SOME VERY SMALL EXTRACTS FROM

PRISM AND LENS MAKING

BY

TWYMAN

Descriptions of microscope objective testing, mounting and adjusting.

CHAPTER 8

MICROSCOPE LENSES

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161 This type of work falls into a slightly different category and is therefore enlarged upon in this chapter. The outstanding features to be considered are those which are inherent in the small dimensions and, often, the large solid angular value of a surface with reference to its centre of curvature. To obtain a proper perspective of this type of work it may be worth while recalling some commonly accepted industrial tolerances. It is usually considered that, if a steel shaft is to slide in a steel bearing, a clearance of 0·001 in. will be required if the shaft is under 0·5 inches in diameter. It is obvious however, that this tolerance will be related to the length of shaft engaged and could be reduced for shorter lengths. For small lenses this diametral tolerance can be reduced to as small as 0·0001 in. For such accurate work it is essential that the lens mounts are truly cylindrical, and the lens itself must be edged very accurately. Also it must be held square to the axis of the cell when mounting, or have a chamfered edge to act as a lead, otherwise it will be impossible to get it into the cell. The preceding remarks are in the nature of circumstantial evidence, and it is very difficult to be more specific; but there is no doubt whatever that the last decade has seen a great deal of progress in matters of precision.

Another aspect of the matter is that all microscope lenses of high power and large numerical aperture can have their residual aberration balance easily disturbed by an error in thickness of certain of their component lenses. In the following table are given values in wavelengths of the deformation from sphericity of a wave-front due to the introduction of a parallel plate of glass 0·001 in. thick, and of refractive index 1·52, for homocentric beams of light of various numerical apertures incident normally upon it. Thus a table of this sort can be used to determine the effect of incorrect thickness on the wave-front emerging from a lens.

Numerical aperture ...	0·5	0·6	0·7	0·8	0·9
Deformation in wavelengths	0·15	0·35	0·73	1·51	3·22

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The term " numerical aperture " is defined as follows—

If a point source of light is placed on the axis of a lens system, then a beam of light with a conical boundary is received by the lens and the sine of the semi-angle at the vertex of this cone is known as the numerical aperture of the lens with regard to the point source.

If the angle which edge rays, passing through a lens make with the axis is known, then the sine of this angle when multiplied by the refractive index of the glass of the lens is the numerical aperture of the beam within the lens. If the thickness is varied, then the corresponding change in deformation of the wave-front can be assessed from the preceding table, always providing that none of the other circumstances of refraction are changed as well. This last condition is not usually fulfilled except in the case of the plano-convex front lens of a microscope object glass.

The table then may be used to determine the effect of incorrect thickness on the wave-front emerging from a plano-convex front lens of a microscope object glass, without any reservations.

To measure the thickness of the lens, the workshop usually adopts a unit of 0·001 in. and profitably makes use of dial gauges (" clocks ") reading to 0·0001 in. by estimation, but the commercial article usually requires a little modification before it can be safely used. As one would expect, the use of " tweezers " and a watchmaker's eyeglass or high-power magnifier are necessary to complete the picture.

It is necessary to enlarge a little on the performance required of an object glass. Its wave-front should not exhibit departures from sphericity of as much as one quarter-wavelength (preferably less) under actual working conditions. Reference to the preceding table will show that this means that minute variations of thickness are important with large numerical apertures. It is a fact, however, that lenses which are highly sensitive to thickness variations are also highly sensitive to a change in magnification, which can be varied by altering the position of the adjustable calibrated draw tube with which all standard microscopes are supplied. If, therefore, a lens of large numerical aperture has a deformed wave-front due to residual spherical aberration, this can usually be corrected by a small alteration in the position of the draw tube. For most biological work, the object is mounted under a cover glass, and the complete objective system consists of the object glass, the cover glass, and any layer of material between the cover glass and the object proper. It is clear then that to ensure good definition at all times, the microscopist must have a means of controlling the continuously varying residual spherical aberration. This is achieved by using an adjustable draw tube.

Cover glasses are sold as follows—

No. 0 thickness	... ...	0·004 in.
No. 1 ,,	... ...	0·007 in.
No. 2 ,,	... ...	0·010 in.

This is, however, only a very rough calibration. The area of the cover glass surface which intervenes between the object and the objective is very small and this perhaps accounts for the fact that they are not optically worked. It is well worth while, however, to inspect them before use. The manufacturers adjust object glasses for use with a particular thickness of cover glass at a given tube length, and these values are often engraved on them. The microscope itself is provided with a " fine adjustment " of a calibre sufficient to deal with the exceedingly small movements. If carefully used, this adjustment will remain free from perceptible " back-lash " for a long time.

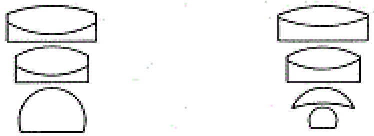

Fig. 105—Microscope objectives
(*Left*) 4-mm dry objective
(*Right*) 2-mm oil-immersion objective

Construction of a hemispherical or hyperhemispherical front lens

162 Fig. 105 gives the construction of two typical lenses, a 2-mm oil immersion objective and a 4-mm dry objective, and the procedure adopted in manufacturing the *front lenses* of these two objectives will be described. It should be realised, however, that with lenses of this type, one must expect a higher percentage of failures than with more normal sizes, against this may be set the almost negligible cost of the raw material.

Details of the procedure described below vary somewhat from glass-shop to glass-shop and the general description may be taken as an averaged one.

The optical glass is prepared first of all by being cut with a slitting saw into flat plates of convenient size, somewhere about an inch square. One side of the plate is ground and polished flat, and the other side is ground down until the thickness of the plate is somewhat greater than the thickness required in the finished lens ; usually about 0·002 in. in excess. This plate is then cut into squares by means of a light-weight diamond, the size of the squares being somewhat greater than the diameter of the finished lens. The small square plate is mounted with its polished side on a steel peg. The end of the steel peg, being smaller than the finished flat surface will be, is flat or slightly concave and the cement used is usually a shellac mixture. Using the peg as a holder, the plate is then applied to a flat-ended, rotating tool and rotated by hand until it is roughly cylindrical, number 302 emery being applied to the rotating tool. This procedure is carried on until the cylindrical blank is about 0·02 in. oversize. The procedure is then repeated with finer emery (number 303) until the size is about 0·007 in. oversize. A rough curve may also be put on top of the flat surface so as to save time, this operation is usually called " rolling."

The starting procedure may be varied as follows—The plate after being worked to a thickness a little in excess (0·003 in.) of the finished dimension, is left grey on both sides and cut up into squares with a wheel cutter and it is then edged circular but large (again 0·003 in.), and a number of these cylindrical blanks are made up into a block and one side ground and polished flat to within 0·0005 in. of final thickness. The cylindrical blank is then mounted, polished face in contact with a steel peg, and work proceeds as above.

A variation of the " rolling " technique would be to use a " Hooster " ; this is a rotating plate with a groove of circular cross section cut into the flat surface near the edge. After this tool has been charged with emery, the peg with the cylindrical blank is applied to the groove, rotating the peg meanwhile and so generating the required rough curve.

A variation of the edging process to be applied to lenses which are slightly under the hemisphere and not quite as small as a hyper-hemispherical lens is as follows—

The square plates are cemented together with beeswax to form a stick of glass, which is cemented with toughened shellac to a spindle. This is placed in a headstock, and the blanks are edged cylindrical by means of a carborundum wheel with a bevelled edge. (This operation is sometimes called " sausaging.")

The lens is now ready for the first roughing tool. This usually consists of a brass rod which has a nearly hemispherical hole in the end. The axial portion of this cavity is removed to give good edge contact, which is an essential feature. The effective radius of the tool is determined from the size of the work it produces (for the first roughing tool this is 0·004 in. greater than the finished lens). Since the wear is considerable, frequent trueing is required.

Care must always be taken in the early stages to see that there is a " spot " or " witness " left on the glass on the axis (*i.e.*, a portion of unworked surface). This is an indication that the substance of the lens is still sufficient. A second and third tool are used, each being about 0·001 in. smaller in radius. The lens, when finally smoothed and the " witness " removed, is about 0·0005 in. to 0·00075 in. large on diameter. Sometimes more than three tools are used with correspondingly smaller differences in their radii of curvature and roughing is sometimes started with 302½ emery instead of 302. For the roughing operations 302, 303, 303½ emeries are used in succession.

These emery numbers are in the British–American Optical Company's notation for " Watford Abrasives " and are given as follows—

Number	Grading
BM 60	Extra coarse
BM 180	Coarse
BM 302	Medium
BM 302½	Finishing
BM 303	Fine
BM 303½	Extra fine
BM 304	Super fine
BM 305	Ultra fine
BM 309	Polishing compound

The lens is now ready for polishing. The polisher may be made by lining a slightly oversize tool with pitch, the layer of pitch being very thin, of the order of 0·003 in. in thickness. The polisher is shaped by using either the smoothed lens or a rejected lens as a former. If a rejected lens is used, one that is a bit " starved " in diameter is chosen, thus ensuring that the polisher is a good fit on the diametrical portion of the lens to be polished. It is *usual* to provide a small hole at the apex of the polisher with the same end in view, *i.e.*, the obtaining of a good diametral fit. Two or three polishers may be used having pitch with various degrees of hardness and, in some cases, shellac may be used as the polisher. The polishing agents are usually E type ceri-rouge (a trade name for cerium oxide), followed by jeweller's rouge. There is a great deal of individuality allowed or allowable in this work.

The figure obtained by polishing is checked from time to time with a proof glass or similar equipment and the figure is controlled by varying the pressure at different angles and rotating the holder between the fingers and varying conditions from time to time. The whole operation requires a very high order of manipulative skill and intelligence.

Proof plates

163 The examination of the perfection of sphericity of a curve by means of a proof glass causes some little trouble if the curved surface has a large angular value. Proof plates are usually constructed in the manner shown and it will be seen that if the lens and proof plate have a small difference of radius, one will be looking at a uniform spherical film of air. It will be apparent that the different foreshortenings of the various elements of the film will cause the effective thickness in the line of vision to vary considerably, hence a ring system may be seen unless the film is of zero thickness. If there is a first order contact then the surface appears blue-black all over and there is little wrong with it. If the surface is perfect spherically and within the dimensional tolerance, but not quite the size to give a first order contact all over, then rings will be seen. In this case, considerable experience and manipulative skill is needed to apply it properly to the proof glass, and to decide whether or not it is perfect.

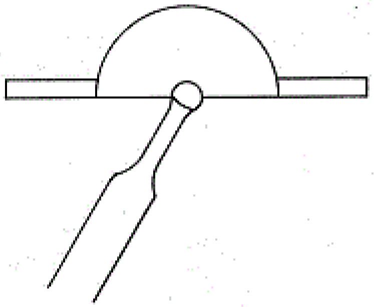

Fig. 106—Testing front lens of microscope objective with a proof sphere

A method of producing a convex curve to test a concave proof plate which is sometimes used, is to turn up a disc of glass to the required diameter, to round and polish the edge of this disc of glass and then to test the proof plate on the rim. When the proof plate is of the correct radius, an interference figure, consisting of a black line, bordered by coloured figures can be seen extending along the line of contact.

It has been found worth while to construct apparatus whereby the surface can be inspected with the proof-sphere very nearly as a whole and the light used for the inspection purposes is made to traverse normally the thin film of air between the lens and proof plate over nearly the complete extent of the film. Precise details of the methods used will vary from maker to maker, but the testing is usually based on the simple principle of the inspection of the Newton ring pattern with the appropriate instrumental modifications which are necessary to render this inspection foolproof.

There is no doubt that nowadays the hyperhemispherical front lens of a microscope objective is a portion of a very perfectly made sphere, in spite of the fact that it is one of the most difficult surfaces to make and that any small error shows up to a marked degree.

Larger microscope lenses

164 For lenses of somewhat larger dimensions the procedure will be different, and is *sometimes* as follows : The glass is cut up into square rods, the cross section being greater than the required lens diameter. The rods are then ground cylindrical in a centreless grinder. The cylindrical rod is next set in a matrix of plaster and slit with a diamond saw, perpendicular to the axis so that blanks of the correct thickness are obtained. With such lenses, which might be components of the middle and back lenses of a 2-mm or 4-mm object glass, a diamond wheel or cup is sometimes used and the spherical surface generated in the usual way. The machine can be set up so that the lens is brought true to curve and thickness at the same instant. As the wear on the diamond wheel is practically imperceptible with such small lenses, little attention is needed over very long periods. It is possible, furthermore, with a diamond cup, to generate a hyperhemispherical surface ; if, then, the blanks are mounted on a suitable " ball " chuck, a larger number can be accommodated by working right over the hemisphere, and this has the advantage that a direct micrometric reading of the radius of curvature of the lenses that are on the block may be made at any stage. Chucks for such hyperhemispherical blocks, however, require careful making and ensuring their adequate ventilation presents no small problem. Very accurate machining of the shoulders, recesses and clearances is necessary. The block, after being diamond ground, is ready for fine smoothing, the same chuck being used for this and the polishing. Co-ordination between the fine smoothing dimensions and polishing dimensions allows for a very close control of results, and, in the case of large work, the time taken is so constant that it is said to be a suitable measure of the finish produced on the lens.

When the lens has been worked and polished on both sides, it is necessary to edge it with a cylindrical rim which is coaxial with the lens. To do this it is mounted on a hollow cylindrical chuck with a shellac cement, and an inspection is made of the reflected images of a target as the spindle is rotated. The cement is softened by heat and the lens adjusted till the images are stationary. It would be hard to over-emphasize the importance of this procedure being adequately carried out. The lens can now be edged by bringing an edging wheel up to the work, or vice versa. This procedure may be varied somewhat, the edging wheel may be a diamond wheel mounted on the same bed as the centring spindle ; or the centring spindle may be transferred to an edging machine, in this case both machines are fitted with split headstocks. The edging process may be combined with a chamfering process, or the chamfer may be put on separately, but the importance of having a chamfer to act as a lead-in assembly (and also to avoid splintering) has been mentioned above. Generally speaking, all lenses are edged and chamfered except the front lenses of 4-mm and 2-mm object glasses. There may, however, be borderline cases.

Cementing, mounting and centring

165 The cementing is usually done with Canada balsam which has been pre-treated by filtering and baking. Two grades are used, " Medium " and " Hard." The medium is used for large lenses, *i.e.* over ½-inch in diameter, and the hard for lenses smaller than this. The medium can be indented with the thumbnail, whilst the hard shatters under this treatment. Matters are sometimes arranged so that no further baking is necessary.

The lenses are placed in the cell with the aid of heat, and the cell is mounted on the centring lathe and gently heated. The front surface is run true with a chucking stick, the back surface gradually coming to rest on the shoulder.

Examination of the " faint " images is made at this stage to see if they run true, if they do not and the lenses have been edged to be a good fit to the cell, then the lenses must be rejected. If, however, the fit is not so good, the lenses may be lifted from the shoulder and rotated slightly and the centring repeated, then the " faint " images may be better centred. The perfection of the final centring depends mainly on the accuracy of the centring lathe and this is usually a specially designed or adjusted piece of equipment.

Centring tolerances

166 If a surface has its centre of curvature displaced from the optical axis, it is said to be out of centre. The general refraction through the defective surface is now slightly oblique and accompanied by all the errors due to obliquity. The optics of the system now become a little complicated, but by making certain justifiable simplifying assumptions they can be dealt with and quantitative figures given for the permissible tilt of any surface (derived from a consideration of the physical optics of image formation). In general the most serious effect is due to the introduction of the unsymmetrical aberration known as coma into the centre of the field. This causes the image of an unresolvable point of light to have a slight " side flare," a most annoying defect

It follows that some sort of compensation is possible by tilting other surfaces different amounts in the opposite direction, but circumstances have to be favourable for this to be a satisfactory cure of all the obliquity errors due to defective centring.

As an illustrative example, consider the tilt permissible on the flat outer surface of a 4-mm object glass of a given numerical aperture. This is given approximately by—

$$\text{(permissible tilt in radians)} = \frac{\text{One wavelength}}{\text{working distance} \times (\text{numerical aperture})^3}$$

Thus, for a lens with a working distance of 1 mm, a numerical aperture of 0·70, and light of wavelength 0·0005 mm—

maximum tilt = 0·00146 radians
i.e. ,, ,, = 0° 5′

The metal work

167 The mounts fall into two classes, and reference may be made to the accompanying sketches which illustrate *diagrammatically* two ways of mounting the same set of components. The first system may be described as the "screw-on" type and the second system as the "plain fitting" type. It will be seen that the "plain fitting" type is likely to be more expensive to manufacture. The operations involved in making these mounts satisfactorily demand rigid adherence to certain engineering principles which will not be enlarged upon here, except to point out that the most perfect set of components may be spoiled by unsatisfactory mounting. When the lens is mounted, a final test is made to see whether its tube length is correct, or whether the total sum of the individual thickness errors calls for correction. If correction is needed, the distance between the front lens and the next component is varied. With the screw-on type of cell, this may be achieved by shortening the cell carrying the front lens to reduce the distance, or shortening the cell containing the middle lens to increase the distance, the second separation being insensitive. It will be appreciated that this procedure calls for very true threads and shoulders With the plain-fitting type, the countercells merely need unlocking and readjusting. These cells have the further advantage that faults, if any, can be tracked down to the defective unit by selective rotation where feasible.

It will not be out of place to point out that, in view of the extraordinary precautions taken to control their manufacture, the number of lenses calling for individual adjustment is small. For the same reason, it is quite unnecessary to provide means of adjustment for lenses of low power.

As previously stated, Fig. 107 is only diagrammatic; with some types of 2-mm and 4-mm object glasses, the rigid lens and cell assemblage is protected from stresses and thermal changes due to the fingers. This is achieved by enclosing it in an outer tube with a small clearance. This type of mounting is thought to be useful for petrographic objectives which must be free from strain.

In the original design of the lenses and their mounts, care is taken to see that, for the main run of objectives, the distance from the shoulder of the "Society screw" to the object plane is constant. Hence, one can change from one objective to another, using objective changers or a rotating nose piece and it will merely require a manipulation of the fine adjustment to refocus the object. When this is the case, the objectives are said to be parfocal.

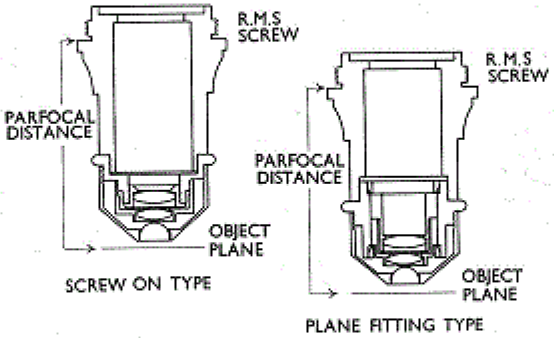

Fig. 107—Microscope objectives and mountings

Care is also taken in the construction of the objective changer to allow means of ensuring that the object remains in the centre of the field of view.

The "Society screw" (Royal Microscopical Society) is a standardized thread having the following dimensions—

Number of threads ... ... 36 per inch
Form of thread ... ... Whitworth

	Maximum in.	Minimum in.
Male		
Outside diameter	0·7982	0·7952
Root diameter	0·7626	0·7596
Female		
Top	0·8030	0·8000
Root diameter	0·7674	0·7644

Testing the completed lens

168 The usual (but not universal) test is to examine the object glass on some sort of artificial star. In other words a test object is made in which brilliant pseudo-points of light are available to the observer, but the size of these objects must be below the limit of resolution of the lens. For low powers one may use globules of mercury obtained by splashing from a larger globule. These are illuminated from the side by an intense beam of light, the image of the source being the artificial star. A useful source of clean mercury is a broken clinical thermometer; the mercury should be clean so that its surface tension is unimpaired and good spherical globules obtained. For higher powers, a 3-in. × 1-in. microscope slip may be silvered, and pin holes may be found which when illuminated from below will act as artificial stars. These may be covered with cover glasses of different thicknesses forming a useful test object. The silvering should not be quite opaque as this reduces the chance of pinholes being formed. If there are insufficient pinholes, they may be made artificially by dropping coarse carborundum from a height of a few inches on to the silver. The slide containing the pin-holed silver is often termed a "silver point" slide. Such a slide should be illuminated by focusing on it the image of a bright source and, to get the best results, the condenser used should have a numerical aperture equal to that of the object glass being tested. Testing proceeds as follows: The image of the artificial star is examined below, above and at the true focal plane; this is easily achieved by the use of the fine adjustment. The appearances are carefully studied for symmetry of form, intensity and colour. A high-power eyepiece is most useful for this purpose. For dry lenses of large numerical aperture the use of different thicknesses of cover glasses also forms an invaluable adjunct. This test can be made a quantitative one with the aid of the proper technique, but the microscope interferometer if available will give better results in a shorter time. The main use of the star test at this stage is to determine whether the lens is properly centred and properly adjusted, *i.e.* whether the sum total of inevitable incidental errors is negligible.

The procedure with a dry lens such as a 4-mm is briefly as follows: examine a "silver point" having a cover glass of the correct thickness, inspect the ring pattern in the neighbourhood of the focal plane. If the ring system is in evidence inside the focal plane, but not outside, then the lens system is undercorrected for spherical aberration. If the ring system is visible outside the focal plane but not inside, then the lens system is overcorrected. Spherical aberration can be reduced by the use of a thicker cover glass if the system is *undercorrected*; or with most types of lens by increasing the draw tube extension. If the lens is overcorrected the cure is a reduction of cover glass thickness or a shortening of the draw-tube length. By these means it is possible to determine the relation between cover glass thickness and corrected tube length (*i.e.* tube length at which the system is free from spherical aberration) for any particular lens.

Then to a first approximation this relation is of the form—

$$1/T = At/F^2 + B$$

where A and B are constants

$$\left.\begin{array}{lll} T & = & \text{the corrected tube length graduation} \\ t & = & \text{the cover glass thickness} \\ F & = & \text{the focal length} \end{array}\right\} \begin{array}{c}\text{All}\\ \text{expressed}\\ \text{in}\\ \text{millimetres}\end{array}$$

The constant A does not vary much from one lens type to another with the normal run of object glasses, whilst the constant B is merely the reciprocal of the tube length for an uncovered object.

In other words the reciprocal of the corrected tube length varies directly as the cover glass thickness and if the lens is of relatively long focus, varying the cover glass thickness will have little effect on the corrected tube length. For homogeneous immersion lenses, the question of cover glass thickness does not arise, and the corrected tube length is checked by actual trial. It is worth while pointing out in this connection, however, that the refractive index of the immersion oil changes fairly rapidly with temperature; this change introduces some spherical aberration which requires a change in tube length for its removal.

The corrected tube length or cover glass thickness having been ascertained, the lens may now be set at this position and the star image in the centre of the field examined for freedom from coma and astigmatism. It is of no use undertaking this examination until the object glass has been corrected for spherical aberration. If the central image has a slight haziness on one side, the centring is defective and the lens must be readjusted. Sometimes there is inevitably a little residual coma in the design, and this may balance the out-of-centre coma so that a coma-free image is obtained, but not exactly in the centre of the field. The central or nearly central coma-free image is next inspected with the aid of a rapid movement of the fine adjustment up and down through the focal plane. This will detect residuals of astigmatism which are not large enough to show up as deformations (ellipticities) of the ring system. There is an evanescent impression of a short bar of light rapidly rotated through a right-angle on focusing through the focal plane, whereas a static examination shows nothing. By this means, astigmatism can be traced down to the equivalent of a quarter-diopter cylindrical spectacle lens as used by the eye, an amount which is imperceptible to many observers—the actual astigmatic deformation of the wave-front emerging from the lens, being of the order of $\frac{1}{8}$th of a wavelength. It is usual to reject any lens which has as much astigmatism as this, although it is not a very obnoxious fault. In testing an apochromatic object glass the corrected tube length functions are ascertained for three colours which may be obtained by isolation with filters, and particular attention is paid to the elimination of all defects outlined above. In addition, a certain chromatic difference of magnification is required to allow for use with compensating eyepieces, but this is more a matter of design than of adjustment.

Other test objects

These are available in considerable variety, but the most popular ones are diatoms ; to use them satisfactorily a fairly wide experience is required. In general the satisfactory resolution of a *suitable* diatom into its appropriate dotted structure, where this exists, is a check on the resolving power of the lens. The coincidence of the focal plane of the dotted structure with the focal plane of the main outline is a test for the residual spherical aberration. The residual secondary spectrum can be judged on more coarsely dotted structures as these are brought in and out of focus. The actual blackness of the dotted structure is again a very severe test—if too near the limit of resolution it will be lacking in contrast. The diatom test is rendered more extensive by mounting the specimens in media whose refractive indices vary from that of the diatoms, thus varying the contrast in the object. It is clear that defects such as coma and astigmatism in the centre of the field of view may prevent a full resolution into dots, and one may get the impression of a fine-lined structure. It will be apparent from the foregoing remarks, that this type of test is qualitative rather than quantitative.

The microscope interferometer

169 This instrument, which is described in §§250 and 251, will give directly quantitative results in terms of the fundamental unit in image formation, *i.e.* the wavelength of light. It is moreover, in the writer's opinion an instrument of highly educative potentialities. Experience, lasting over many years, has served to confirm this view. With a little practice it is easy to set up and use. The instrument is so arranged that the light traverses the object glass precisely as it would in ordinary use, but this passage occurs twice, so that all errors are doubled. It would be out of place here to give the many details of the instrument, but some little discussion may be of interest. For those who are unfamiliar with object glass testing by interferometric methods, the following analogy, although very imperfect, may be a help. Single lenses are tested by means of a proof glass, and an inspection of the ring system gives all the necessary information about the surface. If one could imagine a proof glass which could be applied to a system of several lenses at one and the same time, and give readings of their total errors at once, then the action of such a proof glass would be rather like that of the lens-testing interferometer. In effect it applies a proof glass to the image forming properties of the complete object glass. It will be apparent from the foregoing that a perfect lens will have a very uninteresting interferogram. Most microscope object glasses are very good, but not perfect, and there are usually some points of interest. As is well known, the interferogram may be likened to a contour map, and the elevations in the most important one, that of the axial pencils, do not usually reach much beyond the first contour, if as far. If, however, in a contour map the ground is sloping, then hills and valleys will be indicated by waviness in the contour lines. This principal can be used in the microscope interferometer by tilting the comparison beam. The axial interferogram for test purposes is usually a series of say 5 or 6 more or less straight bands, and the departure from exact linearity tells at once its own story about the residual spherical aberration in the lens. If the contour bands are not symmetrical about a diameter perpendicular to their length, then some of the component elements of the lens are out of centre, or one of the surfaces may not be spherical due to an actual mechanical strain in mounting. The most important monochromatic aberrations of a microscope object glass are spherical aberration and coma. The spherical aberration governs the contrast in the image and the defining power, whilst the coma to a large extent limits the size of the usable field. There is also, except in very special objectives, curvature of

Fig. 108—Axial residual spherical aberration

Fig. 109—Oblique residual astigmatism and coma

field and astigmatism. Coma, astigmatism and field curvature are extra-axial phenomena, and a slight rotation of the object glass will suffice to produce an interferogram containing these errors in addition to the axial spherical aberration. The pattern is now complicated and there is no need to tilt the comparison beam since the pattern contains all the necessary elements for its own analysis. It is worth while pointing out that the coma error has a single axis of symmetry whilst the spherical aberration, astigmatism and field curvature errors have double axes of symmetry in the interferograms. It is customary, at this stage, slightly to readust the focus of the object glass so that the pattern consists as far as is possible of vertical lines. Then in a very simple fashion the curvature of the central vertical band is a measure of the coma in the lens.

Figs. 108 and 109 give photographs of interferograms which show (Fig. 108) *axial* residual spherical aberration with a tilted comparison beam ; and (Fig. 109) *oblique* residual astigmatism and coma.

CHAPTER 9

THE PRODUCTION OF PRISMS IN QUANTITY

170 We shall now consider the manufacture of prisms in quantity, in so far as the methods and machines differ from those already described in the previous chapters.

Included in this chapter will be found some remarks on the making of parallel plates of high accuracy, as these can fairly be regarded as prisms of zero angle.

Raw material

171 Prisms in large numbers are now usually made from mouldings, and what was said in §122 about lens mouldings applies equally to prism mouldings, except that the mass of glass and the path length traversed inside a prism are usually greater than is the case with a lens, and the glass makers have therefore to exercise commensurately greater care as regards homogeneity and annealing (but see §180).

Surface flaws and inclusions caused by moulding have been reduced to such an extent that roughing off 2 or 3 mm from each surface is usually enough for their complete removal.

The wastage of optical glass in manufacture is considerable. Records kept over a considerable time, and for a variety of prisms, show that the loss during various processes amounted to the following from all causes—

	Per Cent
(*a*) Sawing and roughing - - - - - -	10
(*b*) Smoothing and polishing (by damage or otherwise)	10
(*c*) Edging (in lenses) - - - - - - - -	6
(*d*) Faulty material - - - - - - -	12
Total - - - - - - -	38

If moulded prisms are used some of the loss coming under (*a*) is avoided.

It is right to add that the record was made during a period when much unskilled labour was employed.

Machining

General considerations

172 In the machining of a lens we were concerned only with the generation of the required curves and the reduction of the blank to a given thickness.