocity varies and there is then relative motion of the tool and work and consequently abrasion. This rotation is always in the same sense as that of the work but it necessarily varies throughout the cycle, although the momentum of a heavy tool acquired when in the concentric position tends to make the rotation uniform.

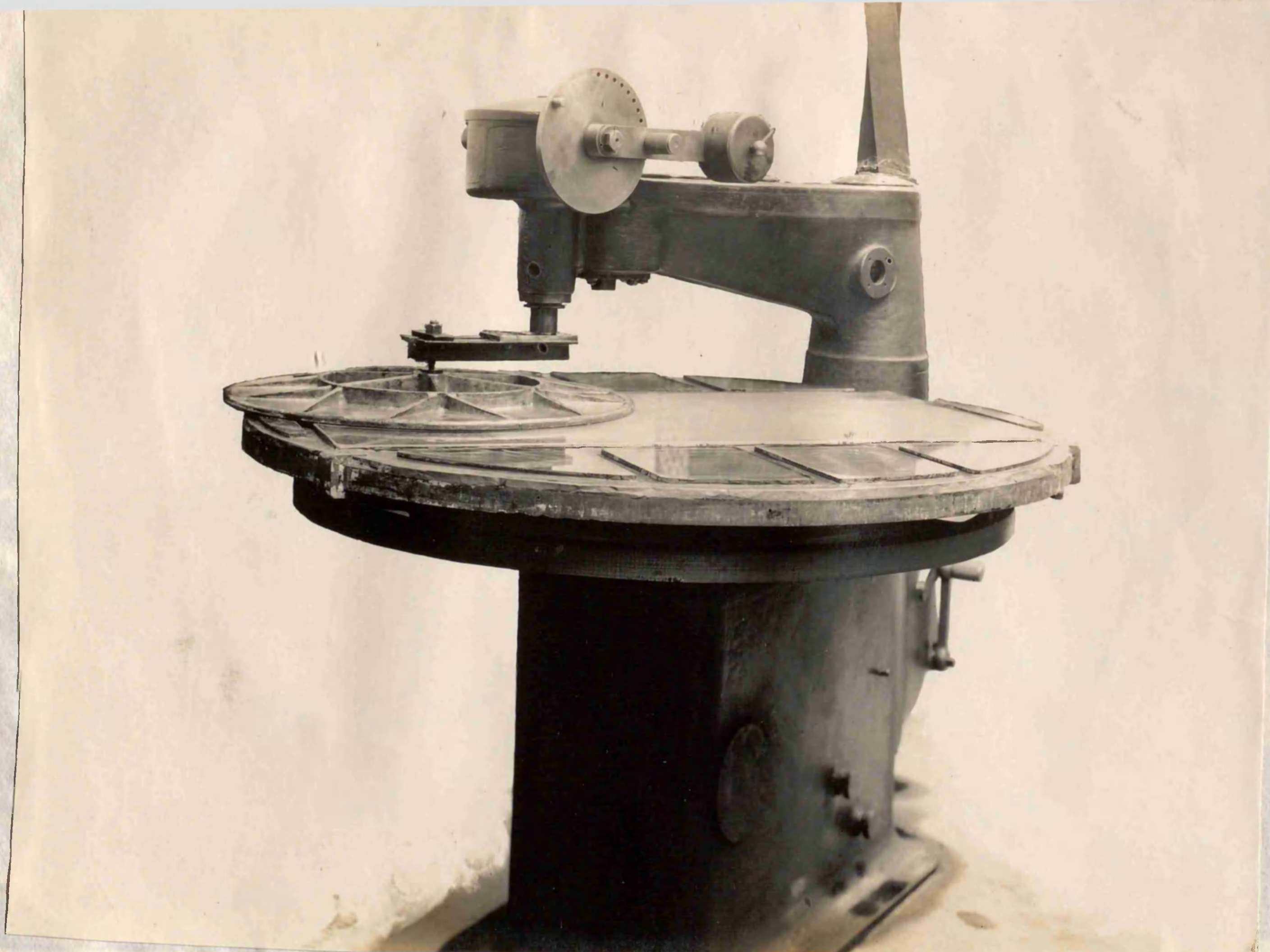
The action at any particular point depends upon the time the part is acted upon by the tool, and this varies with the relative positions of the tool and the work, as the stroke is generally such that the tool sometimes overlaps the work at continually varying positions and by varying amounts.

The action is also propostional to the load, and this is not constant as the area of the tool in contact with the work varies in the overlapping positions.

From these considerations it will be evident that the problem of determining the distribution of the action even under the simplest conditions is a very complex one.

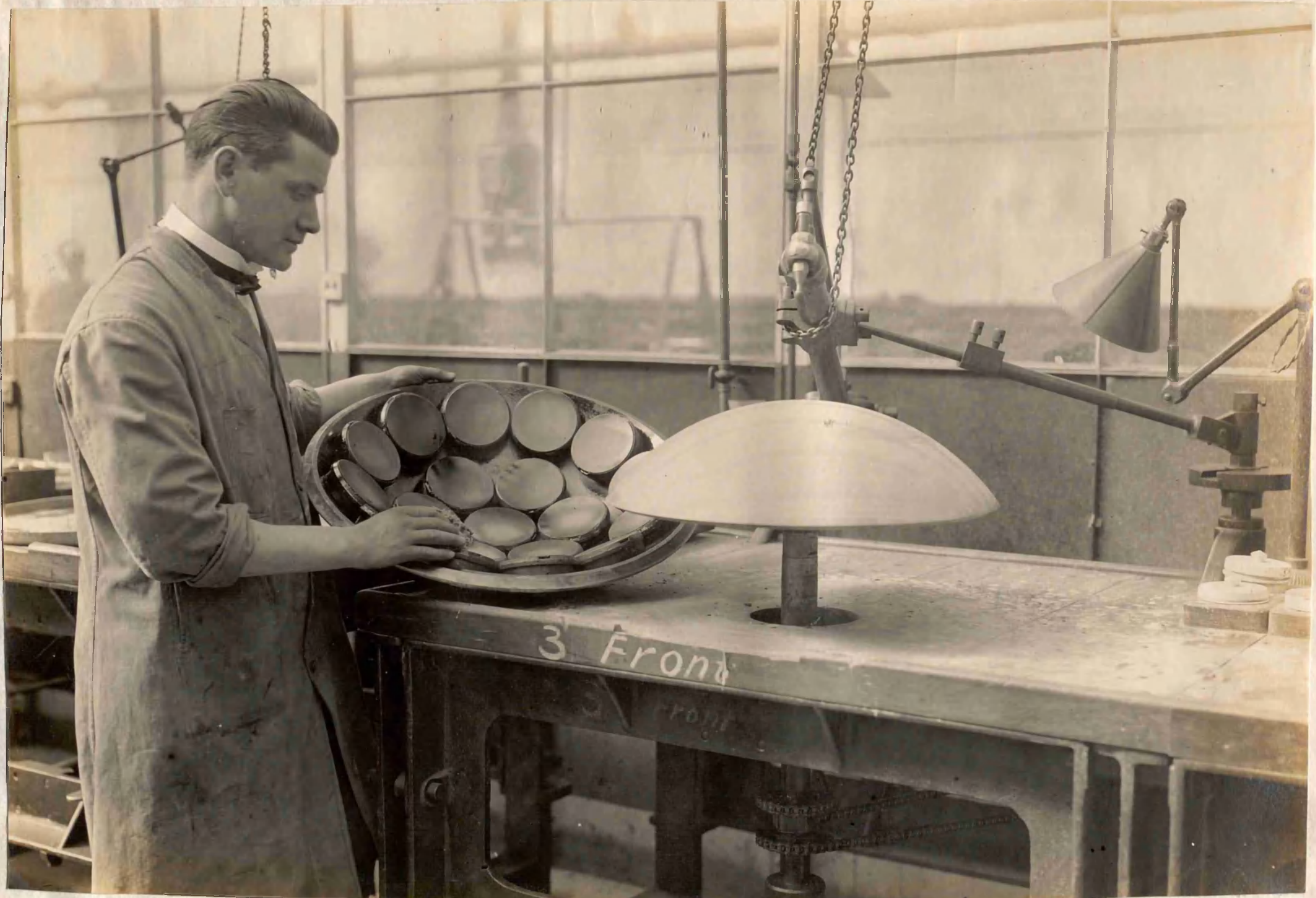
The object of the smoothing process is to remove irregularities of the total surface arising principally from small errors in the laying down or assembling of the individual parts and minor distortions of the mass, and to remove any accidental small holes or cuts introduced by the coarser abrasive during forming. If the work has been well done the amount of material to be removed is small, but as the rate of removal of material during the smoothing operation, when fine emery or carborundum is used as an abrasive, is much more rapid than during the polishing stage when rouge is employed, the importance of good smoothing will be evident.

The polishing process is practically a continuation of the smoothing, the same methods and type of machine being employed; but a polishing medium such as rouge is used in the first instance instead of an abrasive, and a pitch, wax, or cloth polisher instead of a metal tool. As in the hand polishing process previously described water



Smoothing or Polishing Machine
Fig.22.

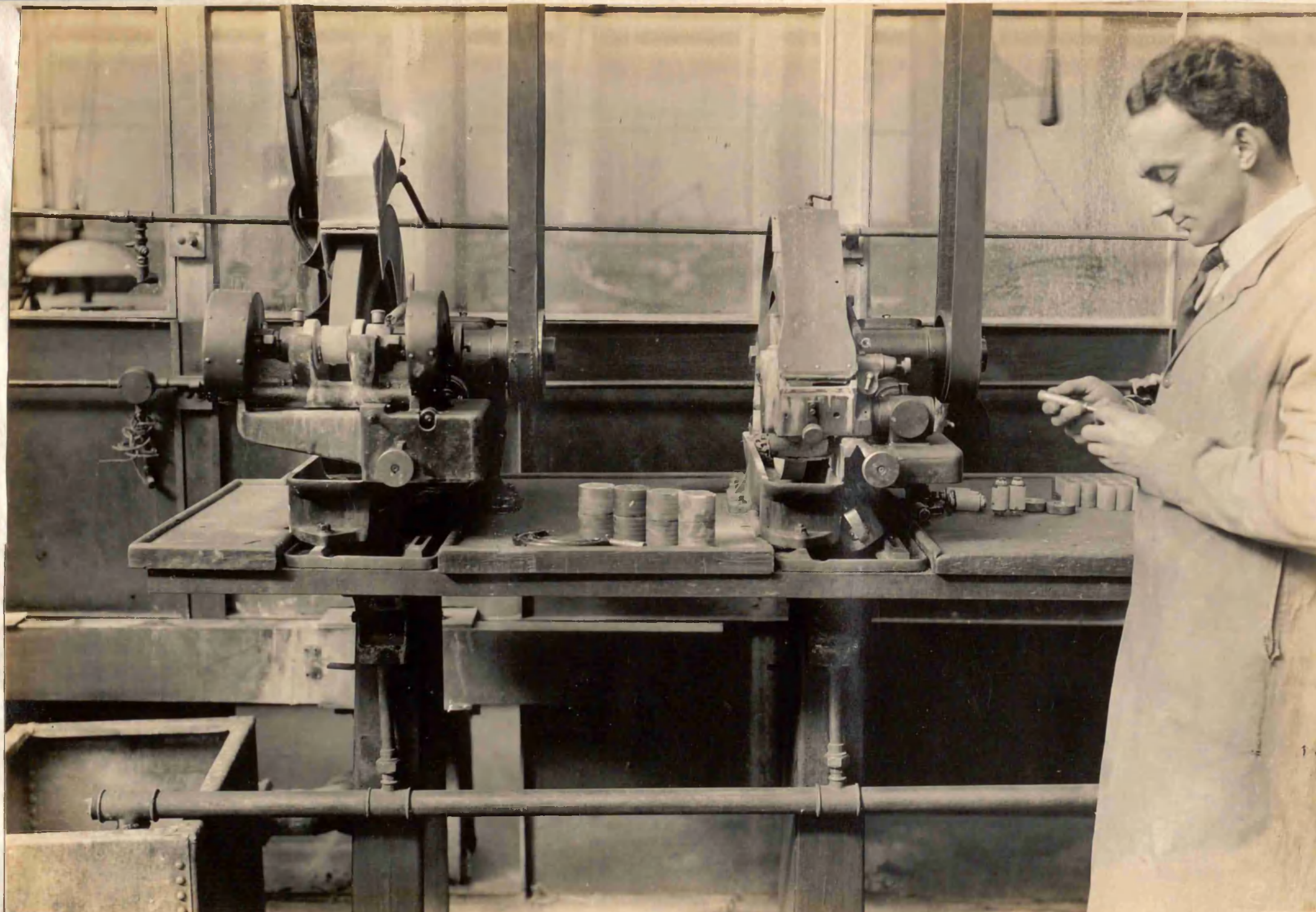
79B.



Lens Smoothing Machine

Fig. 32.

79 C



Multiple Lens Edging Machine.

Fig. 34.

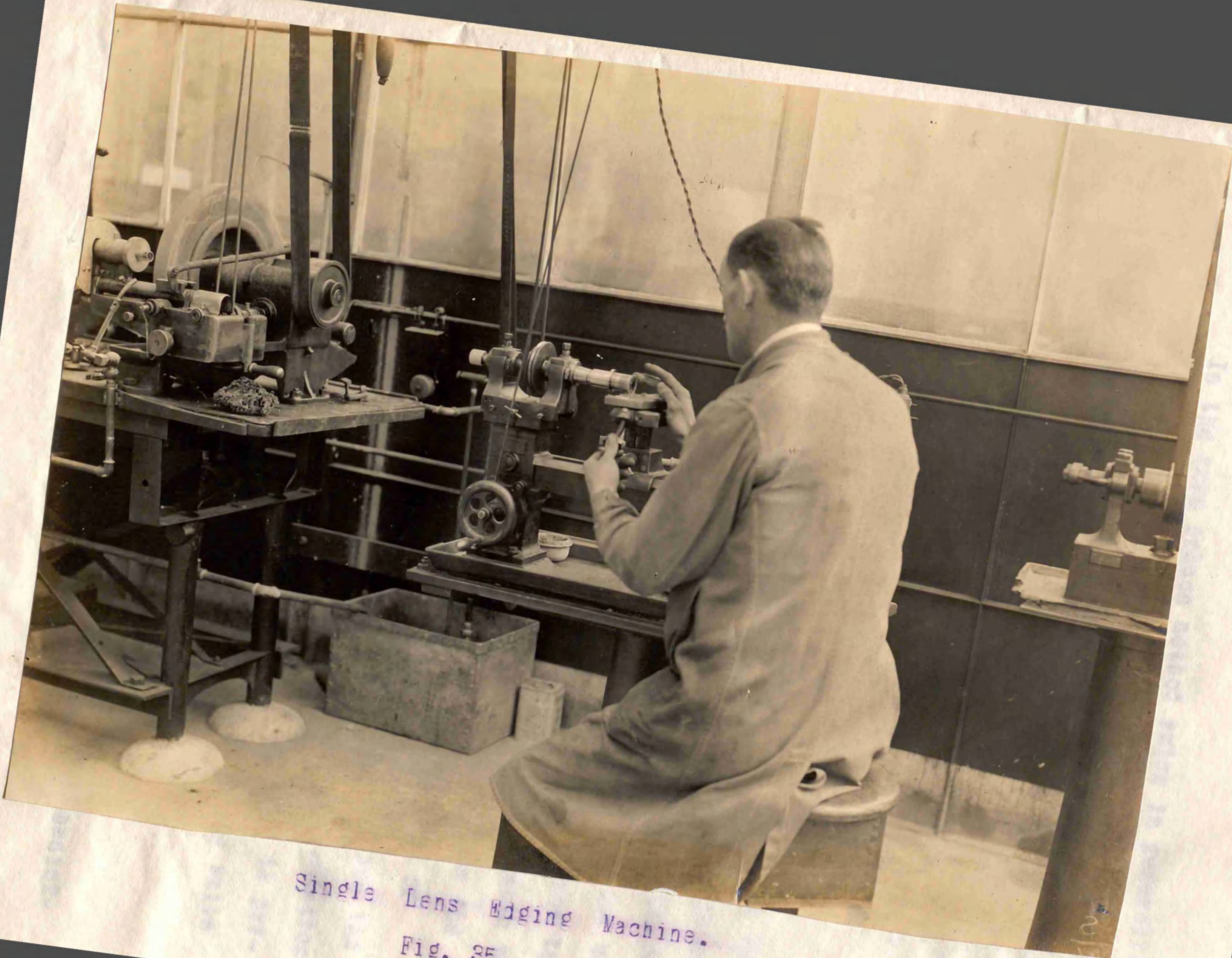
only is used as a polishing medium in the final stages of the operations.

Another type of machine capable of polishing a block about 1.5 metres in diameter is indicated in Fig.32, and the working of a concave block of large diameter lenses is illustrated in Fig.33.

Two methods may be employed for the production of curved work such as the elements of an objective or an eyepiece.

In the first method which is not extensively adopted on account of the accurate jigs that are involved, the lens blanks are ground to the final diameter to within a limit of about minus $\frac{1}{20}$ mm. Several piles of discs cemented together preparatory to being ground to the correct diameter are shown in Fig.34, which also illustrates the carborundum wheel edging machine.

The edged blanks after being separated and cleaned are mounted in the tool indicated in Fig.38, and the curve is then ground true with the periphery, provided the jig and workmanship are sufficiently accurate.



Single Lens Edging Machine.

Fig. 35.

In the more common method which is generally used for spectacle and other lenses, the unedged and partially shaped blanks are secured individually with pitch within the holder. They are then ground and polished in the usual manner and after being removed and cleaned the periphery of the lens, if circular, is ground true with the optical axis of the lens.

This operation is indicated in Fig. 35. The lens to be edged is slightly heated and cemented to the nose of the hollow spindle of a small lathe head. While the cement is soft the position of the lens is adjusted until the two reflections of a light or other object from the front and back surfaces of the lens[1] do not rotate when the spindle is slowly revolved. This occurs when the optical axis of the lens coincides with the axis of rotation. The cement is then allowed to harden and the grinding of the periphery true with the axis of rotation, and therefore with the optical axis of the lens, is performed by pressing a brass plate against the edge while using emery or carborundum as an abrasive.

(1) Dioptricks. 1692. Molyneux, Chap. IV of Mechanick-Dioptricks, p.220.

Various types of machines are employed for special operations and more particularly for the production of spectacle lenses.(1)

Astigmatic lenses are produced on machines in which a cylindrical tool is made to oscillate about the axis of the cylinder, the work itself being prevented from rotating. For the multiple production of Toric lenses in which the two axes of curvature are approximately at right angles to each other, the lenses are worked upon cylinders of the appropriate radius and ground by means of tools whose cross section corresponds with the curvatures.

Single and special toric lenses are ground individually upon small special machines, but in an article such as this which is concerned more with general principles than with the mechanical appliances, it is not possible to describe in detail the numerous types of machine that are employed. The most complete information on this particular subject is obtainable from the catalogues of the optical machine tool makers or from the practical handbooks already referred to.

(1) Schule der Optik, Gleichen und Klein, 1914.
Praktischer Teil.