CHAPTER III

LENS DESIGN AND LENS MAKING

3.1 The Optical Glass Selection

The two types of optical glass were selected according to the method described in section 2.8 for making an achromatic doublet objective, namely :

Flint : no. "689310" at 24.5 °C

$n_D = 1.68881$

$\nu_D = 30.97$

Dense Barium Crown : no. "623569" at 24.5 °C

$n_D = 1.62290$

$\nu_D = 56.89$

while for eyepiece, we choose

Extra Light Flint : no. "541472" at 24.5 °C

$n_D = 1.54082$

$\nu_D = 47.19$

3.2 Objective Design

Equations (2.44),(2.45), and the method described in section 2.6 were used to calculate the specification of the objective which would give 3 times of magnification. The results are as follows:

$$f'_o = \frac{160}{3} = 53.33 \text{ mm.}$$

$$K_o = \frac{1}{f'_o} = 0.018750 \text{ mm.}^{-1}$$

$$K_1 = -\frac{K_o \nu_1}{\nu_2 - \nu_1}$$

$$= -\frac{0.01875 \times 30.97}{56.89 - 30.97} = -0.022403 \text{ mm.}^{-1}$$

$$f'_1 = \frac{1}{K_1} = -44.64 \text{ mm.}$$

$$K_2 = \frac{K_o \nu_2}{\nu_2 - \nu_1}$$

$$= \frac{0.01875 \times 56.89}{56.89 - 30.97} = 0.041153 \text{ mm.}^{-1}$$

$$f'_2 = \frac{1}{K_2} = 24.30 \text{ mm.}$$

Keeping $c_1 = 0$, for Fraunhofer type and applying equation (2.43), we have

$$c_2 = 0.032524 \text{ mm.}^{-1}$$

$$c_3 = -0.033543 \text{ mm.}^{-1}$$

The lens central thickness be used for ray tracing was determined as follows:

for a small positive lens;

$$\text{the central thickness } d \geqslant \frac{(\text{radius of a lens})^2}{\text{focal length}} \qquad (3.1)$$

While for a small negative lens;

$$\text{the central thickness } d \geqslant \frac{1}{10} \times \text{diameter of a lens} \qquad (3.2)$$

If we let the radius of the lens = 5.0 mm and the diameter of field stop = 12.0 mm,

then $d_1 \geqslant \frac{1}{10} \times 10.0 = 1.0$ mm.

We choose $d_1 = 2.0$ mm. for an extra margin of safety,

and $d_2 \geqslant \frac{(5.0)^2}{24.30} = 1.03$ mm.

To provide for an additional margin of safety, we pick

$d_2 = 3.0$ mm.

Since the curvatures c_1, c_2 and c_3 are not likely to give minimum aberrations, we determined what the curvature would be by using ray tracing and bending methods described in sections 2.12 and 2.13.

The ray tracing began at the field stop and passed through the objective as shown in Fig. 3-1. Equations (2.13),(2.17),(2.20),(2.21),(2.22),(2.23),(2.24),(2.25),(2.50),(2.51),(2.52) together with the methods described in sections 2.12 and 2.13 were used to calculate the aberrations by the aid of the computer program given in Appendix 3. We then set x = 5 %. This resulted in aberrations near the turning point listed in Table 3-1.

There was too large of a gap between the values of r_2 in Table 3-1. We therefore reset x to be 0.1 % in the computer program as shown in Appendix 4 to get the values of r_2 listed in Table 3-2.

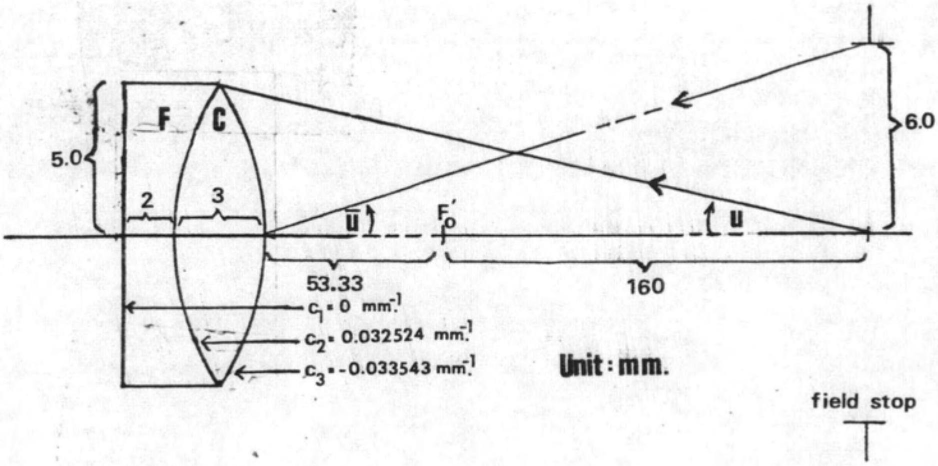

Fig.3-1. Objective ray tracing.

r_2 (mm.)	S_I (mm.)	S_{II} (mm.)	S_{III} (mm.)
-24.97	0.00417464	0.00046485	0.00035631
-23.87	0.00378931	0.00026730	0.00035233
-23.12	0.00360278	0.00007143	0.00034812
-21.93	0.00361604	-0.00012261	0.00034369
-21.09	0.00383019	-0.00031476	0.00033905

Table 3-1. The aberrations of some radii of curvature of the objective.

r_3 (mm.)	r_2 (mm.)	r_1 (mm.)	S_I (mm.)	S_{II} (mm.)	S_{III} (mm.)
46.18	-22.65	-82.15	0.00358852	0.00002858	0.00034716
46.27	-22.63	-81.89	0.00358770	0.00002469	0.00034707
46.35	-22.61	-81.64	0.00358696	0.00002080	0.00034699
46.43	-22.59	-81.38	0.00358631	0.00001691	0.00034690
46.51	-22.57	-81.13	0.00358573	0.00001302	0.00034681
46.59	-22.55	-80.88	0.00358523	0.00000913	0.00034672
46.68	-22.53	-80.63	0.00358482	0.00000525	0.00034664
46.76	-22.51	-80.38	0.00358448	0.00000136	0.00034655
46.85	-22.50	-80.14	0.00358422	-0.00000252	0.00034646
46.93	-22.48	-79.89	0.00358405	-0.00000640	0.00034637
47.01	-22.46	-79.65	0.00358395	-0.00001029	0.00034628
47.10	-22.44	-79.41	0.00358394	-0.00001417	0.00034620
47.18	-22.42	-79.17	0.00358400	-0.00001805	0.00034611
47.27	-22.40	-78.93	0.00358414	-0.00002194	0.00034602
47.35	-22.38	-78.69	0.00358437	-0.00002582	0.00034593
47.44	-22.37	-78.46	0.00358467	-0.00002970	0.00034584
46.53	-22.35	-78.23	0.00358506	-0.00003358	0.00034575
47.61	-22.33	-77.99	0.00358552	-0.00003746	0.00034566
47.70	-22.31	-77.76	0.00358607	-0.00004134	0.00034558
47.79	-22.29	-77.53	0.00358669	-0.00004521	0.00034549

Table 3-2. The aberrations of radii of curvature set at a closer interval of the objective.

The curves of S_I, S_{II} and S_{III} versus r_2 taken from Table 3-2 were constructed as shown in Fig. 3-2.

A compromised point for r_2 between the values of S_I, S_{II} and S_{III} was selected from graph. We picked

$$r_2 = -22.50 \text{ mm.}$$

Table 3-2 indicates that :

$$r_3 = 46.85 \text{ mm.}$$

$$r_1 = -80.14 \text{ mm.}$$

For these radii of curvature of objective, the aberrations were found to be

$${}_0W_{40} = 0.00044803 \text{ mm.}$$

$${}_1W_{31} = -0.00000126 \text{ mm.}$$

$${}_2W_{22} = 0.00017323 \text{ mm.}$$

Equations (2.26),(2.27),(2.28),(2.31),(2.32),(2.33) and (2.34) were used to calculate the other specifications of the objective shown in Fig. 3-3. The resolving power can be determined by equation (2.38) and by using the sodium light ($\lambda = 5893$ Å). We found S to be 4.99×10^{-3} mm.

3.3 Eyepiece Design

The methods described in sections 2.6, 2.9 and equations (2.29),(2.30),(3.1) were used to calculate the radii of curvature of Ramsden type eyepiece with a 10 times magnification. This

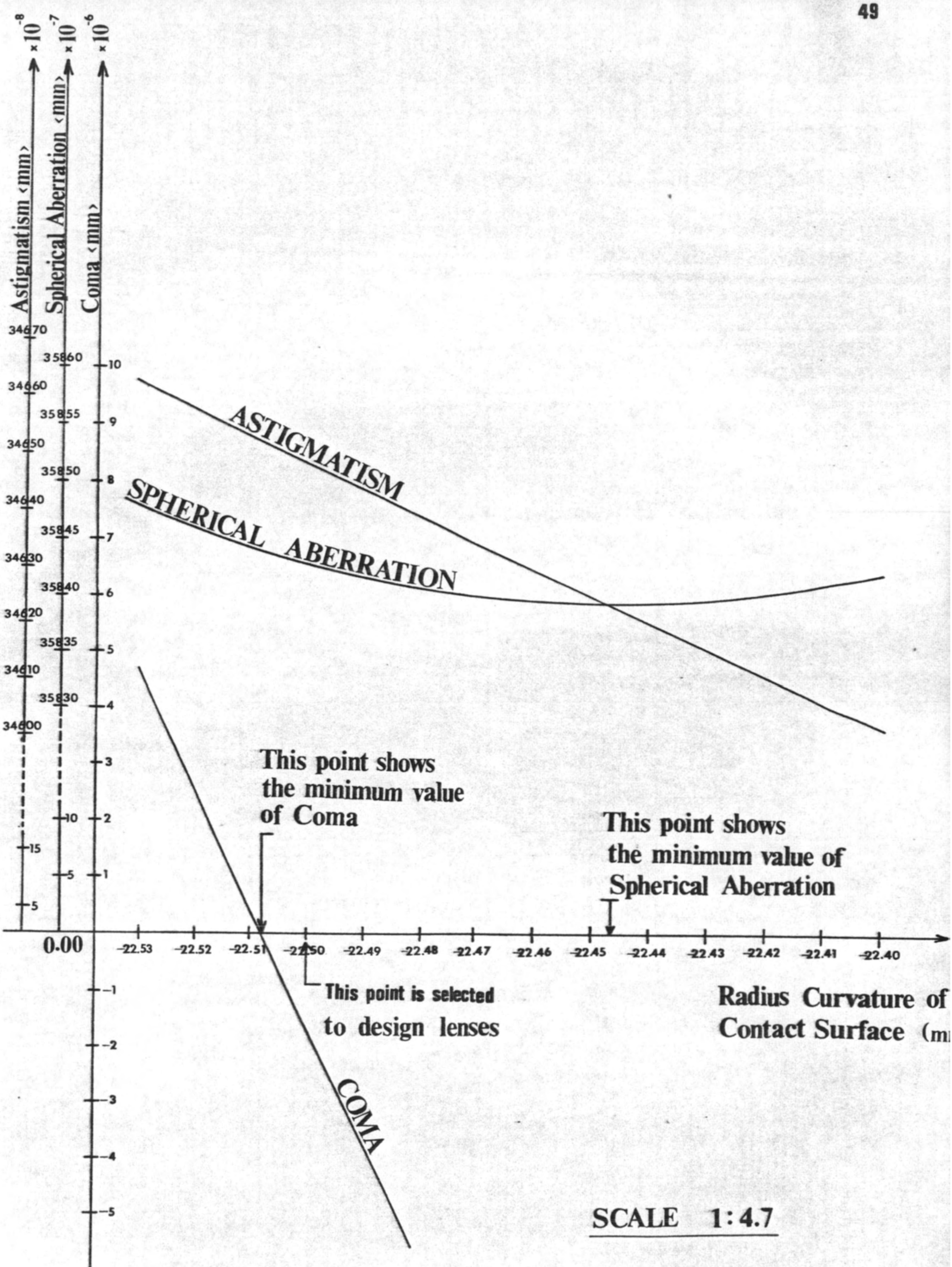

Fig. 3–2. The graph of the lens design.

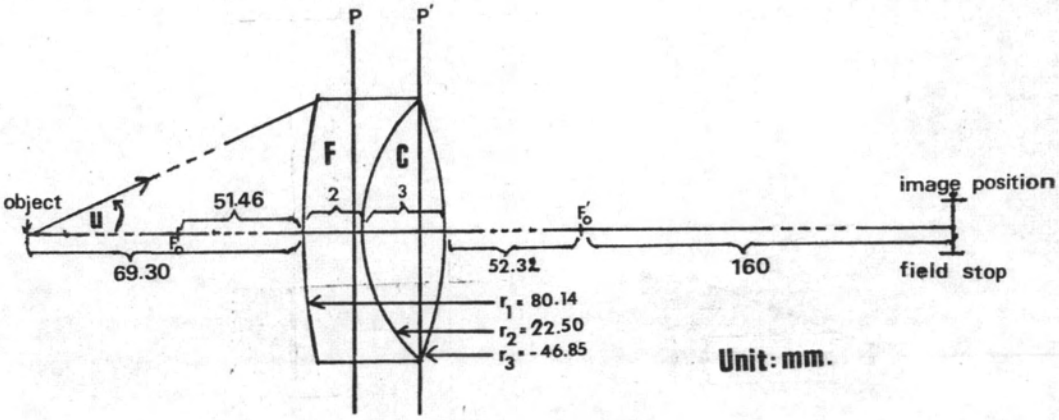

Fig.3-3. Diagram of the objective design.

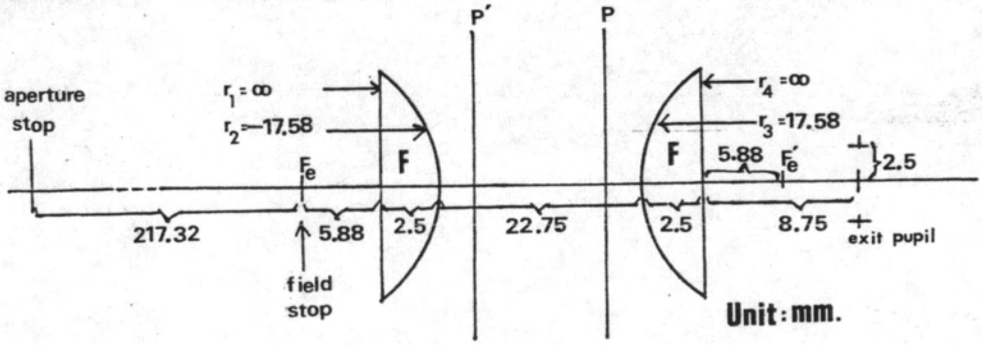

Fig.3-4. Diagram of the eyepiece design.

methods gave the following values

$$f'_e = \frac{250}{M} = \frac{250}{10} = 25.0 \text{ mm.}$$

$$K_e = \frac{1}{f'_e} = \frac{1}{25} = 0.04 \text{ mm.}^{-1}$$

$$K_1 = K_2 = 0.030769 \text{ mm.}^{-1}$$

$$f'_1 = f'_2 = 32.5 \text{ mm.}$$

$$r_1 = r_4 = \infty \text{ mm.}$$

$$r_2 = -r_3 = -17.58 \text{ mm.}$$

When the lens thickness is introduced into the ray tracing, we find that

the central thickness of each lens $\geqslant \frac{(6.0)^2}{32.5} = 1.11$ mm.

For a margin of safety, we choose $d = 2.5$ mm.

We then let the diameter of the exit pupil be 5.0 mm, and the diameter of the field stop be 12.0 mm.

The separation distance of lenses is $\frac{7}{10} \times 32.5$ or 22.75 mm.

At this separation, using the method described in section 2.12, the aberrations of eyepiece were found to be

$${}_0W_{40} = 0.00119325 \text{ mm.}$$

$${}_1W_{31} = -0.00015473 \text{ mm.}$$

$${}_2W_{22} = 0.00342537 \text{ mm.}$$

If we fix r_1, r_2, r_3 and r_4 of eyepiece and vary the separation distance of the lenses, the aberrations at any state could be obtained by using the computer program given in Appendix 5. The results are given in Table 3-3.

The results from Table 3-3 show that the minimum of coma is at the separation distance = 26.0 mm, but a distance of 32.5 mm gives the minima of spherical aberration and astigmatism. The separation distance = 26.0 mm could be used in eyepiece, however this distance was not used because the power of eyepiece would be different from the design. So that the separation distance = 22.75 mm was selected to design lenses.

The exit pupil is the image of the objective formed by the eyepiece. The position of the exit pupil was found to be 8.75 mm from the eye lens by using equation (2.16). The other specifications of the eyepiece were calculated using the methods described in sections 2.4 and 2.5 as shown in Fig. 3-4. The ray diagram of the designed traveling microscope is shown in Fig. 3-5.

Separation Distance d_2 (mm.)	${}_0W_{40}$ (mm.)	${}_1W_{31}$ (mm.)	${}_2W_{22}$ (mm.)
22.75	0.00119325	-0.00015473	-0.00342537
24.38	0.00117986	-0.00013238	-0.00291827
26.00	0.00116890	-0.00013207	-0.00236969
27.63	0.00116041	-0.00015365	-0.00179046
29.25	0.00115443	-0.00019686	-0.00119201
30.86	0.00115106	-0.00026122	-0.00058629
32.50	0.00115045	-0.00034604	+0.00001431
34.13	0.00115277	-0.00045626	+0.00059724
35.75	0.00115826	-0.00057245	+0.00114989

Table 3-3. The aberrations of some separation distances of the eyepiece.

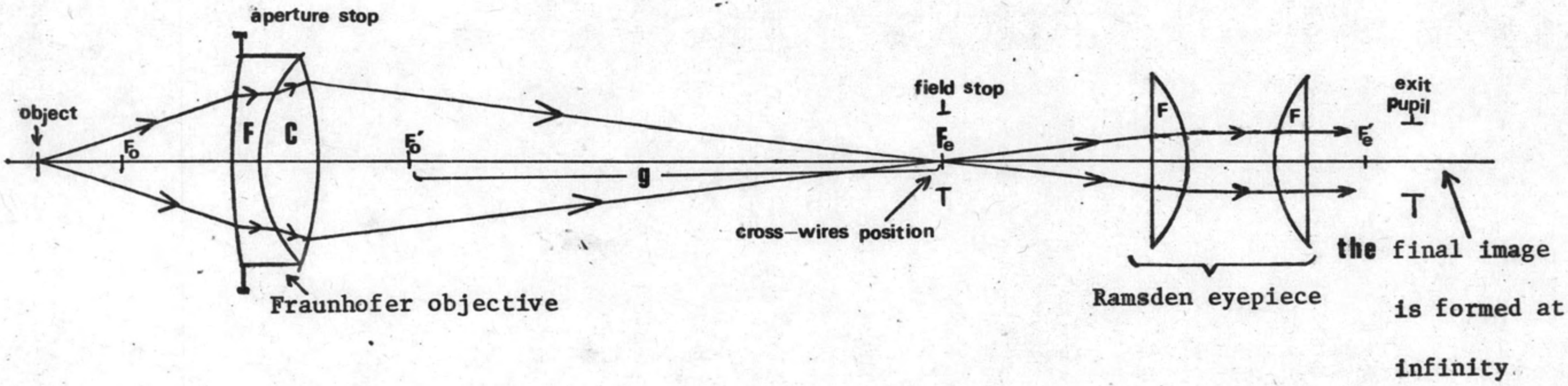

Fig.3-5. Ray diagram of the traveling microscope.

3.4 Lens Making[18,19]

Fig. 3-3 and Fig. 3-4 show the completed lens design. The production of such ordinary optical parts as lenses proceeds in the following manner.

3.4.1 Tool making

The drawing of the tools are shown in Appendix 1. The tools were constructed on a lathe. Their radii of curvature were tested with a gauge. Two tools were constructed for making one curvature, one from cast-iron and the other from brass. The constructed tools are shown in Fig. 3-6.

3.4.2 Rounding and sawing

A small piece of cylindrical optical glass was cut using a trepanning drill fed with carborundum no. 70 and water. A diamond saw with coolant was also used as is shown in Fig. 3-7 and Fig. 3-8. The typical grain size of the abrasive materials used in grinding and polishing are listed in Table 3-4.

3.4.3 Milling

Milling, or round-grinding the surface to the approximate curvature required, is done by grinding with a lens grinding machine (with coolant) which is illustrated in Fig. 3-9.

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[18] R.M. Scott, "Optical Manufacturing", Applied Optics and Optical Engineering; edited by Rudolf Kingslake. (New York: Academic Press, Inc., 1970), vol.3, pp.52-86.

[19] G. Franke, "The Production of Optical Parts", Advanced Optical Techniques; edited by A.C.S.Van Heel. (Amsterdam: North-Holland Publishing Co., 1967), pp.255-308.

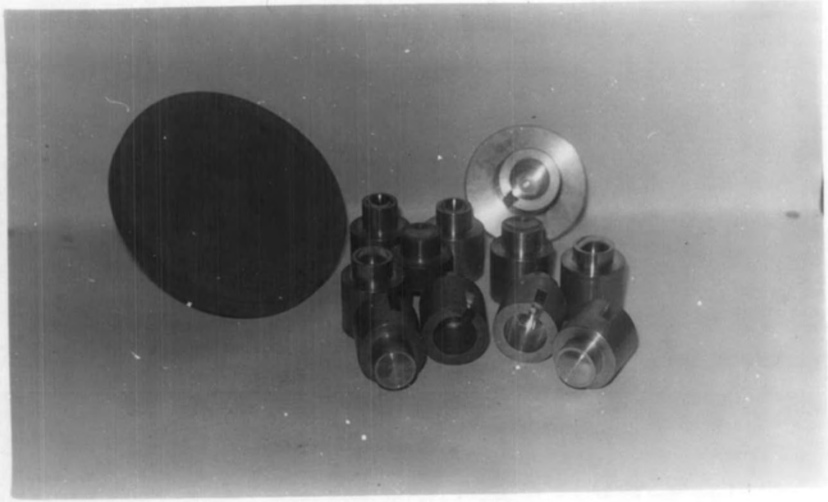


Fig.3-6. Tools.

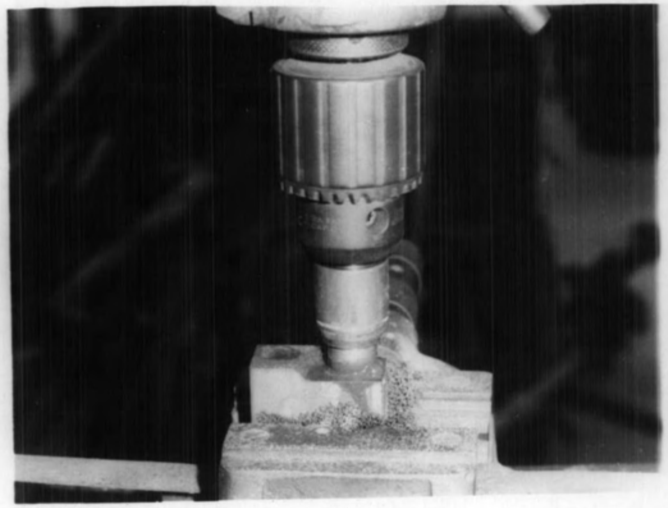


Fig.3-7. Rounding.

Fig.3-8. Sawing.

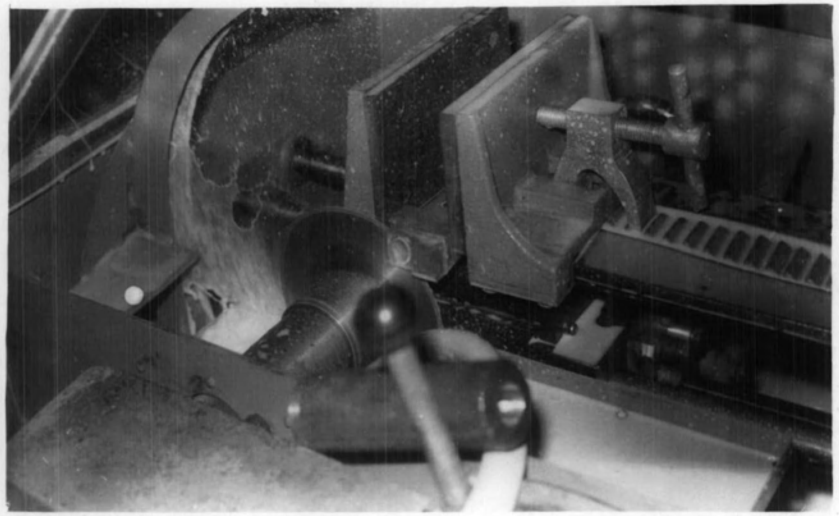
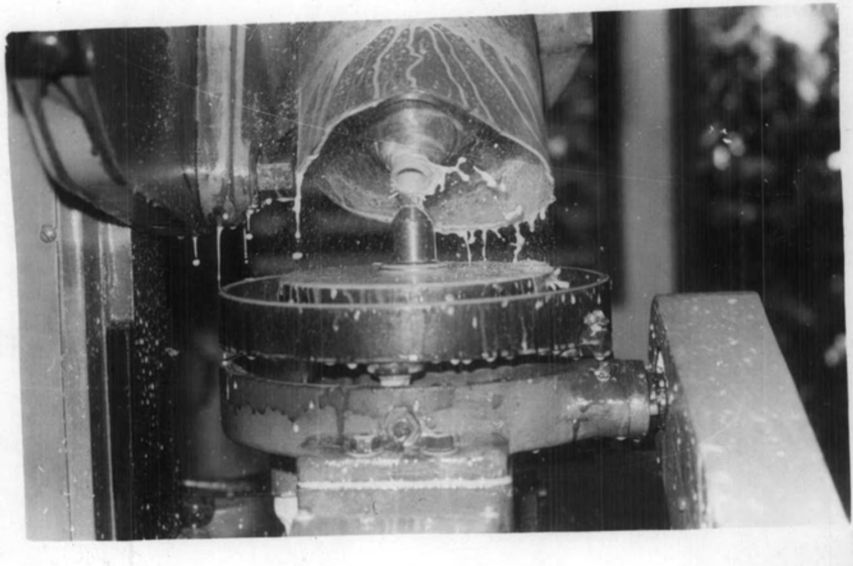


Fig.3-9. Milling.



No.	Abrasive material	Typical grain sizes (µm)
70	Carborundum (SiC)	376-540
320	"	26-41
400	"	17-24
1000	"	8-15
-	Cerium Oxide	0.6-1.0
where, 1 mm. = 1,000 µm.		

Table 3-4. Abrasive material grain sizes.

3.4.4 Trueing

Trueing is done by grinding to the correct curvature with carborundum no.320 and no.400 respectively. Grinding concave and convex surfaces were done by hand, with the aid of a rotating convex or concave cast-iron tool at moderate speed. Carborundum no.320, mixed with water to form paste, was smeared between the tool and the lens. The lens was moved slowly back and froth with light hand pressure, so that all areas of the tool and the lens were in contact. Lens surface was ground until smooth and then followed by a similar grinding using carborundum no.400 (see Fig. 3-10).

3.4.5 Smoothing

This operation was similar to trueing but a brass tool and carborundum no.1000 were used instead to obtain a smoother lens surface.

3.4.6 Polishing

The pitch polishing tool was made for polishing the lens surface. Polishing gives the surface its final finish. Cloth over pitch technique was used in this step and which is explained as follows :

1. Turpentine was added into pitch and heated until it melted. The pitch was then stirred to intimate mixture. Test for the best pitch viscosity was obtained when a nail could penetrate into the pitch at the shop working temperature.

Fig.3-10. Trueing.

Fig.3-11. Pitch polishing tool making.

Fig.3-12. The constructed lenses.

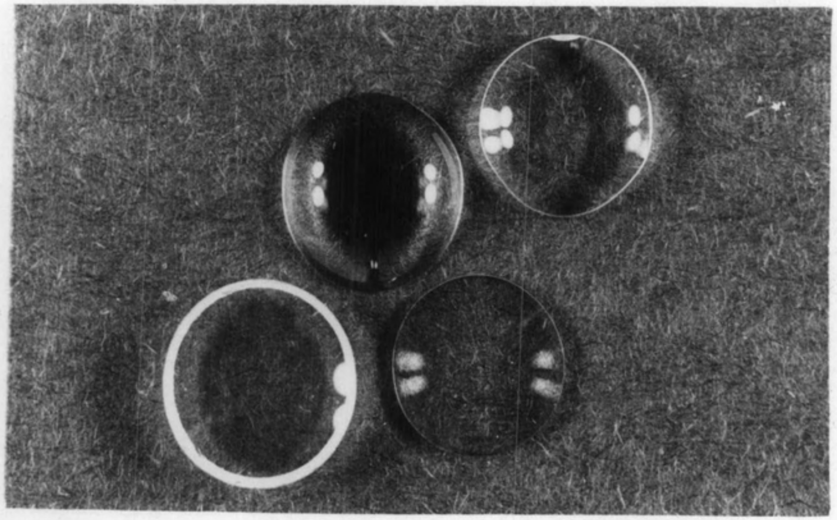
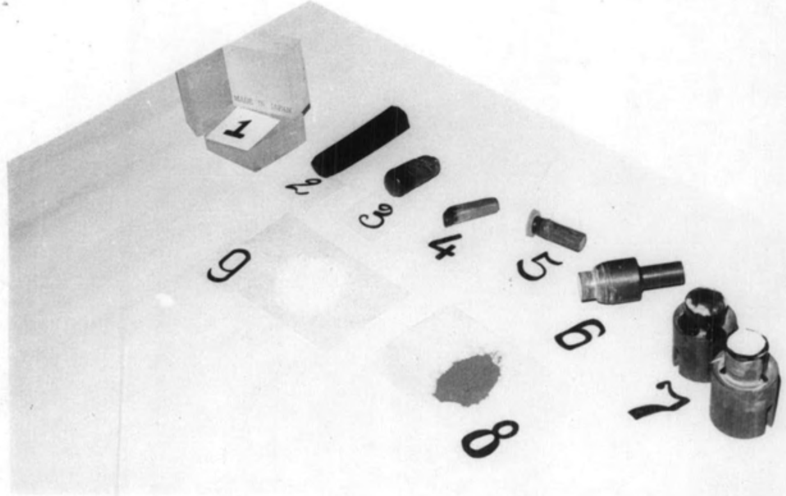


Fig.3-13. The materials as used for making lense.



2. The melted pitch was then poured on to the hot tool. When it was becoming harder, a piece of cloth was put on to the pitch and it was pressed on with a surface of lens to be polished. The correct curvature of the pitch polishing tool was formed by this technique and is shown in Fig. 3-11. The pitch polishing tool and cerium oxide mixed with water were used to polish a lens surface in the manner similar to trueing but the rotating tool was set at a lower speed.

3.4.7 Centering and edging

One method of centering the lens on the spindle, in order that the optical axis coincides with the axis of rotation and which is still widely used, consists of mounting the lens with pitch or wax so that one of its polished faces is in good contact with the lip of a cup which runs true on the spindle. The lip must lie in a plane perpendicular to the axis of rotation and be circular with its centre on the axis. To insure that the lip is concentric and perpendicular to that axis, it is trued with a turning tool while mounted on the spindle. This insures that the centre of curvature of the surface which is against the lip lies on the axis of rotation. A little heat applied to the cup will soften the pitch or wax enough to permit the lens to be slid along its face in contact with the cup, which is pivoted about the centre of curvature of that face. A stick of soft wood may be used to slide the lens without scratching it by pressure on the outer face while the spindle is slowly rotating.

A small light source is observed by reflection from the outer surface with a telescope. The source and telescope are rigidly mounted to the frame of the machine. If the reflected image does not move while the spindle and lens rotate, the centre of curvature of the outer surface is also on the axis of rotation. The lens is therefore in proper position for its edge to be ground. Some machines are equipped with hollow spindles so that a beam of light may be sent through the lens. If this beam does not move with the rotation of the lens, both surfaces have their centres of curvature on the axis of rotation.

The lens is now centred on the axis of rotation while the pitch or wax are cooled. The rotating lens is now ready to be edged using a diamond wheel.

The constructed lenses are shown in Fig. 3-12. The materials, which were used in the process of lens making are shown in Fig. 3-13. They are:

1. Optical glass
2. Pitch
3. Sticky wax
4. Sealing wax
5. A small lens attached to a rod of wood
6. Trepanning drill
7. Pitch polishing tool
8. Carborundum powder
9. Cerium oxide powder