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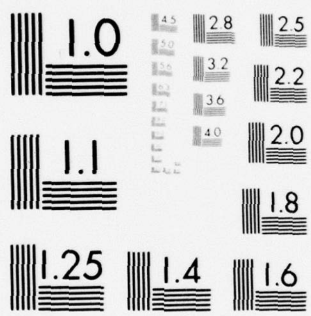
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HIGH SPEED FABRICATION OF PRECISION OPTICS

by

Martin H. Horchler

October 1976

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Manufacturing Technology Directorate

FRANKFORD ARSENAL · U.S. ARMY ARMAMENT COMMAND · PHILADELPHIA, PENNSYLVANIA 19137

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This study was an effort to reduce the time required to manufacture high quality military fire control lenses by utilizing high speed production techniques currently being used to produce medium quality optics. The effort was successful, and the results as well as the procedures for making the tools and using the techniques are summarized in this report. Some work was done on loose abrasive and barrel tumbling methods and is reported in the Appendix. It was unsuccessful.

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INTRODUCTION

The manufacture of precision optics is an extremely conservative field where quality and production rates still depend primarily on the skill, experience, and motivation of the individual optician. Recent years saw tremendous advances in the manufacture of electronic circuits and the machining of metals; however, during this same time period, very little has changed in the field of optical element manufacture.[1] (The last major breakthrough in this field occurred around the time of WWII with the development of diamond impregrnated tools.) This plus the high rate of inflation in recent years creates a situation where the price of the optical components of a system becomes relatively high compared to its electrical and metal parts components.[2] However, the development of lasers and large scale integrated circuits has created an ever growing demand for precision optics. At the present time, there is pressure on the optical element manufacturer to find new methods of fabricating precision optics.

Optical elements can broadly be divided into commercial optics and high quality optics. Commercial optics are those elements which go into a large volume product, and are manufactured by high production methods. Shops which specialize in this type of optics will spend considerable time and money in setting up a production process; however, once set up, production will be handled by semi-skilled operators. The quality of such optics is not necessarily poor. Since the primary concern is low cost production, chances are that the product will have loose tolerance requirements.

High quality precision optics, on the other hand, usually involve small lot production. All the critical manufacturing steps are handled by highly skilled opticians whose primary concern is excellence. This excellence has its price. The time required to make a precise optical element can be as much as ten times longer than that to make a similar commercial element using high speed techniques. Since few customers require this quality, the number of capable shops and skilled opticians are steadily declining.

The optical elements that go into military fire control instruments are typically high quality, low production optics which can best be produced by precision optical shops. The two major problems confronting the military, a major consumer of precision optics, are, increasing prices and decreasing production facilities.

---

[1] D.F. Horne, "Optical Production Technology"; Crane, Russak & Co., Inc., N.Y., N.Y, 1972.

[2] Anderson, Michals Asso., "Description of Manufacture Optical Elements for Fire Control Instruments"; (PB 157062) U.S. Dept. of Commerce 1951.

The purpose of this project was to investigate the feasibility of using high speed lens production methods to produce military fire control optics without sacrificing quality.[3]

BACKGROUND

The Frankford Arsenal Optics shop(where this investigation was conducted)is a typical example of a high quality lens production facility. The shop has both the expertise and the tooling required to fabricate practically every lens design used by the military. However, it can only meet a very small part of the total military optics requirements of the U.S. Army.

The current method of lens fabrication, employed by the Frankford Arsenal Optics shop, consists of the following steps:

1. Coring - Oversized lens blanks are cut from slab glass with diamond coring drills (Figure 1), or pressed blanks are used.

2. Rough Size - The blanks are ground parallel to a uniform thickness at least .03 inches greater than the maximum blank thickness allowed. This step can be eliminated if the production size is large enough to facilitate the use of pressed blanks.

3. Rough Generating - The two spehrical curves are generated (Figure 2) using a 120 grit diamond ring tool.

4. Fine Generating - The speherical surfaces are regenerated with a 500 grit diamond tool. The center thickness is now within + .002 of the maximum center thickness.

5. Bench Grind - The generated lens blanks are hand ground with 30 micron carborundum loose abrasive and a cast iron lapping tool (Figure 3) to improve the sphericity and surface finish of the generated surface.

6. Beveling - Lens blanks are beveled to eliminate the possibility of glass flaking off the edges and scratching the surface during later operations.

7. Backing Up - Pitch buttons are molded on one side of the lens with a quarter inch layer of sealing wax.

---

3 W.J. Rupp, "Mechanism of Diamond Lapping Process", Applied Optics Vol. 13, No. 6, June 1974.

8. Blocking - The wax coated lens is placed in a blocker tool with the coated surface exposed (Figure 4). A mounting tool is heated and the two tools are pressed together. The wax bonds the lens to the mounting tool to form a lens block.

9. Fine Grinding - The curve of the block of lenses is established by grinding the block with a precisely made spherical cast iron lap and 8 micron loose carborundum.

10. Polishing - the ground surface is polished to the required finish with a lap made of pitch (formed to match the lens curve while heated to its flow temperature) and a cerium oxide slurry.

11. Steps 7 through 10 are repeated for the second curve of the lens.

High speed techniques, associated with high production, follow a somewhat different process. Spot blocks, spherical blocks with machined cavities for lens blank retention (Figures 5 and 6) are used. Hence all operations after blank acquisition are gang operations performed on blocks of lenses. In addition, diamond pellet grinders and polyurethane polishers are used.

The sequential steps using high speed/high production technics are as follows:

1. Core blanks, or procure pressed blanks.

2. Mount blanks on spot blocks.

3. Generate first curve.

4. Fine grind.

5. Polish.

6. Steps 2 through 5 are repeated for the second curve of the lens.

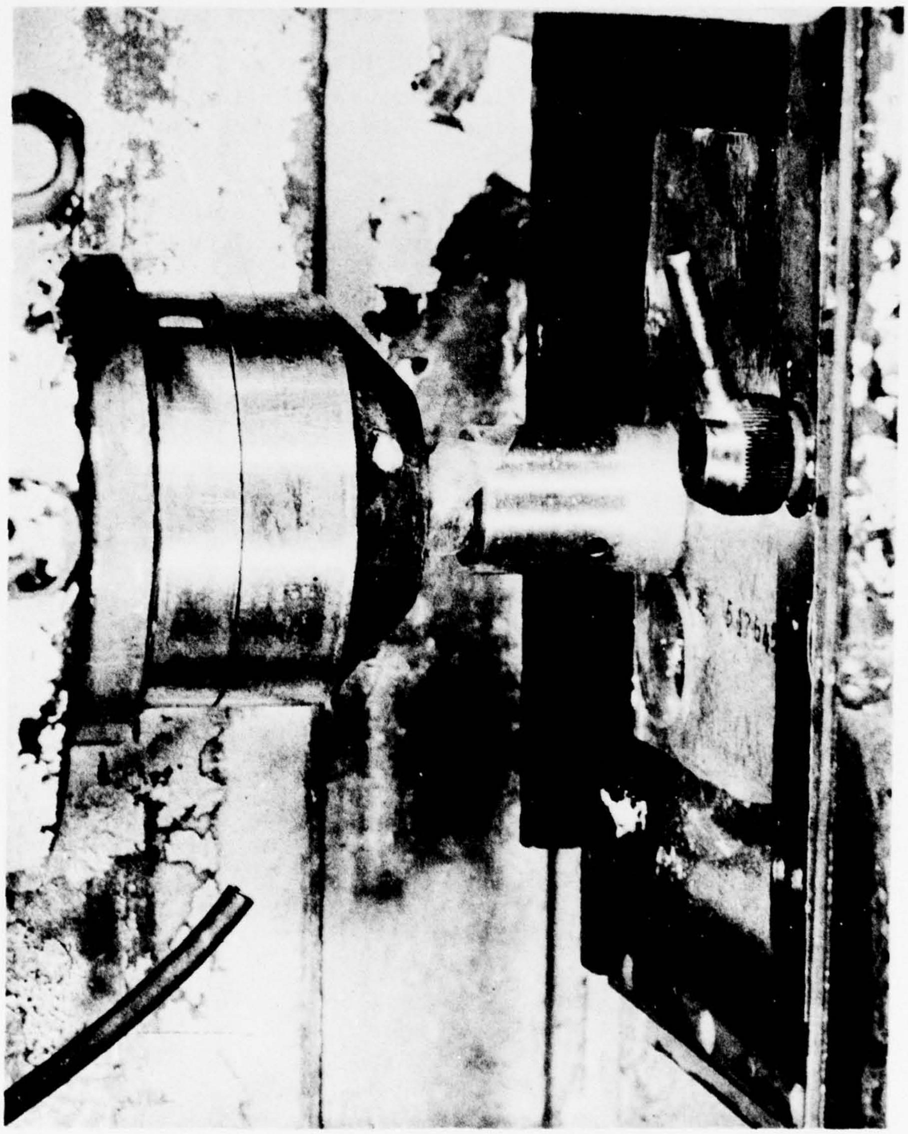

Figure 1. Coring

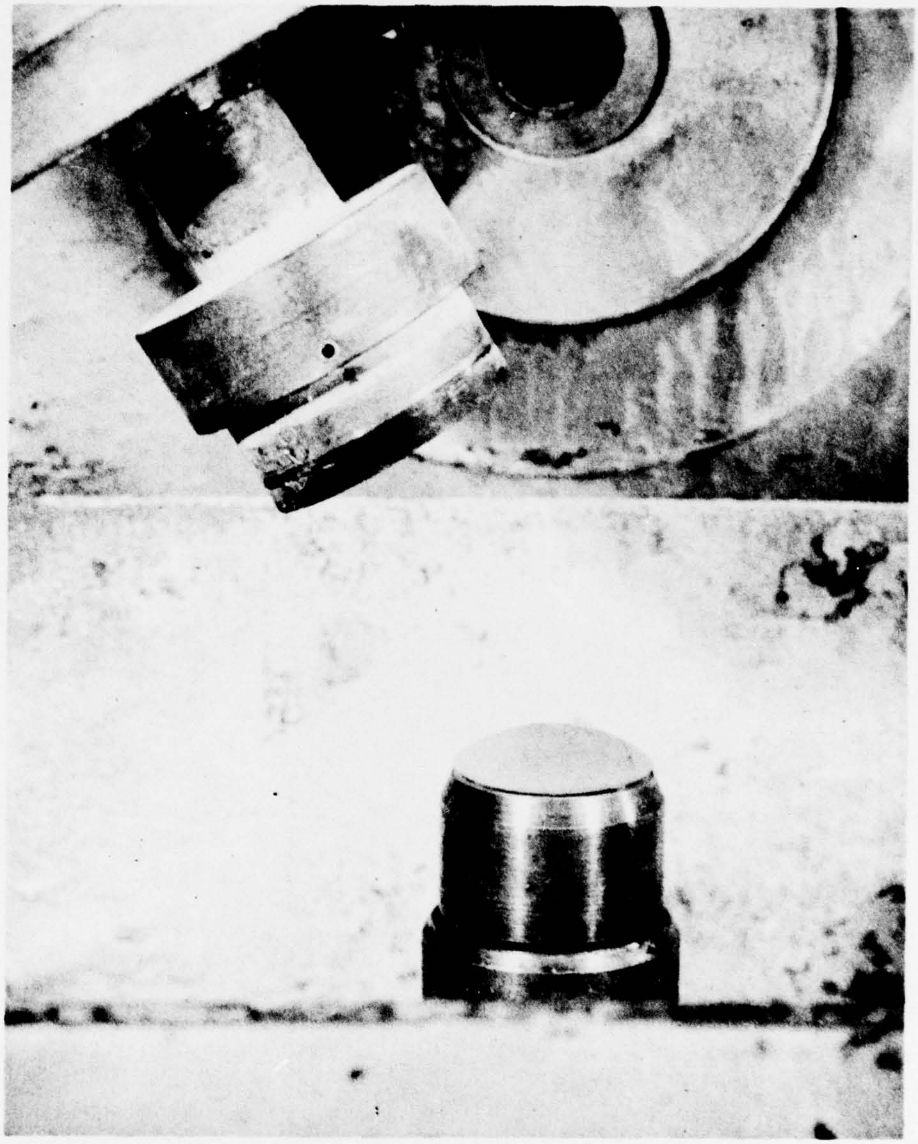

Figure 2. Generating

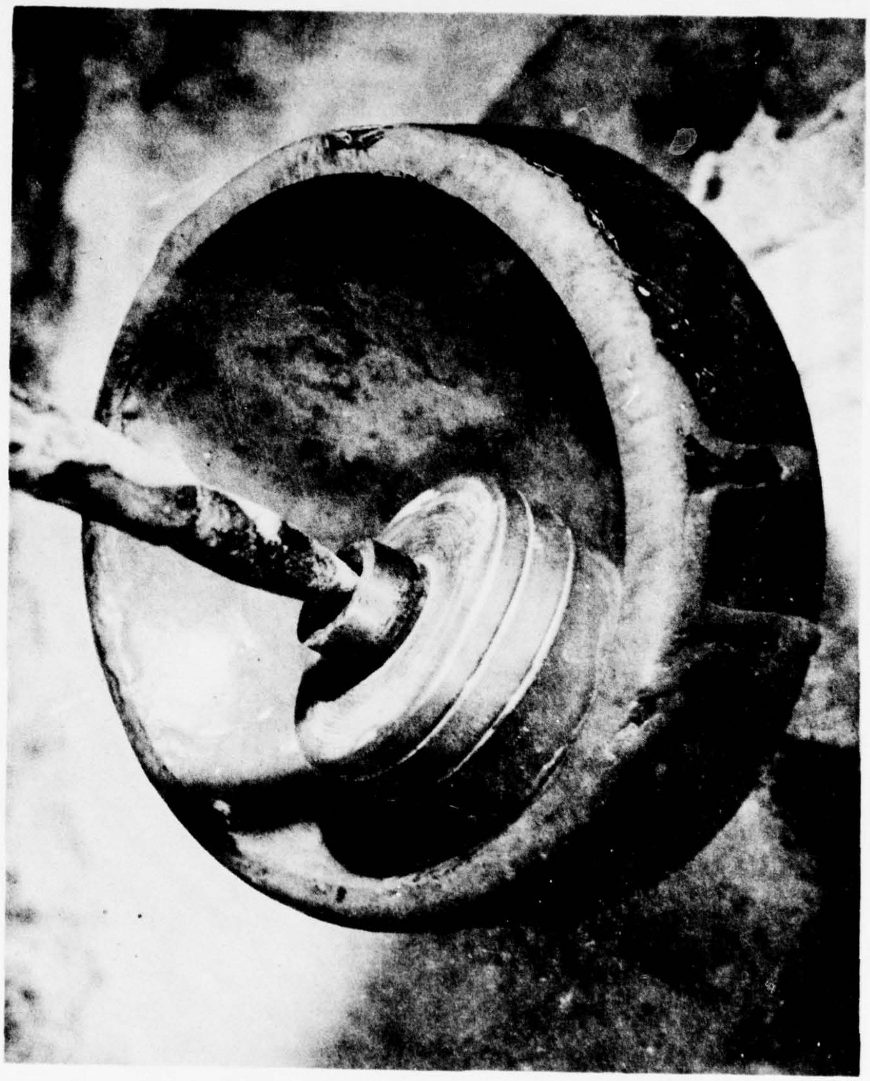

Figure 3. Rough Grinding

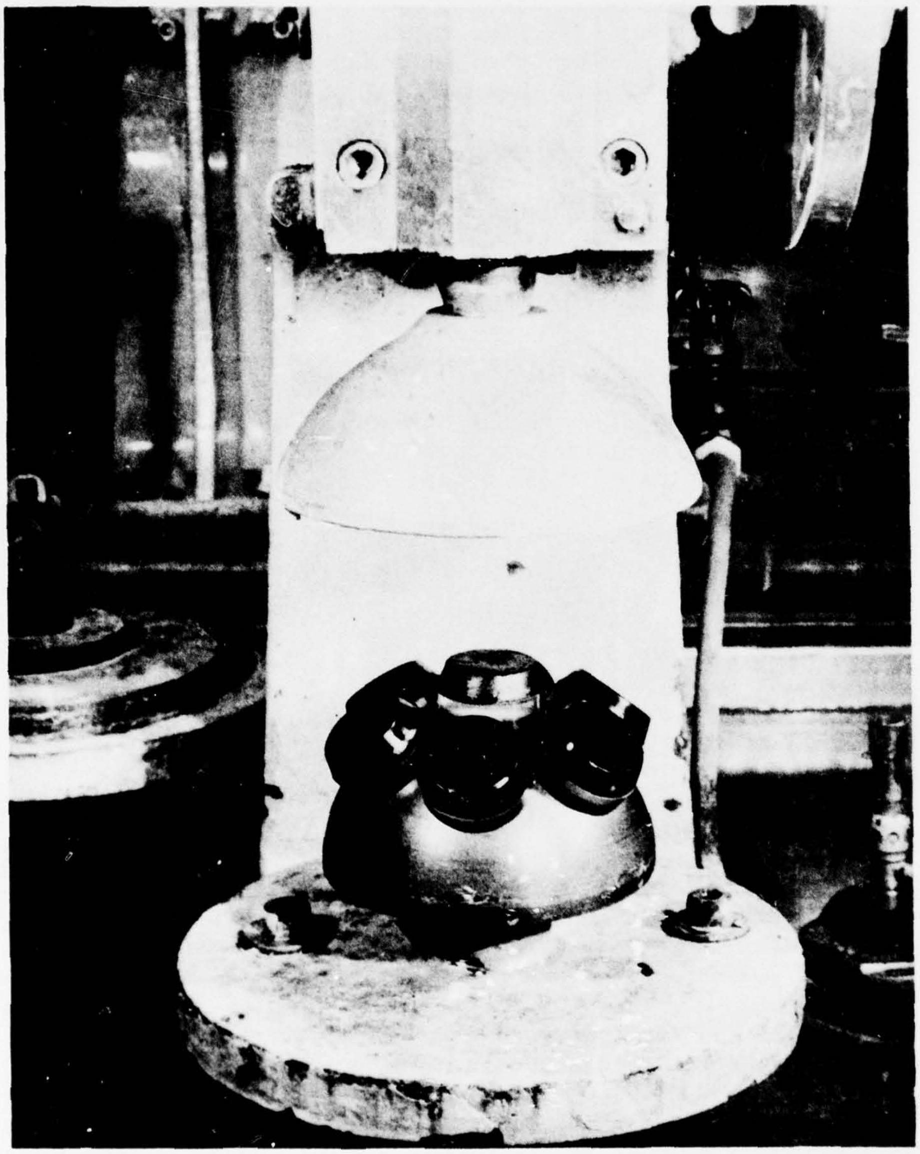

Figure 4. Pitch Button Blocking

PROCEDURES

A typical lens, Figure 7, was selected to be the experimental optical element for this study. The required tools were designed. Tool components were made and/or procured and, where applicable, assembled. Prototype production runs were then mad.

TOOL FABRICATION

1. Spot blocks were designed as shown on Figures 5 and 6, and were made to the indicated tolerances.

2. Diamond Pellet Grinders[4]

(a) Components

1. The purchased diamond coated pellets used in this study were ¼ inch in diameter, ¼ inch in length and had a 1/8 inch layer of 50 percent concentration of brass bonded 10 to 20 micron diamonds on one end.

2. The pellet mounting block was designed and made in accordance with Figure 8.

3. The forming tool, Figure 9, is a precisely made cast iron block conforming to the radius to be ground.

(b) Fabrication

1. The forming tool is coated with a thin layer of low melt temperature wax.

2. The pellets are heated, on a hot plate, to about 180°F and arranged in a random pattern on the forming tool, Figure 9, with their diamond coated faces making intimate contact with the surface of the forming tool. Upon cooling, the wax forms a temporary band.

3. The mounting block is coated with an epoxy and it and the forming tool are brought together in axial alignment, Figure 10.

4. After the epoxy cures, the temporary wax bond is broken by the application of a small amount of heat.

(c) Break-in

Though formed in a precise manner the pellet faces must be lapped so that they assume the contour of the lenses to be ground. This is done by grinding the pellet tool on the forming block with 30 micron loose carborundum.

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[4] University of Rochester, "Rationalization of Manufacturing Methods in Optical Fabrication" Final Report Contract DAAA 25-74

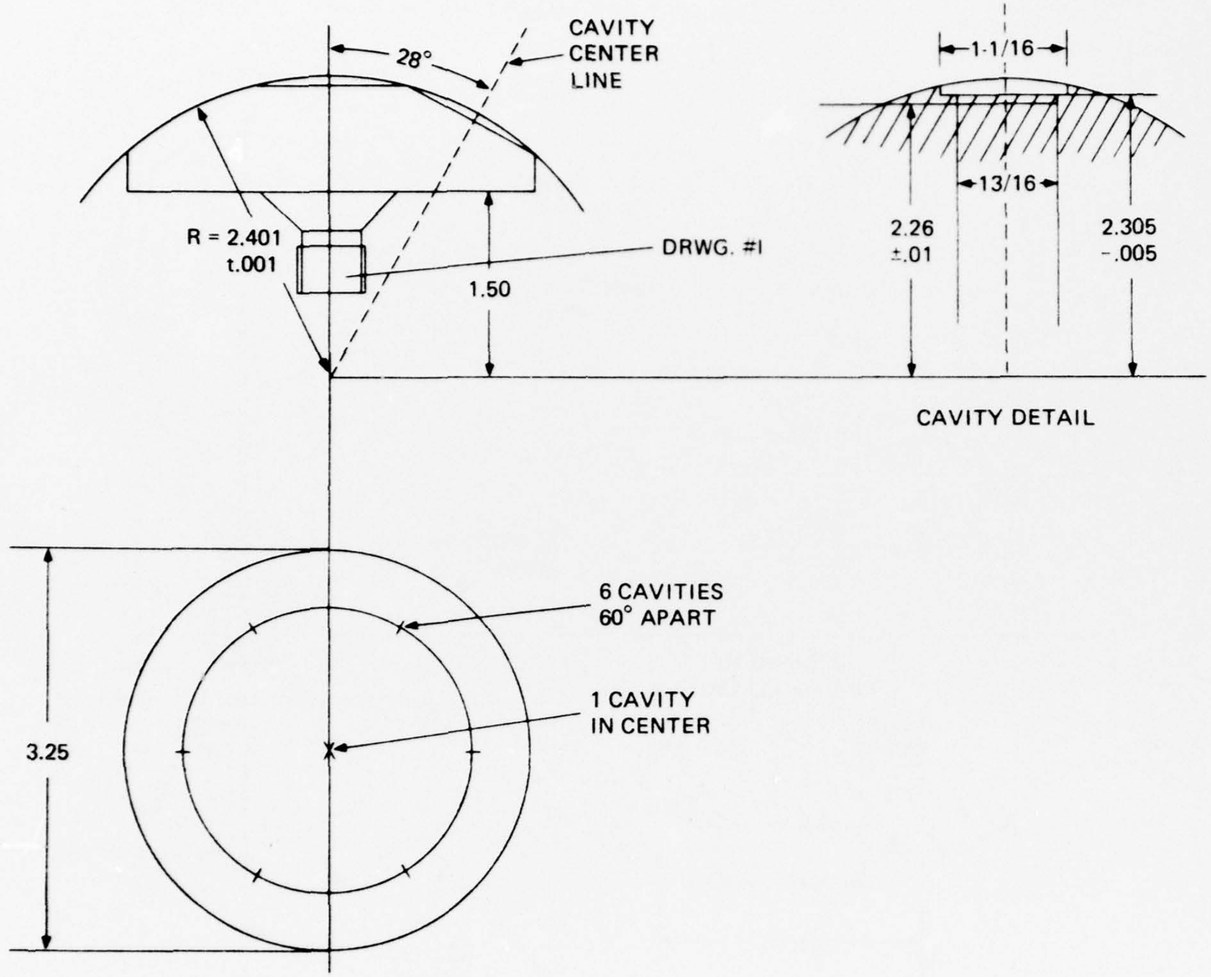


Figure 5. Spot Block Design for 2.529 Inch Surface

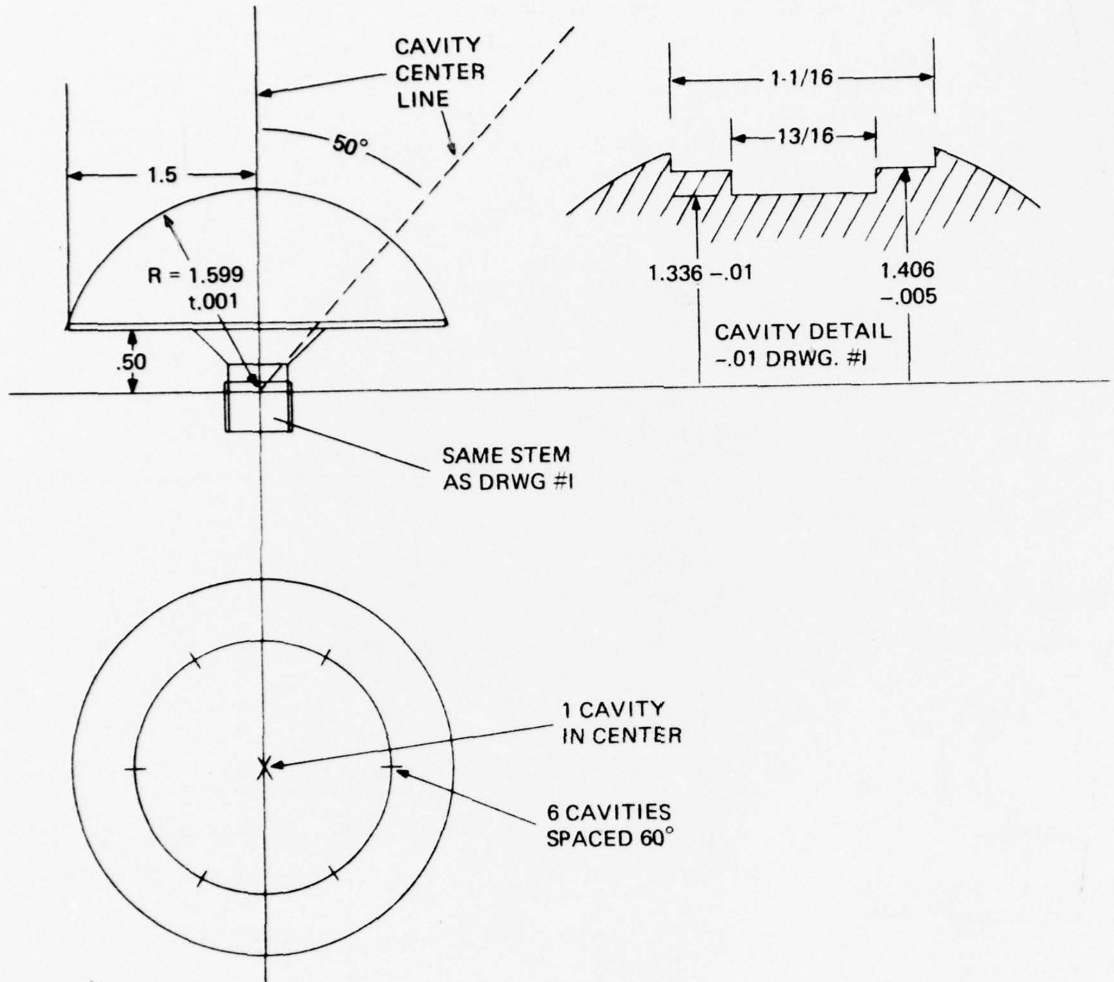
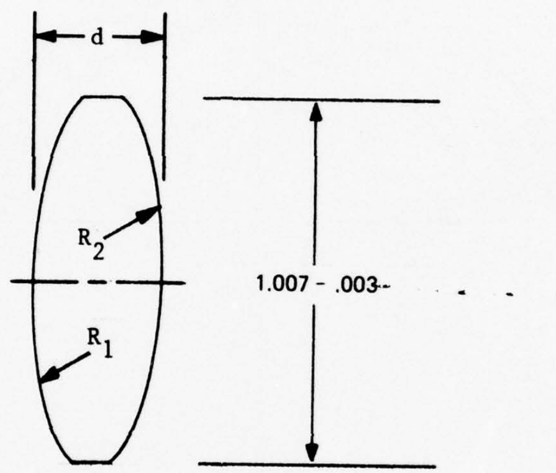
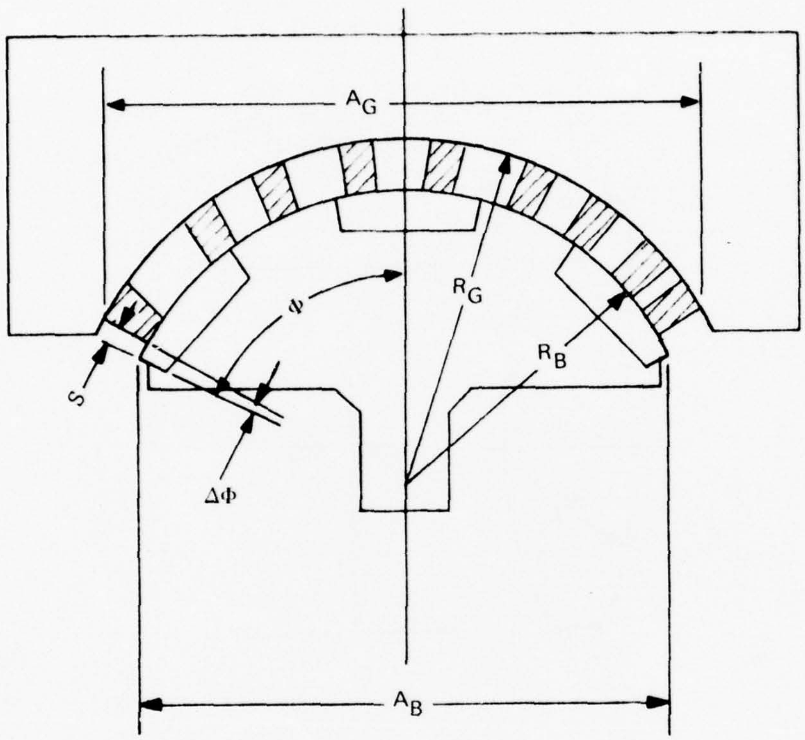


Figure 6. Spot Block Design for 1.688 Inch Surface



Clear Type	R_1	R_2	d
517 - 645	+2.529 ± .004	-1.688 ± .003	.217 ±.010

Figure 7. Lens Used for This Study



R_B = lens radius

ℓ = pellet length

S = Exposed arc of lenes when tools are aligned (¼ inch std.)

ϕ = ½ angle subtended by lenses

$\Delta\phi = \frac{S}{R_B}$, $\Delta\phi$ in radians

$\Delta\phi = \frac{1}{4R_B} \times \frac{180}{\pi}$, $\Delta\phi$ in degrees

$R_G = R_B + \ell$

$A_G = 2\ R_B\ \mathrm{Sin}(\phi - \Delta\phi)$ = Tool Aperture

$A_B = 2\ R_B\ \mathrm{Sin}\ \phi$

Figure 8. Pellet Grinder Design

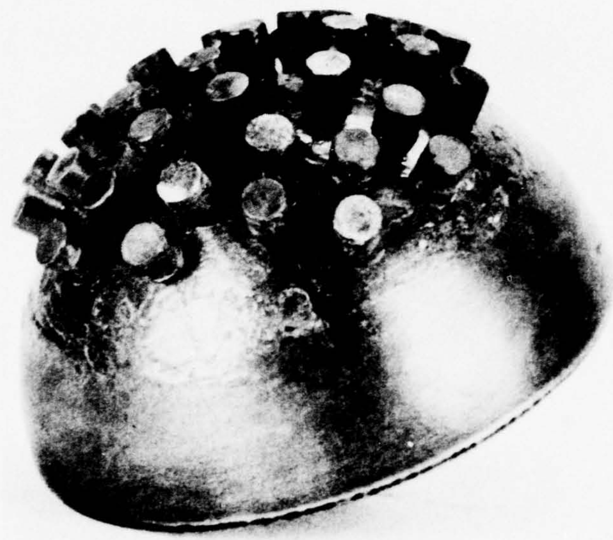


Figure 9. Temporarily Blocked Diamond Pellets

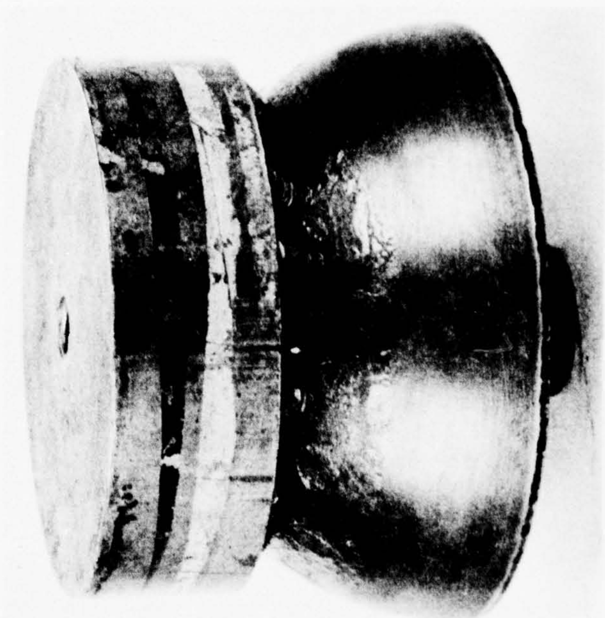


Figure 10. Diamond Pellet Tool Curing

3. Polyurethane Polisher (Figure 11)

Consists of sheet porous polyurethane bonded to a rigid spherical shell that is precisely machined.

PROTOTYPE PRODUCTION RUNS

A series of production runs were made using the high speed techniques shown in the preface and delineated below.

1. Lens blanks were cored out (Figure 1) with a 120 grit diamond core drill to a diameter .003 to .008 inches smaller than the spot block cavities.

2. Blanks were mounted on spot blocks.

3. The 1.688 curve was generated on blocks, Figure 12, with 120 grit ring tools.

4. The generated blanks were ground with the appropriate pellet grinder on a high speed radial machine, Figure 13, at 1000 R.P.M. for a period of 30 seconds. See Figure 14. During this operation, a mixture of 1 part "Quaker Grind" to 10 parts water was center-fed as a lubricant.

NOTE: The first attempt at pellet grinding resulted in scratches on the lens surfaces. This was attributed to the sharp edges created on the pellets in forming pellet faces to a concave shape. A new tool was made with beveled pellets, and the problem was eliminated.

5. Polished the ground blanks at high speed with a polyurethane polisher, Figure 7.

NOTE: The polyurethane polisher produced a high quality surface finish in a very short time; however, it introduced some irregularities of form that had to be removed by conventional polishing techniques.

6. The blanks were deblocked and cleaned and steps 2 through 5 were carried out on the obverse side of the blanks, See Figures 15, 16, and 17.

The above process was repeated on 125 blocks (7 blanks per block) on each of the lens curves shown on Figure 7. Neither diamond pellet grinder was redressed or modified during these runs. Since the polyurethane polisher introduced problems, conventional polishers were used to complete the production runs. A total of 1750 lenses were generated ground and polished.

W.J. Rupp, "Mechanism of Diamond Lapping Process", Applied Optics Vol. 13, No. 6, June 1974.

4

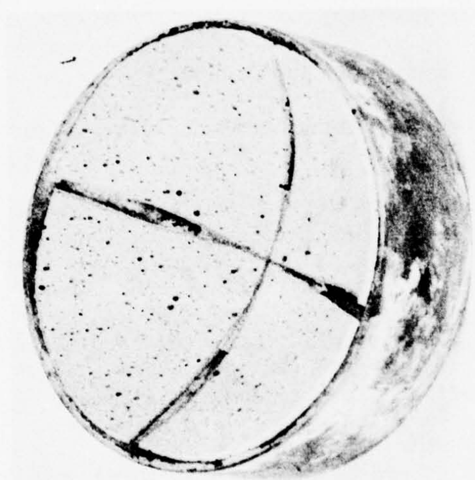


Figure 11. Polyurethane Polisher

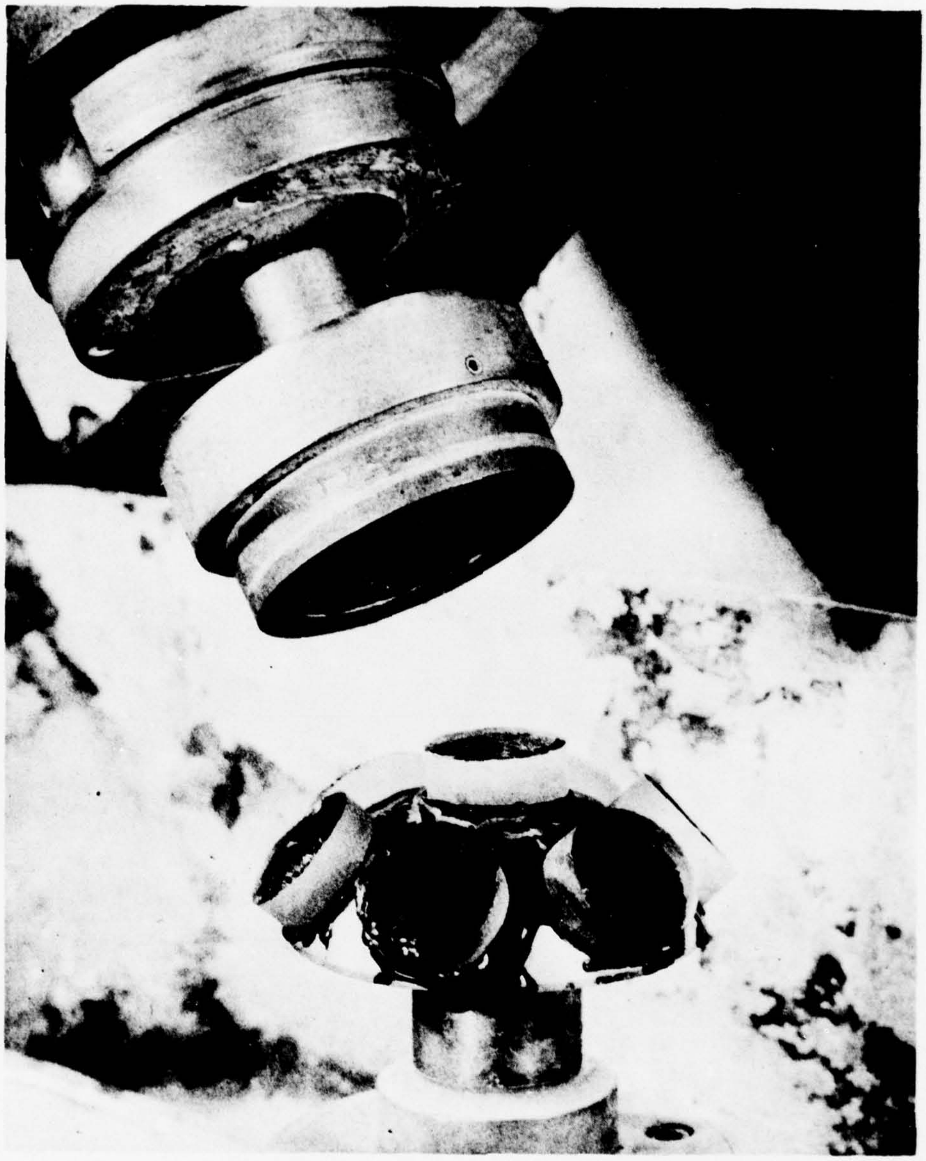


Figure 12. Generating the 1.688 Inch Surface
(No Thickness Operation Blanks were
Mounted Immediately After Coring)

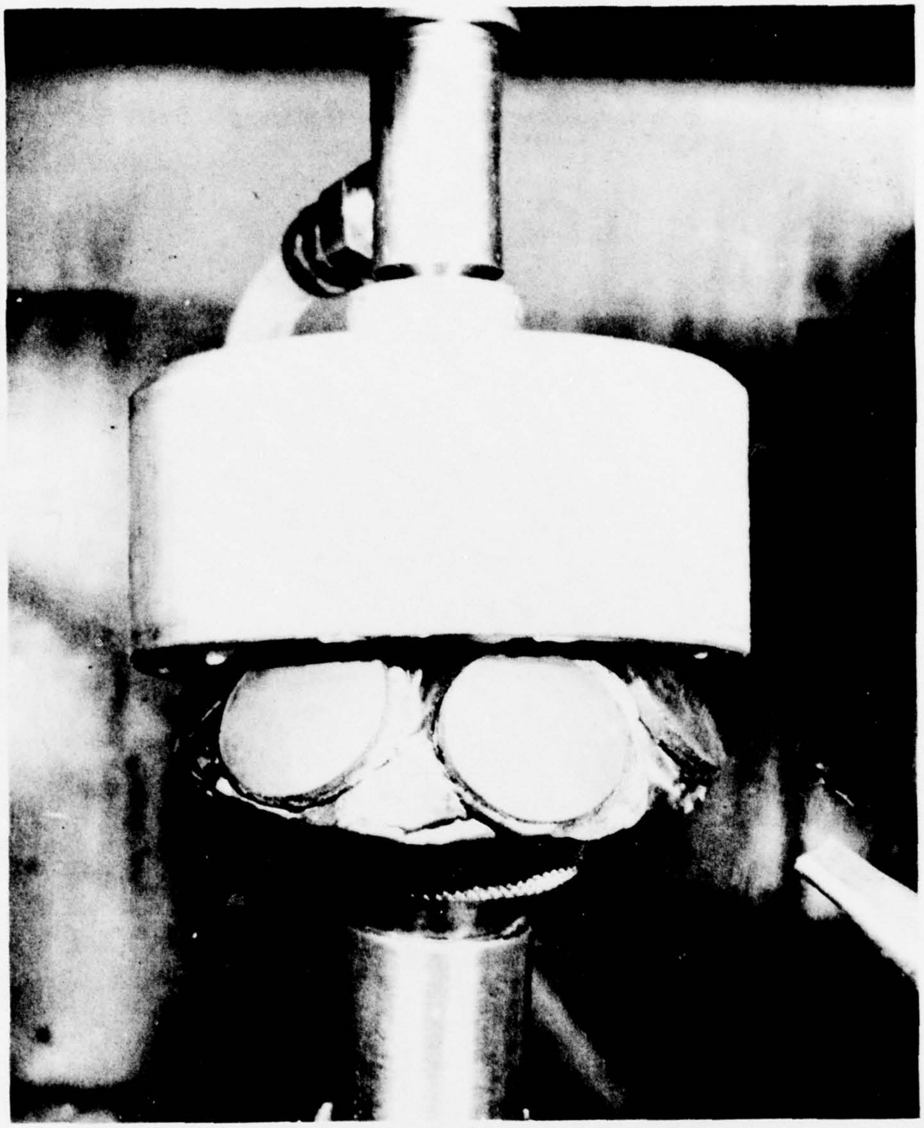


Figure 13. Pellet Grinding the 1.688 Inch Block With High Speed Radial Machine

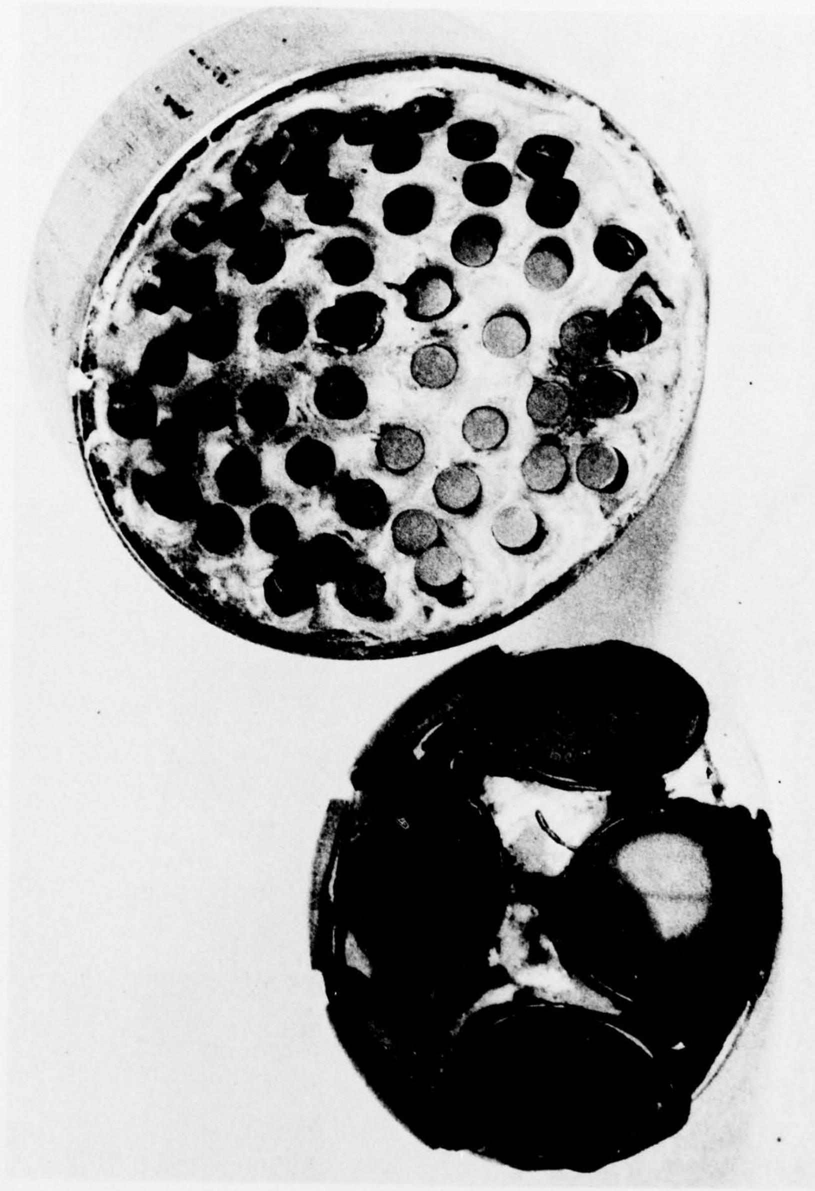


Figure 14. Diamond Pellet Tool and Ground 1.688 Inch Block

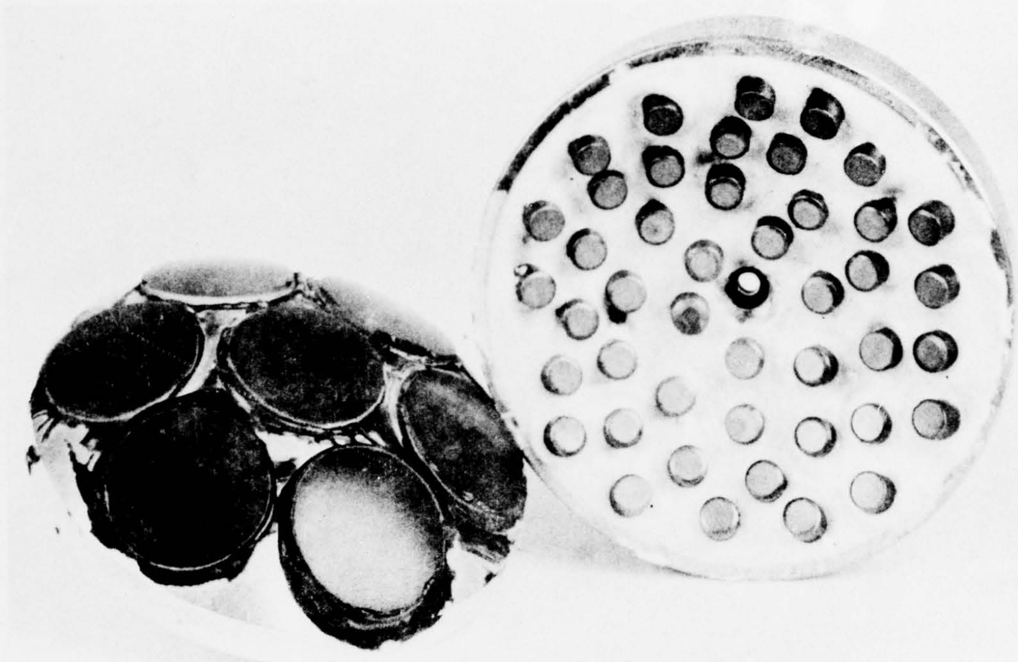


Figure 15. Diamond Pellet Tool and Ground 2.529 Inch Block

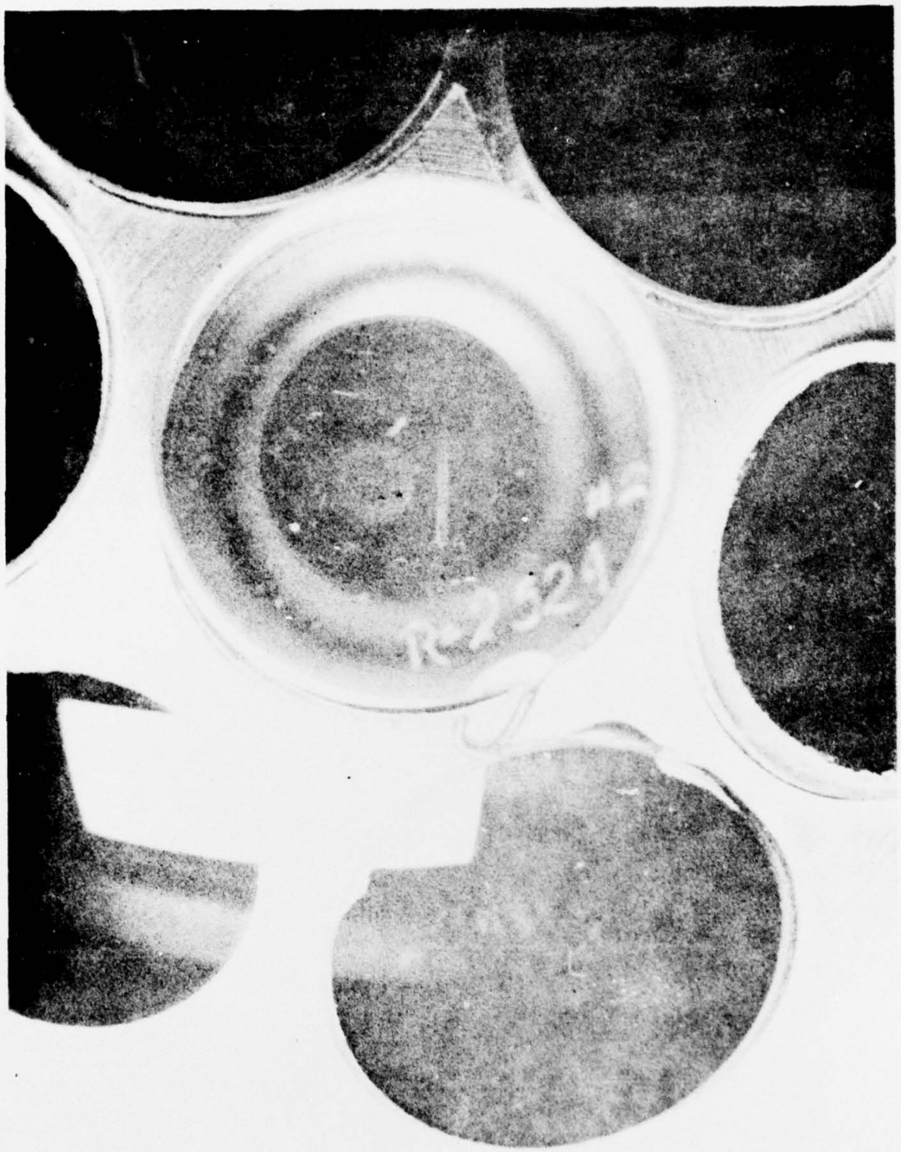


Figure 16. 2.529 Inch Surface Polished for 20 Minutes After Pellet Grinding.

Figure 17. 1.688 Inch Surface Polished for 20 Minutes After Pellet Grinding.

RESULTS

All optical surfaces produced in the prototype production runs using the high speed techniques delineated in the study were brought to a high quality finish in approximately 30 minutes per block. The curves were within 3 rings of their respective test glasses and surface regularity was within a quarter wave length of light. There was no evidence of scratches or generating marks. The diamond pellet tools remained sharp and clean throughout the production runs so long as coolant was centerfed.

Polyurethane polishers produced a fine quality finish in a very short time, but introduced irregularities of form that were undesirable.

TABLE 1. Comparison of Fabrication times, per Lens Element with Pitch Button and High Speed Method.

Production Step	Conventional Time/element (Minutes)	High Speed Time/element (Minutes)
Coring	.50	.50
Thickness	.50	N.A.
Generating (120)	.35	.5
Generating (500)	.35	N.A.
Hand Grind	.75	N.A.
Beveling	.50	N.A.
Backing Up	1.00	N.A.
Blocking	1.25	1.00
Fine Grind	2.50	.1
Polishing	2.50	2.50
TOTAL	10.29	3.7

CONCLUSIONS AND RECOMMENDATIONS

The time to fabricate a lens element is greatly reduced using high speed techniques, without a loss in quality. One large factor is the grinding time reduction brought about by the use of diamond pellet tools, and the other is the process changes brought about by the use of spot blocks in place of pitch buttons.

Diamond pellet tool life is adequate for long or short production runs with proper coolant feed.

The cost of making spot blocks and pellet tools, as was done in this study, is obviously to high to justify these methods on short run production lots; however, a computerized method of design and fabrication of spot blocks has been developed[5], and a "Manufacturing Methods and Technology Project #7745" Diamond Tool Fabrication is now underway.

Interfacing the three studies should produce a vehicle for using "High Speed Techniques" for all lens production. Additional work should be done on polyurethane polishers, since the results obtained with them were not conclusively bad.

[5] R.J. Cavaliere, C. Zimmerman, "Optical Tools Design & Manufacture Automated" Frankford Arsenal Unpublished Report.

REFERENCES

1. D.F. Horne, "Optical Production Technology"; Crane, Russak & Co., Inc., N.Y., N.Y. 1972.

2. Anderson, Michals Assoc., "Description of Manufacture Optical Elements for Fire Control Instruments"; (PB 157062) U.S. Dept., of Commerce 1951.

3. W.J. Rupp, "Mechanism of Diamond Lapping Process", Applied Optics Vol. 13, No. 6, June 1974.

4. University of Rochester, "Rationalization of Manufacturing Methods in Optical Fabrication" Final Report Contract DAAA 25-74 C0692, 1975.

5. R.J. Cavaliere, C. Zimmerman, "Optical Tools Design & Manufacture Automated" Frankford Arsenal Unpublished Report.

GLOSSARY

Test Glass - A precisely made lens of opposite curvature to the lenses to be tested used to check curvatures.

Newton Rings - Interference fringes formed by the diffraction of monochromatic light when reflected by the tested surface through the test glass. One ring per inch of diameter equals a gap of 11 microinahes.

Surface Irregularity (form) - Refers to the departure from sphericity in an optical element when tested with a test glass and indicated in rings.

Sharp - A lens radius approaches sharpness as its radius decreases.

Flat - A lens radius approaches flatness as its radius increases.

High - A lens curve is high when it is flatter than its test glass.

Low - A lens curve is low when it is sharper than its test glass.

APPENDIX

LOOSE ABRASIVE AND BARREL TUMBLING METHODS IN THE FABRICATION OF OPTICS

I LOOSE ABRASIVE MACHINING

Loose abrasive machining can be divided into two general categories:

1. Abrasive Jet Machining (AJM) is basically a cutting operation, it uses a well defined abrasive stream, exiting from a nozzle of .005 to .032 inches wide, to cut extremely hard and brittle materials. The distance that the nozzle is from the work piece determines the definition of the cut and the cutting rate. The stream tends to diverge at about 1/16 of an inch from the nozzle and optimum cutting is between 1/4 to 1/2 inches. The depth of cut, however, is determined by the material. The primary advantage of AJM is that the abrasive stream, composed of 10 to 50 micron sized particles traveling at 1100 ft/min, has very little momentum, and can, therefore, be used for shock free cutting of extremely fragile parts.

2. Deflashing and deburring machines. These machines are quite similar to AJM machines in fact AJM machines can be used for this purpose by simply increasing the nozzle to work distance sufficiently to allow the stream to diverge to several square inches. Naturally the geometry of the nozzle is not as critical in this operation as it is for precision cutting. These machines can also be used for cleaning or frosting and will produce surface finishes of between 6 to 55 micro inches RMS depending on the abrasive particle size.

In the fabrication of optics there is only one cutting operation, which is the cutting or curing of blanks from slab glass. In large production lots molded blanks are preferred because of the tremendous waste of glass in coring,however, coring is the most practical way of forming blanks when small lot sizes are involved.

Coring is done with 80 grit diamond core drills which demonstrate the following performance characteristics:

1. They can handle any thicknesses of optical glass and can make a 1/32 of an inch wide cut all the way through.

2. They can remove glass at the rate of 10 grams/minute.

3. They will last indefinitely if properly used.

4. They require only a recirculated lubricant for cutting.

On the other hand AJM demonstrates the following performance characteristics.

1. It can only cut glass to a depth of 1/4 of an inch (most optical glass is at least 3/8), and the stream at this distance from the nozzle has already diverged 30% from its original shape.

2. It can remove glass at the rate of .03 gram/min. using 50 micron sizes particles.

3. The nozzle should be replaced after 30 lb. of abrasive has passed through it.

4. The abrasive powder should not be reused.

There is no deflashing, deburring or frosting in the lens fabrication process. The only critical cleaning operation is the one which is performed prior to coating, however, at this stage the lenses are already finished, and loose abrasive cleaning would ruin the surface.

The surface finish obtained from either frosting or cleaning is in the range of rough and fine grinding (30 to 8 micro inches RMS), however, grinding is primarily a shaping process where the generator irregularities are removed. A ground precision optical surface is spherical to within a fraction of a wave, there is just no way that loose abrasive methods could achieve this.

A number of manufacturers of loose abrasive machines were contacted and the general consensus was that it has no application in precision optics.

These manufacturere were:

SS White Industrial Products
151 Old New Brunswick Rd.
Picataway, N.J. 08854

APM Corp.
1325 Industrial Highway
Southampton, Pa. 18966

Pressure Blast Mfgr Co. Inc.
41 Cahapel St.
Manchester, Conn. 06040

Cyclone Abrasive Blasting Equip. Co.
P.O. Drawer 8454
Stockton, Calif 95208

II BARREL TUMBLING

Barrel tumbling is a method of surface finishing where the work and abrasive are mixed in a container and agitated. The agitation is usually provided by rotating the container in a horizontal plain thereby causing the mixture to tumble. Another method is to vibrate the container.

Tumbling of ground lenses was tried with a mixture of Barnsite and lenses of various geometries. A very slight change in the surface finish of high spots on some lenses was noticed after 24 hours of tumble, however, all the lenses were chipped because they had been bumping one another. Water added to the mixture in an effort to eliminate chipping made very little difference, however, now the Barnsite pushed itself into the concave surface eliminating all possibility of ever polishing them.

At this point a manufacturer of vibrating tumbling equipment was contacted and given two lenses to try in his laboratory. These lenses had a double convex surface of 1.688 inch radius and a surface finish of 8 microinches RMS. After 96 hours of tumbling in a cerium oxide slurry the surface finish showed considerable improvement, however, the geometry of the surface was terrible and could not be evaluated with a test glass.

A small vibration machine was purchased and tried on additional lenses. Vibrating the slurry eliminated lens chipping however, no matter how long they were vibrated no lenses ever came near a good finish and always demonstrated the tendency of favoring the high spots and therefore destroying the surface geometry.

The manufacturer of the tumbling equipment was:

Vibrodyne Inc.
125 Sunrise Place
Dayton, Ohio 45407

CONCLUSIONS:

The possibility of using loose abrasive and barrel tumbling methods for fabricating precision optics was obviously suggested by someone completely unfamiliar with both the method and with optical fabrication. The critical requirement of a precision optical surface is not only that it have a high quality finish but also that it be spherical to within a fraction of a wave. The problem, therefore, is not simply to shine the surface but to shine it in a manner that assures regularity,i.e. spherical surfaces with rotating and oscillating spherical tools.

This is impossible to do with such uncontrolled processes as barrel tumbling and loose abrasive blasting.

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