OPTICAL FABRICATION
CHAPTER 40
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40.1 INTRODUCTION

Traditional optical fabrication is the craft of producing spherical surfaces of about 0.1 micrometer peak-to-valley accuracy using common materials and relatively simple techniques applied in a consistent manner. Recently developed techniques can also produce nonspherical or steeply aspheric surfaces to similar accuracies. Many of the techniques used in optical fabrication tend to be unfamiliar because most optically worked materials are brittle (as opposed to metals which are ductile and easily worked with familiar tools) and the surfaces are truly spherical, or nearly so, as opposed to many other technical products that have rectilinear features.

Additional barriers to understanding optical working of materials include the statistical nature of producing geometrically perfect spheres and the actual mechanisms that produce specular surfaces during polishing. Even the most knowledgeable workers do not have a rigorous understanding of why two surfaces become more like each other as they are rubbed together using traditional methods as is evidenced by a lack of literature on that subject.

Polishing is likewise a rather miraculous process. It can improve the surface finish of ground glass by nearly three orders of magnitude, it uses unsophisticated materials, and it can be accomplished by persons with little training in polishing. On the other hand, the actual nature of the process by which this is accomplished has probably been debated since Newton’s time and certainly since Lord Rayleigh’s. Works by Preston, Silvernail, Bach, Golini, and Cook are now shedding some light on the nature of the glass-polishing mechanisms.

In this article, we introduce the various fabrication steps involved in producing accurately polished glass lenses and mirrors, touch on the somewhat different methods used to produce flats and prisms efficiently, and then address crystalline optics such as are used in the UV and IR. Then we address aspherics and the diamond-turning of optical surfaces. Finally, we say a few words about purchasing optics.

40.2 BASIC STEPS IN OPTICAL FABRICATION

The five basic steps in optical fabrication consist of\(^\text{7-10b}\):

- rough shaping the raw glass into a blank about 1 mm oversize to the finished part
* generating the optical surfaces to the correct shape to better than 0.1 mm
* loose abrasive lapping the surfaces to remove damage due to generating and producing a curve good to a few micrometers of the desired shape
* polishing the ground surface to make it specular and accurate to about 0.1 μm
* edging the lens element to make the periphery coaxial with the optical axis as defined by the two lens surfaces.

Because glass is a brittle material, all material removal must be done by grinding rather than the more familiar machining processes used with metals that produce relatively large, curved chips. Grinding works by introducing a controlled network of small fractures into the surface such that glass particles fall out of the surface when the fractures intersect. The fractures must be kept below a critical fracture depth or the fractures will continue all the way through the brittle part. On the other hand, the fractures must be deep enough to insure efficient material removal. In any case, material removal by grinding is a much slower process than machining because the brittle material removed must be disintegrated into micrometer-sized pieces. For this reason, the rough shaping is done by sawing or trepanning (core drilling) so that a minimum amount of material has to be disintegrated to achieve the rough blank shape. For production runs, the rough shaping is done at the glass manufacturer by pressing or molding the hot glass into correctly shaped blanks a few tenths of a millimeter oversize.

Generating is similar in purpose to the machining of raw metal parts. The generating imparts dimensionally true surfaces on the workpiece so that subsequent operations can be performed accurately and efficiently. With glass lenses, the generating is done with cup-shaped grinding wheels with a lip of diamond grit in a metal or resin matrix. When the rotating cup wheel touches the rotating glass blank, a spherical surface is produced, the radius of which depends on the angle between the two axes of rotation. The simple geometry in Fig. 1 shows that this arrangement will produce a spherical surface, either concave or convex, depending on the angle at which the grinding wheel is set.

Loose abrasive lapping is then used to remove sufficient glass to eliminate the deeper fractures caused by generating and to produce a more spherical surface by the action of two rigid bodies abrading each other. The abrasive material, typically between 30 and 5 μm in size, depending upon the stage of lapping, preferentially removes the high places on both the lap and the glass until both surfaces are true spheres to less than 0.1 μm and differ in radius by the several-micrometer grit size of the abrasive compound between the two surfaces.

Most lapping is done with diamond-impregnated pellets made of a resin matrix that are loose-abrasive lapped to the correct radius. This bound abrasive lapping with pellets is faster, less messy, and yields surfaces with a greater dimensional consistency and a more uniform finish. As with loose abrasive lapping, pellet lapping is done on conventional lapping and polishing machines where the work is rotated about its optical axis while the lap is moved over the workpiece by an oscillating pin. The lap takes its rotary motion due to friction between it and the workpiece. This combination of translation and rotation produces a random motion between work and lap that, in turn, produces truly spherical surfaces.

Once the lapping has removed all traces of damage due to generating and coarser lapping grits, and has produced the correct sagitta to within a few micrometers, the workpiece is ready for polishing. Polishing takes place on the same type of machine and uses a similar machine motion as with the lapping, but now the lap is made of pitch (or in many modern operations, a synthetic polishing pad) and the polishing compound used is a few percent mixture of cerium oxide in water.

Polishing converts the finely fractured, lapped surface with a roughness of about 1 μm rms into a specular surface with a roughness of typically 3 nm rms. With care, this finish
The geometry for generating a convex sphere where $R$ is the radius of curvature of the sphere, $r$ is the distance from the cup wheel axis of rotation to the point of contact with the sphere, and $\theta$ is the angle between the axes of rotation of the sphere and the cup wheel. The geometry for a concave sphere is identical except the angle is negative.

FIGURE 1

can be reduced to 1 nm rms or less. Our best present understanding of polishing is that the cerium oxide reacts chemically with the glass to soften the outer layer to a depth of a few nm. The relatively soft cerium oxide particles can then physically remove this softened layer and the process starts over again. Behind the lap, it appears that the silica-rich polishing slurry redeposits some of the silica on the surface, leaving a smooth but chemically slightly different outer surface a few nm thick on the bulk glass. Polishing is continued until the level of the surface has been driven below the last remaining fractures from the final lapping step. Typically 10 to 20 micrometers of glass are removed to reach this fully polished condition.

The last step of the fabrication cycle is edging the lens. While the two optical surfaces have been carefully applied to the glass blank, no precision alignment of the glass is usually made and thus the polished lens will have a wedge of some minutes of arc. Another way of stating this is that the optical axis as defined by the line joining the centers of curvature of the two spherical surfaces is decentered from the mechanical axis of the element as defined by its periphery by a few tenths of an mm. Prior to edging, the lens axis defined by the two optical surfaces is aligned to coincide with the axis of rotation of the edging machine spindle. Then a grinding wheel is brought in to reduce the diameter of the lens element to its final dimension while removing any runout in its periphery.

Research continues into methods to reduce the time taken during each step of fabrication and even methods to eliminate some steps. For example, small lenses with reasonably uniform cross sections can be directly molded into finished precision optics by the glass manufacturers and fabricators. Also, a recent project has demonstrated that it is possible to generate spherical surfaces with sufficient accuracy and good enough finish that the surfaces can be polished without the usual lapping step. This research was done on a numerically controlled machine that includes tooling for doing the edging, and, possibly, the polishing as well.
**40.3 PLANAR OPTICAL SURFACES**

Planar optics and prisms are more difficult to produce than spherical optics in two ways. First, a planar surface is a spherical surface with a very specific radius, namely, infinity. Second, while a lens can be brought into correct mechanical alignment during the final edging step, this option is not possible in planar pieces. If a plane window is supposed to be made parallel to 2 seconds of arc, there is no last edging step to make this correction, so the wedge must be reduced to the tolerance level during polishing. Similarly, prism angles must be held within tolerance during polishing using precision tooling and fixtures.

For the polishers of planar work, there are two approaches that help reduce these problems. First, the generating and lapping steps can be more precisely controlled than in the case of spherical optics so the angles are very close to the finished tolerances before polishing begins. Second, much planar work is now done on continuous polishers (CPs) in which a large planar annular lap is “conditioned” to maintain lap flatness independent of the shape of the work put on the lap. Rather than the lap and work ending up at a “compromise” radius as the two work together, the lap on the CP machine is forced by a large glass “conditioner” to stay flat and then the lap forces the work flat in turn. Flatwork fabricators must still keep everything adjusted correctly to maintain flatness, but much more of their time can be spent holding angles rather than fighting just to keep flatness.

The CP machines came into their own during the early days of making glass laser disks for the laser fusion programs and have proved their worth throughout the plano optics industry. These machines call for a large capital investment and need a sufficient volume of work to keep them running nearly full-time. Given those conditions, however, CPs are a cost-effective method of producing planar optics and prisms. Because the techniques for polishing planar work and lenses are different, it pays to find out what type of work potential vendors do best. The job will be less expensive and better when done at a firm that specializes in one type.

**40.4 CRYSTALLINE OPTICS**

As more and more optical work is being done in the UV and IR regions, there is more call for optics made of nonglass materials. Single and polycrystalline materials as well as some elemental materials are transparent far outside the usual spectral transmission range for glass. In most cases, the surfaces of these materials have differing hardnesses depending on the orientation of the crystal boundaries. Unless the lap is very hard (which leads to scratches) or the polishing material is very hard, the surfaces of the crystalline materials will have a light relief pattern as a function of the crystal structure and this produces wavefront errors and scattering. The use of finely graded diamond as the polishing compound eliminates the problem in many cases. Laps of tin, zinc, or cast iron and diamond polishing compound work well on the hardest crystalline materials. Beeswax-covered pitch or synthetic polishing material laps are often used with the softer crystalline materials and metals.16,17

**40.5 ASPHERICS**

Aspheric surfaces are surfaces that are not spherical and thus the convenient processes that nature has given us to make spherical surfaces no longer apply to making aspheric surfaces. This is why aspherics cost many times what spherical surfaces do if fabricated
using traditional techniques. If the aspheric surface is very close (a few micrometers) to a spherical surface, then it may be treated rather similarly to a spherical surface and polished relatively simply. For large departure (fast) aspheres, however, the process is more like sculpturing and is quite time consuming.

In this case, the asphere is ground into the surface as accurately as possible, often with a numerically controlled lathe set up as a grinding machine. Then the surface is polished with a lap of sufficient flexibility to fit the changing curvatures of the asphere. The actual contour of the surface is controlled by dwelling longer on high places than in low spots. Frequent optical testing is required to determine the figure of the surface because convergence to the correct figure tends to be poor because the natural tendency is for the surface to return to a sphere. For larger-size aspheres, computer-controlled polishing or ion milling can be used to good advantage.

Several recent approaches to aspheric polishing are based on the principle of trying to imitate spherical polishing even though it is an asphere that is desired. This approach started with Schmidt, who used vacuum and simple edge support to deform a plane window into a concave shape that included the needed asphericity. The window was polished spherical while held in this distorted condition. When the polishing was complete, the vacuum was released and the window relaxed into a plano shape with the desired corrector asphere imparted in the surface.

The polishing of the Keck telescope off-axis parabolic mirror segments is a logical continuation of the Schmidt method applied to off-axis aspheres, the so-called “bend and polish” technique. For rigid optics where it is not possible to distort the workpiece, the lap shape may be actively controlled to fit the work as has recently been demonstrated. For a broad treatment, Marioge gives a nice review of more traditional methods for polishing aspheric surfaces.

40.6 DIAMOND TURNING

Another method of making both plano and aspheric optics is diamond turning. This precision engineering technology is an outgrowth of atomic weapons fabrication that requires the use of highly accurate, numerically controlled turning machines. Some of the materials used in the weapons were found to be difficult to machine using traditional tool bits so diamond-tipped tools were tried. It was found that some metals could be turned to specular finishes with these techniques employing diamond tooling and precision machines. This is the origin of diamond-turned optics as discussed in Vol. 1, Chap. 41 of this Handbook.

From an optics viewpoint, some advantages of diamond turning are that on plano surfaces, the relationship of one surface to another can be controlled very accurately such as is required in a multifaceted scanning prism. Also, finished aspheric surfaces (including off-axis surfaces) can be turned in a few passes in metals such as aluminum and electroless nickel. This makes diamond turning a cost-effective method of producing types of optics that would be difficult and expensive using the traditional methods.

40.7 PURCHASING OPTICS

Purchasing optics to special order is a costly undertaking. If the needed optics can be found as catalog items, this is always the least costly approach. Failing this, most fabricators have a stock of optics that are too few in number to list in a catalog but are
available at catalog prices just so they can be moved out of stock. Always inquire if there is something available that meets the requirements.

Often a small change in the design of an experiment or piece of hardware will permit the use of a catalog or standard item. Most optical shops maintain a list of test glasses for specific radii. If custom lenses can be designed using these radii, there will be smaller tooling costs. Along the same line, the Germans have a standard that lists “preferred” lens radii. Designs built around these preferred radii will be less expensive to manufacture than those using completely arbitrary radii.

To help protect the customer buying catalog optics, there is a new ISO standard that specifies minimum tolerances on lens parameters not specifically called out in a catalog. The standard is ISO 10110, Part 11—*Indications in optical drawings, non-toleranced dimensions and material indications*. If the catalog does not state that the standard applies to the listed lenses, this requirement can be given on a purchase order.

If custom optics are required, go to vendors that specialize in the type of optics required. Some are best at lenses, some at plano work and prisms, some at aspherics. Better prices and better quality are available from the specialist. When talking with potential vendors, ask if any of the requirements on the drawing unduly impact the cost of the optics. Some requirement that may seem trivial can cause the vendor substantial trouble and vice versa. Be sure too that the requested specifications and tolerance levels are really needed to make the hardware work. Many optics are overtolерanced just to be on the safe side or because the designer did not take the time to understand the true requirements.

When going out for bids, if one vendor comes in substantially lower than the others, there is probably some misunderstanding of the requirements. Rather than giving the order to the lowest bidder immediately, find out if they truly understand what is being asked for and if they have the capability to produce and test it. If it appears unlikely that the vendor can produce, it is better to excuse that vendor than try to hold them to the bid. That will just be a waste of time and money.

Finally, if the optical requirements are for something very specialized or at the cutting edge of the state of the art, the customer may have to supply the vendor with test equipment and supply a test method to demonstrate compliance. In this case, the customer and vendor will have to work together closely to ensure that the customer gets the optics that are needed.

### 4.8 CONCLUSIONS

We have shown that optical fabrication requires the serial application of a number of relatively simple, if not completely familiar, steps. If each of these steps is carefully carried out and good artisanship is observed, highly accurate optics can be made using traditional techniques by workers with reasonable skills. Nontraditional techniques are also being successfully applied to making complex optical surfaces and large volumes of similar surfaces. Finally, we have tried to indicate that purchasing optics is not a simple matter, but that the customer and potential vendors must work together to insure that what is required can be fabricated and tested in a cost-effective manner.

### 4.9 REFERENCES


