PART 2

FABRICATION

9 OPTICAL FABRICATION

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9.1 INTRODUCTION

The novel creations of optical designers have been limited by the fabricator's ability to manufacture and measure the elements of the optical prescription. A solution to a design criteria often existed only on paper as the required elements were not physically realizable. Optics manufacturing technology innovations continually expand the possibilities for optical components. Increasingly, manufacturing is tethered to metrology. Creation of optics metrology instruments with accuracy equal to that of optics manufacturing equipment and vice versa has driven process development. It is this developmental symbiosis that has brought determinism to the art of precision optics manufacturing. Metrology and machine innovations offer optics of higher quality and complexity in predictable timeframes. The requirement for skilled technicians is still vital in the manufacturing process; however, the skill set is increasingly one of craft in combination with science. Artisan opticians of yesteryear still provide value; however, the future of optics manufacturing is in the hands of the 21st century optics technicians.

The methods described below are the most common for typical optical components used in industrial, aerospace, and defense applications. For the spherical lens section, a brief overview of the traditional process is described first and then the latest methods. The remaining sections will provide general overviews. The focus will be exclusively on brittle materials. For our purposes, brittle materials are defined as those where the removal process is achieved by applying mechanical forces that fracture the surface, releasing fragmented particles in a controlled manner. Much has been documented on fine finishing of brittle materials such as optical glasses, ceramics, and crystals. Works by Preston[1], Silvernail[2], Izumitani[3], Buijs[4], Bach[5], Kaller[6], Lambropoulos[7], Golini[8], Cook[9], Jacobs[10] and DeGroote[11] have contributed greatly to the understanding of optics finishing processes.

9.2 MATERIAL FORMS OF SUPPLY

Optical glass is available in boule, slab, and gob forms. Boules are formed in special disposable pots that yield a batch or glass melt of a specific glass type, such as the borosilicate glass BK7, but whose detailed characteristics are unique to that batch. Slab is yielded from a continuous flow process.

Materials are homogeneously mixed and heated, and a continuous ribbon of glass is produced. These ribbons are cut into slabs that are generally 250 mm wide, 25 mm thick, and 350 mm long, although sizes vary significantly based on supplier and material. Gobs are also yielded from a continuous flow process; however, the molten glass flows through an orifice and is sliced like cookie dough at a predetermined frequency that ensures the desired volume for the application. Gobs are almost always made to customer specifications for glass type and volume. They are used as the preblank to produce near net shape molded blanks for high-volume lens systems. Many glass suppliers also provide polished preforms, usually balls. These are used for glass molding finished optics components.

Manufacturers will order the form that best suits their purpose. The closer to final form the material, the less waste and time consumed in bulk removal operations. When rough shaping material blanks from boule or slab forms, most manufactures use diamond impregnated saw blades and core drills to yield a part appropriate to yield the finished optic, generally called disks. Typically blanks or disks are several millimeters oversized from the final part's critical dimensions.

9.3 BASIC STEPS IN SPHERICAL OPTICS FABRICATION

Generating

This is a bulk material removal operation that starts with a near net shape molded blank or a disk.

Generating—Traditional The removal is accomplished through the application of diamonds embedded in a matrix on the cutting surface of a cup-shaped ring tool. The material is ground away as the diamonds create cracks in the surface, sweeping away glass particles where the fractures intersect.[12] The machine accuracy is generally akin to manually set, mechanically based control production equipment used in the machine tool industry. The operator continually monitors results and modifies machine settings as the cupped ring tools wear. Machine precision is adequate to control thicknesses to +/−0.025 mm and radius to +/−0.010-mm sagittal height, but the machine is only capable of coarse removal. Subsequent lapping operations are required in order to reduce subsurface damage[13] to a level where polishing is possible.

Generating—Modern The advent of deterministic microgrinding processes spearheaded by the work at the University of Rochester's Center for Optics Manufacturing[14] in the 1990s shifted the paradigm for finishing expectations from the generating operation. As a result, machines used in the generating operation have evolved to precision machine tool status. Generators manufactured by mainstream optics manufacturing equipment providers such as OptiPro,[15] Satisloh,[16] Schneider[17] and others, have created grinding solutions that enable the generating operation to predictably yield surfaces that are ready for polishing operations. This modern equipment makes use of CNC (computer numeric control) systems, robust motion and motion control systems such as precision linear ball slides, advanced machine base materials, structure design, and improved positioning feedback through optical encoders and other submicron feedback systems. Additionally, most of the machine builders provide in situ metrology options that enable operator assisted or completely automated parameter adjustment optimization. This is an important feature as the tool consumes itself during the process.

Complimenting the advent of advanced generating machine tools for optics generating has been the increased understanding of fixed abrasive grinding mechanisms. Deterministic microgrinding is typically preferred to loose abrasive lapping when fabricators have a choice. The residual damage from microgrinding can be estimated based on glass properties.[18] This aids in determining prepolish finish requirements so the overall process time for the optics can be optimized. Even with recent advancements in understanding the microgrinding process, the industry is far from offering a directory of ring tools optimized for the array of optical materials. Therefore the industry continues to rely heavily on empirical results to determine optimal setups.

Lapping

This process reduces subsurface damage left from generating to a manageable level in preparation for polishing.

Lapping—Traditional Lapping is the application of loose abrasive particles applied as slurry and pressed into the work surface by nominally constant applied pressure.[19] The process typically consists of applying the abrasive slurry between a cast-iron-rotating lapping tool and the optic. Both surfaces abrade away as they remain in random dynamic contact. The fabricator controls the material removal so the operation yields the desired surface radius and smoothness. The abrasive material, often aluminum oxide, is typically between 30- and 5-μm particle size. The operator steps through particle sizes, using progressively smaller abrasives. Removal amounts account for the subsurface damage from the prior generating or lapping operation, ideally completely removing it.

Lapping—Modern The use of diamond particles embedded in a resin or metal matrix have been popular for some time. Initially, these matrices were fabricated in pellets, fastened as desired on metal backing plates, and used as laps. Abrasive work is done by the diamonds and coolant serves as lubricant and carries the glass particulate away. Unlike loose abrasive lapping, the slurry is not the abrasive. Diamond tool manufactures also make diamond-sheet material for ready application to tools, and more recent products such as resin-bonded sheet materials from abrasive manufacturers such as 3M[20] can be used the same way.

Polishing

Polishing converts the finely fractured surface from the lapping or deterministic grinding operation [typical roughness of about 1-μm rms (root mean square)] into a specular surface of a surface roughness typically 1 to 3 nm rms. Polishing is a chemical-mechanical process. Water attacks the surface creating a chemically softened layer, and then the mechanical action of the abrasive in the polishing slurry, usually ceria based for optical glasses, removes the chemically softened outer layer of glass.[3]

Polishing—Traditional The polishing process is expected to remove the damage left from preceding operations, typically 5 to 20 μm of material. The intimate contact between the polishing tool and the optic, working with the slurry, slowly enhances the surface finish. The process is feedback based, and the fabricator works the part for a while and checks the outcome. Reacting to the results, the experienced fabricator controls various parameters to yield the desired form and finish of the polished surface.

The most basic polishing tool is a pitch polisher. Optical polishing pitch is a viscoelastic material. To form a pitch polisher, a metal tool of proper radius is coated with a 4 to 5-mm layer of polishing pitch. The pitch is warmed and formed to the optic. Once cool the brittle pitch will be cut to allow irrigation grooves for slurry access. When performed by artisans, pitch polishing can yield form errors equal to fractional wavelength of visible light routinely. Less capable fabricators may be limited to commercial quality, multiple wavelength form error outcomes.

By the 1980s, high-speed polishing had become very popular. One of the key innovations was the use of polyurethane polishing pads as a replacement for pitch. Polyurethane pads are a viscoelastic thermoplastic material with a higher viscosity than pitch. Polyurethane remains a polishing material staple and is the polishing material of choice for the fast removal seen in high-volume optics manufacturing.

Polishing—Modern Advances in deterministic polishing are dramatically changing the demands placed on optics manufacturers. Deterministic polishing is a feed-forward process, where the outcome is reasonably certain. Industry leaders in deterministic polishing development are QED/Schneider consisting of Magnetorheological Finishing (MRF)[21] and Zeeko/SATISLOH[22] who promote a precessions polishing and air bladder solution. Each has created opportunities for manufacturers to produce optics at more predictable cost. Their application of CNC machining systems to the polishing process is revolutionizing the precision optics industry.[23]

All these new solutions rely on subaperture small "pad" polishing with a known removal rate, where the "pad" may be in the form of variable stiffness polishing fluid or compliant tool made from a variety of materials and consistencies. Originally used to finish large astronomical telescope optics, small pad methods have advanced in recent years to scale cost and size down so these technologies are available to the broader population of precision optics manufactures.

Deterministic subaperture polishing solutions combine a tool's known removal rate with an error map of the optic to produce a removal schedule. This feed-forward process relies completely on the accuracy of actual surface form information. In most cases this information is acquired from a variety of instruments such as coordinate measurement machines (CMM) or surface profilometers like the Taylor-Hobson Form TalySurf.[24] These instruments themselves or the software of the polishing tool convert points of data into an error map for a continuous surface. The removal profile dictates the dwell time for the small aperture polishing pad, and in general form error decreases by a factor of five per iteration. For example, if the form error is 1 wave, it is reasonable to expect that after a deterministic polishing iteration the form error will be ~1/5 wave, and after another iteration would be ~1/25 wave.

Newer technology that is also under development at a number of equipment manufacturers including QED and ZEEKO[25] incorporates fluid jet technology. Surfaces are corrected by directing a jet of abrasive/fluid mixture at a surface, the flow generates sufficient surface shear stress that chemical-mechanical polishing occurs.[26,27] The jet-polishing technology is especially promising for difficult to reach areas seen in asphere and conformal optical surfacing.

Edging

Most applications of lenses require mounting into a lens housing. Lens system performance is maximized when the centers of curvature reside on the cylindrical axis of the housing. The edging operation simultaneously creates a precise (+/− 0.025 mm or less) diameter for mounting and aligns the centers of curvature on the mechanical centerline of the lens.

Edging—Traditional[28] Earlier pitch-based methods consisted of using a precision spindle where a brass cup was trued using a cutting tool. This was basically a lathe-type operation and required a skilled combination of heat, pitch, spindle velocity, timing, and consistent axial force applied by a skilled artisan in order to set the lens in a "trued" position. Once the lens was blocked, a diamond wheel ground the diameter to final dimension. Lenses are typically brought to final polished state with the diameter of the lens 1- to 3-mm oversized.

This pitch method was almost entirely replaced with mechanical bell-clamping edging machines. Bell clamping employs two opposed coaxial synchronized precision spindles and is a pitch-free process. Each spindle is affixed with a precision cup of the appropriate size to capture the lens and allow auto alignment by virtue of the mechanical forces on the variably sloped surfaces. Once the lens is "clamped" into true position, an operator mechanically defines and initiates an automated grinding sequence.

Edging—Modern In recent years, the use of CNC edging equipment is enabling a single setup for multiple grinding operations. For example, it is fairly routine to process the diameter, sagitta with a step, bevel and a fiduciary flat, all in one operation. The CNC controller interface shows a series of cross-sections, and the operator fills in inputs for what is the starting point and what features are needed in the end. Simultaneous creation enssures the features will all run true relative to one another. In addition to facilitating grinding of more complex features, optional features such as micropositioning air blasts for automated alignment optimization and measurement enable precision placement of the optic. Lenses are still mechanically bell clamped.

9.4 PLANO OPTICS FABRICATION

A plano surface has a radius equal to infinity. Typically plano form specification does not differentiate between spherical power and irregularity, specifying lump sum reflected errors as flatness. Therefore, maintaining perfect flatness is critical during plano surface finishing. The process steps for plano surfaces are exactly the same as for spheres. Planos have the advantage of fixed radius, so often, companies, departments within companies, personnel and equipment will be plano specific. This specificity allows economies of scale and development of plano-specific solutions. An example of this are continuous polishers (CPs), in which a large (40–60 inches in diameter) annular lap is "conditioned" to maintain lap flatness independent of the workpiece size. The lap is forced by a large glass (or similar material) "conditioner" to stay flat. This persuasion by the conditioner imprints onto the work piece and maintains flatness as a result.

Double-sided CPs polish both sides of a window simultaneously. Much of the recent technology used in the precision plano window manufacturing has been taken from semiconductor industry's work-optimizing silicon wafer processes.

9.5 ASPHERE OPTICS FABRICATION

Aspheric lenses contain at least one optically active surface of nonconstant curvature. This is the primary differentiator from a spherical lens. Rotationally symmetric aspheric lenses are solids of revolution, where a general equation describes the cross section to be revolved (Fig. 1). Lenses of this style are capable of higher aberration order correction than spherical lenses. While the forms and their promise have been known to optical designers for centuries, for most of that time only the mildest forms have been physically realizable. The methods, machinery, and metrology are specific to asphere manufacturing.[14]

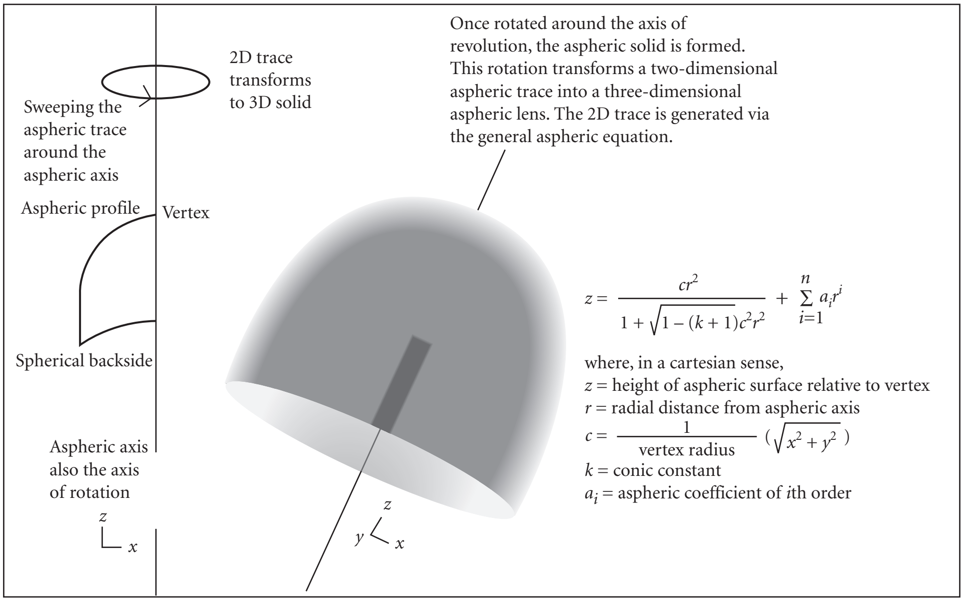

FIGURE 1 Sample general asphere form. (*Brandon Light, Optimax Systems, Inc.*)

Traditional full-aperture fabrication methods are not capable of manufacturing aspheric surfaces due to their nonconstant curvature. By changing the amount of contact from full to a region where change in local curvature approaches zero, some portions of traditional spherical lens-manufacturing techniques can be applied. Brittle removal by high-speed diamond grinding followed by ductile removal using a polishing slurry (ceria, alumina, etc.) can be used to prepare aspheric surfaces. Instead of full contact, curvature-insensitive local contact is used in grinding and polishing.

In aspheric grinding, a peripheral diamond wheel on a CNC platform traces the surface to generate the aspheric profile. In grinding, machine accuracy determines profile accuracy. A more accurate ground profile makes a more accurate polished profile more likely, since there's less correction needed. Particular attention must be paid to wheel wear, wheel balance, positional accuracy, and overall stiffness of the grinding platform. Imperfection in any of these grinding parameters will leave signatures in the ground surface.

The surface is then polished by working only a small area at a time. All of this must be done while maintaining location of the aspheric axis, the axis around which the solid of revolution was formed. Each iteration has an error inducement associated with it, so making as few correction runs as possible is a primary focus. Typically, asphere polishing is a feed-forward, deterministic process. While the local curvature may be constant, globally it is not. Polishing requires an adaptive tool and knowledge of what's ahead. The polishing tool needs to change to suit local curvature at a suitable rate of change. This requires knowledge of how the tool will evolve and how much removal is needed in which region. Deterministic processes provided by Zeeko/Satisloh and QED machinery, discussed earlier, are examples of such tools. These processes characterize the removal rate as a function of curvature for a given tool and combine that with an error map of the surface to be worked. The resulting removal schedule accommodates for volumes to be removed and tool performance at that local curvature.

Conventional interferometric techniques do not translate to aspheric manufacturing either. Since local curvature is nonconstant, interferometric techniques for aspheres are lock and key. The setup and equipment can be unique for a given aspheric form, so time and money demands are large. For example, form-specific computer-generated holograms (CGHs) may be required to provide feedback to the closed-loop deterministic polishing process. For a more cost-effective solution profilometry is the main two-dimensional compromise, and it is the current industry standard. Although more generalized interferometric solutions are beginning to be offered by QED, Zygo, and others.

Errors in centration are unrecoverable. In centering a spherical lens, errors can be removed. With sufficient diameter overage both centers of curvature could be positioned on the same axis and that axis could be made concurrent and coincidental with the mechanical axis. Since an aspheric surface is centered about an axis and not a point such realignment is not possible. Therefore, centration must be conserved throughout processing.

9.6 CRYSTALLINE OPTICS

As more optical work occurs outside the visible spectrum, use of optics made from nonglass brittle materials will grow. Single crystalline and polycrystalline materials are transparent far outside the usual spectral transmission range of glass. In many cases, the surfaces of these materials have differing hardness values depending on the orientation of the crystal boundaries. Soft laps tend to accentuate the grain boundaries of these materials, and that can lead to wavefront errors, mottled surfaces, and scattering. The traditional optical fabrication process can be adapted to crystal materials if some substitutions are made. The lapping process may substitute finely graded diamond for alumina and tin or zinc laps in place of the typical cast iron. Similarly, diamond suspensions are often used in polishing in place of ceria. Polishing laps may consist of synthetic materials like polyurethane or beeswax instead of optical pitches.[29,30]

9.7 PURCHASING OPTICS

There are a number of companies who offer lines of standard optical components. These suppliers can provide off-the-shelf optics in a variety of sizes, shapes, and quality levels. Most optics providers have areas of specialization, and the informed optics buyer will select vendors that match their specific optics requirements. When custom optics are required, it is best to understand the capabilities of prospective suppliers. Most optics companies promote a broad range of capabilities, but many tend to specialize in some manner. Professionals who are engaged in optics purchasing on a regular basis learn where to go for specific optics requirements. Often this education is paid for by awarding of numerous contracts across a broad array of parts and suppliers and experiencing the consequences of the decisions. Much is learned in the contract's postmortem review.

Optics purchasing is further complicated with the predominance of the internet as a research tool. Web sites and promotional materials often do not reflect a supplier's true capability and know-how.

Whether buying off-the-shelf or custom optics, it is always best to engage potential suppliers in dialog, preferably addressing tolerances and other manufacturing cost drivers. The buyer should be satisfied the supplier has the ability to meet and measure all critical criteria. For optics that approach a manufacturer's limits, it is especially important to understand the test and acceptance process, as there can be quite a divergence of metrology equipment and methods available for testing various parameters.[31] This is especially true for aspheres, where full format phase measuring interferometry or transmitted wavefront testing is not always within a supplier's capability.

9.8 CONCLUSION

Optics fabrication requires serial application of relatively simple steps. In the past, these steps were carefully carried out by artisans using traditional techniques. Modern approaches incorporate scientific research into the manufacturing process. Artisan skills integrate with the scientific know-how yielding a new breed of technology workers of the twenty-first century. Nevertheless, the basic process steps of grinding followed by polishing have remained. Introduction of new optical materials, more complex shapes and more narrow tolerance budgets will enable designers to develop improved solutions to old problems over an expanded spectrum, and modern manufacturing methods can make the optics physically realizable. Finally, the tendency for specialization among optics supplier requires open dialog between supplier and designer as a means to optimize successful relationships.

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