Photographic Lens Manufacturing and Production Technologies

by

Daniel Mark Kubaczyk

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Abstract

An investigation was conducted to determine the methods and processes required for the manufacture of photographic objective lenses. Production of photographic lenses requires incredible precision in the melting, mixing, molding and machining of optical glass. Manual inspection methods are required to ensure optimum quality and to avoid inclusion of defects in glass. Manual assembly procedures are required to ensure delicate operation of glass elements but contribute significantly to the consumer expense of these lenses.

Newly developed technologies in the field of lens machining are discussed in terms of commercial advances and scientific advances. Companies like Canon have sought greater automation in pre-assembly procedures as well as a reduction in the number of machining steps. New advances including precision machining of aspherical lenses, fluid-jet polishing and magnetorheological finishing are pushing the boundaries of lens machining and its characteristic surface roughnesses to depths not seen before.

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Finally, I want to thank my parents and family – most of whom would understand almost none of what is written in this document. I owe my diligence to them.
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Chapter 1

Introduction

1.1 – Technical Foundations of Photography

While a well-trained photographer can often “make do” with inferior equipment if the occasion demands, equipment of optimum quality is a very great advantage.

-Ansel Adams

Figure 1-1: A digital photograph (Credit: Author)
Photography is a method for capturing an energy record through means of a permanent chemical reaction in the case of film or through the excitation and storage of charged elements in capacitive elements in the case of digital imaging sensors. Regardless of its purpose, whether it be informative, scientific, artistic or some combination thereof, photography is technically intensive in each and every process that transforms a real and physical scene or object into a processed image.

Modern digital cameras incorporate many engineering implements in order the facilitate image capture. First and foremost, high-precision optics are essential to visual reproduction of a subject along with the electro-mechanical apparatuses that provide the flexibility for such optical instruments to work in varied settings. Electrical components and sensors have enabled instant image review as well as live view (previewing and image before it is taken) along with automation of tedious tasks such as sensor cleaning, light sensing, focusing and bracketing. Storage and editing images have become drastically more time and space-efficient as a result of digital technology; thousands of images can be stored in thin memory cards and edited within minutes after capture.

Such technical intensiveness requires a minimum level of technical aptitude for basic proficiency and even greater stores of knowledge for more advanced photographers. A critical aspect of this technical awareness, especially from an engineering standpoint, is an understanding of how these products are manufactured and how they achieve such advanced levels of performance. While expert photographers can easily get by without such knowledge those who comprehend and appreciate the complexity and craftsmanship of their optical and photographic instruments will stand at a technical advantage.
1.2 – Camera and Lens

The engineering and optical science behind photographic cameras and lenses are an immense topic deserving many volumes of elucidation; the following is nothing more than a cursory summary. The information provided will focus on modern digital cameras due to their prevalence in consumer and professional spheres as well as their use of state-of-the-art technology.

The modern digital camera offers the user a multitude of options which allow for almost limitless sets of customizable settings. Even consumer-friendly "point-and-shoot" cameras include many settings for flash, color temperature, time delay, shake reduction and more while high-end professional digital single-lens reflex cameras (DSLR) contain many more adjustable features. Yet almost all cameras contain a core set of optical, mechanical and electrical components which enable image capture.

A digital DSLR camera can be broken into two subsections: body and lens. The body houses all of the camera’s components outside of the lens including the shutter, mirror, image sensor, viewfinder, pentaprism, display screen, battery, image processor, flash bulb and an array of switches, dials and buttons used to alter exposure settings. The lens houses the optical glass lenses used to focus incoming light into an image on the sensor. The lens is also responsible for housing the aperture ring, focusing controls, focal length control and can also include mechanisms for vibration reduction (VR). Figure 1-2 shows some of these features as well as the path of light rays through the camera/lens apparatus.
Light enters the camera/lens apparatus through the glass of the lens. Based on a variety of optical properties and settings, light may contact that glass at many different angles and travel varying paths in order to bring an image onto the sensor. Light is refracted through the glass elements at certain angles based on the glass lens’ structure and optical properties. Most lenses allow for relative motion between the various glass elements in the lens allowing for changes in focal length and focus distance. Focal length corresponds to the distance between where light rays intersect the lens plane and where they converge. Larger focal lengths correspond to shallower angles of refraction and allow for magnification of distance objects. (2) Lenses with larger focal lengths (typically from 100 – 500 mm in photographic cameras) are known as “telephoto” lenses and are often seen on the sidelines of sporting events. Lenses with smaller focal lengths correspond to sharper angles of refraction and wider angles of view. Such lenses are known as landscape lenses (typically with focal lengths from 12 – 55 mm). (2)
Focusing distance is the distance from the lens to an external object that gives perfectly focused lights at the focal point of the lens. Objects nearer the focusing distance tend to appear sharper and clearer than objects a great distance away from the focusing distance. Control of focal length and focusing distance allows for versatile operation of a camera lens. Most modern camera/body systems are capable of autofocusing images through electronic distance measurement, also known as triangulation. Such a process is similar to how humans perceive depth through the angular convergence of the eyes. (3)

Some lenses contain vibration-reducing elements which help to keep the lens stable at longer exposure times where undesired or unavoidable movement of the camera/lens is sufficient to blur or distort the image. This motion is counteracted by sensing and compensating for the unwanted movement. Nikon’s Vibration Reduction (VR) mechanism utilizes piezoelectric sensors that analyze any lens displacement at a rate of 1000 Hz and instruct the voice-coil motors (VCM) how to correct for such movements, as seen in Figure 1-3. (4)

Figure 1-3: Nikon’s Vibration Reduction system for preventing image blur (4)
At some juncture in the lens, light rays pass through (or are impeded by) the aperture, as seen in Figure 1-4. The aperture controls the amount and angle of light that passes through the lens.

![35 mm focal length lens with a narrowed aperture](image)

**Figure 1-4: 35 mm focal length lens with a narrowed aperture (3)**

As the aperture narrows, less light is admitted into the camera but the admitted rays become more collimated (more parallel), allowing for a sharper image with relatively more objects in-focus. As the aperture widens, more light is admitted, allowing for faster shutter speeds but also leading to a blurrier image around the focusing distance. In this case, the distance over which the image will retain sharpness decreases, as seen in Figure 1-5.

![Photograph taken with a narrow aperture showing sharpness over a great distance](image)

**Figure 1-5: (a) Photograph taken with a narrow aperture showing sharpness over a great distance (b) Photograph taken with a wide aperture showing limited sharpness (5)**
Most digital cameras use charge coupled devices (CCD) as sensors which capture incident radiation and convert it into an analog signal comprised of electrons in an array of pixels. Complementary metal oxide semiconductor sensors (CMOS) are also used and use transistors at each pixel location. Each pixel on a sensor represents one data point that makes up an image; thus raw, unprocessed images have the capability of storing the number of bytes that is essentially equivalent to the number of pixels on a camera’s sensor. Larger stores of pixels give higher resolution and higher image quality (especially for enlargements). Many modern digital cameras house sensors with more than 10 megapixels with high-end professional DLSRs topping out at 25 megapixels. As a reference, typical 35mm film has a resolution of about 20 megapixels. Figure 1-6 shows a typical CCD sensor. After images are converted to digital signals they are then processed by the camera’s internal hardware and stored in memory.

![Figure 1-6: CCD sensor from a Nikon D40 DSLR camera (3)](image)

Single-lens reflex cameras have the enormous advantage over double-lens reflex cameras (now mostly obsolete) by having the photographer see through the very lens through which the photograph will be taken. This is accomplished by an angled mirror and a piece of optical glass known as a pentaprism. The pentaprism, seen in Figure 1-2, rectifies the image and allows the user to see through the viewfinder almost exactly the image that will be projected onto the
sensor. Many cameras also feature “live view” which shows the user a digital display of the photograph on an LCD screen, thus avoiding having to peer through the viewfinder to preview the image.

Modern cameras contain a plethora of technological upgrades that enhance and better integrate all of these features. For our purposes, full exposition of these is unnecessary for the following discussion regarding manufacturing processes. A basic understanding of a modern camera’s optical and electromechanical complexity has been provided and will suffice for proceeding discussion.
Chapter 2

Photographic Lens Manufacturing

2.1 - Material Selection and Processing

Prior to the 20th century, most optical glasses were made up of materials similar to those found in modern non-optical glasses (windows, food containers, etc.) These glasses belong mainly to two groups: simple crown glasses that are formed from SiO₂ (fused quartz, about 70% by weight), Na₂CO₃ (soda, 15%) and CaO (lime, 12%) and flint glasses made from lead oxide (PbO, 14%) and potash (K₂O, 14%) along with SiO₂ (55%) and other oxides. (9)

A much wider range of optical glasses soon emerged in the 20th century, first with the incorporation of barium oxides and boron oxides. These compounds yielded very low dispersion (leads to chromatic aberration which induces fringes of color where sharp edges should be seen) at high refractive indices (barium oxides) and at low refractive indices (boron oxides). (9) The index of refraction of a given material determines the angle at which incident light will travel through the medium. Incorporation of novel materials greatly expanded the optical range of
glasses used for photographic instruments and allowed for more freedom in optical design and engineering.

Optical glasses used today contain a myriad of materials and most photographic lens manufacturers keep the chemical content of their glass lenses as proprietary as possible. Figure 2-1 shows the range of optical glasses available to modern manufacturers. Many of these glasses contain rare earth materials, especially lanthanum (indicated by “L” in Figure 2-1. (9) Abbe’s number is a dimensionless parameter that quantifies dispersion (high Abbe = low dispersion).

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**Figure 2-1**: Optical glass types representing a wide range of refractive indices and Abbe’s number (B indicates boron, K indicates crown-type glasses, F indicates flint-type glasses, S indicates heavy glasses [high refractive index], L indicates light glasses [low refractive index] and La indicates lanthanum) (9)
Once material selection is made and optical properties for the soon-to-be-made lenses are determined, the raw materials (in the form of a grainy powder) are mixed together in a mixer to filter out impurities such as iron (to the order of parts per million) that reduce light transmittance. (10) After mixing the raw ingredients, the mixture is heated in a crucible and blended together above the melting temperature of the included materials (around 1500 °C) with special stirring equipment. (11) The contents are then poured into a large, flat rectangular steel mold to cool and solidify before further processing, as seen in Figure 2-2. (9)

![Figure 2-2: Pouring of blended glass melt into steel mold for cooling (10)](image)

The cooled glass is then crushed into smaller pieces before undergoing further melting processes. The glass is then cast into a continuous fusion machine (at 1300°C) where it undergoes fusion, mixing/churning, clarification and homogenization. The liquid glass is shaped into a long sheet that cools very gradually along a temperature-gradient, slow cooling furnace seen in Figure 2-3. The resulting output is a homogenous glass mixture that is devoid of air bubbles. The control of temperature and the fusing/cooling processes are critical for the production of high-quality optical glass.
Prior to cutting, glass sheets can be ground close to their specified thickness (usually leaving an excess of 0.3 mm for future finishing). The glass plates are secured lightly to a fixture with wax and ground using rough iron abrasives or diamond milling tools, as seen in Figure 2-4.

Test pieces from each piece of glass are cut out and run through a quality inspection to test for defect before further manufacturing processes are carried out. After passing the
inspection is passed, the lenses are repeatedly ground and heat-pressed (seen in Figure 2-5) into lens blanks that take on a general lens shape that will be finely tuned in future grinding and polishing operations. (10) The glass lenses are formed such that they are approximately 10% oversized from their final dimension. (12)

![Automated pressing of lens blanks into a general lens shape](image)

**Figure 2-5: Automated pressing of lens blanks into a general lens shape (10)**

The lens blanks, now having a shape very similar to that of a finished lens, are heated to 500°C in an electric furnace and are annealed to remove internal stresses developing from pressing and shaping operations. The lens blanks are allowed to cool at a very slow rate to prevent the reformation of thermal gradients and thermal stresses. Residual press marks and other surface deformities still reside on the lens blanks and are to be removed to achieve an optimal surface finish through machining processes. (10)
2.2 – Lens Machining Processes

After general shaping processes, photographic lenses are precisely machined through a series of steps that begin with rough cuts used to remove bulk material and end with polishing operations that leave the surface of the finished lens sufficiently smooth.

Rough grinding is carried out first. This type of machining gives the lens the desired curvature using ultra-hard diamond grindstones. Lenses are fixed on the outside of a fixture block using either the pellet-sticking method or the hard-block holding tool method. Many lenses are fixed on a block to facilitate economical production of lenses. (10) The fixturing process proceeds as follows: the radii of the block holder and the laying-in shell are calculated in order to set the lenses such that they are ground at the correct spherical radius. The lenses are then fixed to the block holder with pitch pellets (a sticky adhesive that melts around 70 °C) around the melting point and is then cooled with water so the lenses stick to the block holder. This is seen in Figure 2-6. (10) Once the lenses are adhered to the block holder, the block holder is nested within a grinding wheel with a specified radius of curvature as seen in Figures 2-7 and 2-8. Any irregularities in lens fixturing are corrected through compliance in the pitch as the grinding wheel and block holder are essentially rigid compared to the pitch. (12) The abrasives are typically “loose” and mixed in with the water; thus there is a slight difference in curvature between the desired lens curvature and the grinding wheel curvature. This difference is the grain size of the abrasive.
Figure 2-6: Lenses fixed to blocking with pitch (13)

Figure 2-7: Rough grinding of convex lenses, a - machine arm, b - grinding shell, c - block holder, d - abrasive grains (12)
Coarse-grain abrasives are used first, with an intermediate-grain and a fine-grain abrasive used to bring the lens dimension to within approximately 10-20 microns of its finished dimension. As the grain size of the abrasive becomes finer, the need to control the applied grinding force on the glass lenses increases. While modern lens grinding is fully automated, rough grinding historically could be carried out with manual pressure applied, as seen in Figure 2-8. Rough grinding fractures and crushes the outer layer of glass and removes approximately 0.5 mm of material with some ranges given the size of the lens as seen in Table 2-1. (12) Material removal increments for various levels of grinding can be seen in Figure 2-9.
Table 2-1: Radii of grinding shells for various grinding stages, relative to finished radius (12)

<table>
<thead>
<tr>
<th>Grind radius (mm)</th>
<th>Stage of grinding</th>
<th>Finest grinding</th>
<th>Fine grinding</th>
<th>Medium grinding</th>
<th>Initial grinding</th>
<th>Rough grinding</th>
</tr>
</thead>
<tbody>
<tr>
<td>r up to 30</td>
<td></td>
<td>0.01</td>
<td>0.04</td>
<td>0.08</td>
<td>0.12</td>
<td>0.30</td>
</tr>
<tr>
<td>r = 30-60</td>
<td></td>
<td>0.02</td>
<td>0.05</td>
<td>0.10</td>
<td>0.15</td>
<td>0.35</td>
</tr>
<tr>
<td>r = 60-100</td>
<td></td>
<td>0.03</td>
<td>0.06</td>
<td>0.13</td>
<td>0.20</td>
<td>0.40</td>
</tr>
<tr>
<td>r = 100-150</td>
<td></td>
<td>0.05</td>
<td>0.09</td>
<td>0.22</td>
<td>0.35</td>
<td>0.52</td>
</tr>
<tr>
<td>r = 150-200</td>
<td></td>
<td>0.08</td>
<td>0.12</td>
<td>0.34</td>
<td>0.50</td>
<td>0.70</td>
</tr>
<tr>
<td>r = 200-300</td>
<td></td>
<td>0.12</td>
<td>0.28</td>
<td>0.50</td>
<td>0.80</td>
<td>1.00</td>
</tr>
</tbody>
</table>

Figure 2-9: Grinding increments for a lens with a finished radius of 100.00 mm, a - Mold radius = 100.6 mm, b - milled and roughed radius = 100.15 mm, c - medium ground radius = 100.1 mm, d - fine ground radius = 100.05 mm, e - finest ground radius = 100.02 mm, f - finished radius = 100.00 mm (12)

Diamond tools tend to be used more heavily in finer grinding stages to achieve more precise surface roughness and curvature. Diamond tools also enable higher grinding speeds and the increased precision also allows for significant time savings during the polishing steps where the optical glass is given its characteristic translucence. (10) Larger lenses, as seen in Figure 2-10 are often worked individually with diamond tools due to their shallow curvature and large size. This eliminates the need to switch loose abrasives from rough to smooth as the abrasive is locked into the grinding wheel (which is much smaller than grinding wheels used with loose abrasives.
to grind sets of lenses). (12) In order to obtain such precise results a radius of curvature accuracy of ±0.0008 mm is required of the diamond tool. (12)

![Figure 2-10: Fine grinding of lenses (gray disks) with precision diamond grinding tools (white) (10)](image)

After fine grinding, glass lenses are polished to achieve their characteristic transparency. Polishing removes visible machining marks left over from previous processes using a similar setup as fine grinding. Lenses are polished until the surface roughness has been reduced to a characteristic length on the order of a sub-micron. (10) A cast iron shell, similar to a grinding wheel is use to house the layer of polishing pitch that polishes the lenses. On the surface of the polishing pitch is a layer of polishing rouge (usually cerium oxide) mixed with water and it is this rouge that physically polishes the lenses. (12) This polishing pitch is very similar to the pitch described above that is used to fix lenses onto a block holder for rough grinding processes. (12) Since polishing removes very little material per unit time relative to grinding operation, adjustments for thickness are either negligible or on the order of 0.01 micron or less for precision.
lenses. (12) Polishing is typically carried out with a constant stream of lubricant, typically water, that removes the heat generated from the friction of the polishing rouge on the glass. This heat could potentially warm the polishing pitch or the lens-fixing pitch and induce errors in the lens geometry. (12) After both sides of the lenses are polished and removed from the block, they are thoroughly cleaned with solvent that removes any debris (pitch, cement, etc.) from the surfaces of the lens. Use of automated ultrasonic machines can help to ensure cleanliness in this process.

Once lenses have been made transparent, they can be inspected once again before finishing processes are performed. The precision of the critical dimensions of the lens is measured using lasers and based on the observed fringe patterns the lenses are either passed onto the next stage or sent back into whatever machining processes are needed. (10) Lenses are checked for cosmetic appearance and striae, or undesired visible streak lines, as well as for thickness, centring accuracy (addressed in the next paragraph), surface accuracy and imaging quality. (12) Some cosmetic defects are permissible and are dependent on the position of the optical component as well as the size of the defect. The closer the component is to the image plane, the more scrutiny it must bear to pass inspection. Otherwise, as long as the blemish does not affect image quality or it cannot be seen easily it may not be remedied. This of course depends on the reputability and quality standards of the manufacturer and the lens brand. (12)

After passing inspection, lenses must be adjusted such that their mechanical axis (axis of the outer cylindrical edge) and optical axis are coincident as seen in Figure 2-11. This process is called centring and is seen in Figure 2-12. The element is first aligned on a centring device such that its optical axis is exactly perpendicular to the cutting surface. (3) This device typically uses lasers or some form of transmitted light to find the lens’ optical center. The edges are then
ground to a specified diameter. Lenses with larger radii of curvature require more attention to ensure proper alignment, as seen in Figure 2-13. (12) The edges are typically ground using a rough grinding wheel as optical transparency of the edges is unnecessary. Some lenses may also be given a chamfer at the point where the cylindrical edges meet the edges of the lens' spherical surface. This chamfer is used to provide a flat surface for the lens when in contact with other parts in the final assembly. (12)

![Figure 2-11: Lens decentration, a - axial displacement centring error, b - optical axis, c - axis of the outer edge (12)](image-url)
Figure 2-13: Centring of an optical lens in between brass chucks shortly before edge grinding. The operator centers the lens using a microscope (not seen). (10)

Figure 2-12: Centring accuracy that can be achieved by optical methods depending on the sum of lens surface curvatures \((1/r_1 + 1/r_2)\) with concave radii having a negative sign (12)
2.3 – Finishing Processes and Assembly

After lenses pass through quality-control inspection they are then ready for finishing operations which include another cleaning cycle and the application of an anti-reflective film coating. The lenses are thoroughly washed in an ultrasonic washer in large batches and placed inside a large vacuum evaporator, seen in Figure 2-14 for the application of the film coating. Proper cleaning and evacuation ensures atmospheric debris such as dust does not get coated onto the optical lens. (12) Brushes with radioactive elements can also be used to remove any electrostatic charge from the lens surface. While evacuation is occurring, the optical surfaces are again cleaned by a glow discharge in the vacuum chamber bombards the lenses with cleansing molecules. (12)

Figure 2-14: Vacuum evaporator with optical lenses awaiting cleaning and coating (10)
Anti-reflection (AR) coatings are critical for maximizing transmission of incident light as an untreated glass substrate will reflect 4% of incoming light at both interfaces. An anti-reflection coating will help to prevent ghost images which form as a result of reflections of light traveling in the wrong direction. An AR coating can reduce light reflectance by 70 percent or more. (14) The coating must be an odd number of quarter wavelengths (approximately 125 nanometers) such that any incoming light rays that reflect off the coating and the light rays that reflect off the outer glass surface undergo destructive interference since their phase difference is one-half wavelength, as seen in Figure 2-15. (14) Because each coating is tuned to eliminate a specific wavelength, many modern lenses utilize multiple coatings which reduce reflection over wide chromatic bands. (12)

![Figure 2-15: Anti-reflection coating inducing destructive interference in reflected light rays (14)](image)

The anti-reflection coating is made of magnesium fluoride (MgF₂) which is evaporated onto the lens surface while they are heated to 300°C. (12) MgF₂ is evaporated from molybdenum boats as a white powder and deposited on the surface of the lenses and the deposition thickness is monitored by watching the characteristic color of a reflection with a spectrophotometric detector.
The anti-reflection coating also serves the purpose of protecting the glass surface of the lens against stain formation and other irregularities. (12)

After application of protective coatings, various glass lenses are brought together to form lens systems, as seen in Figure 2-16. Most modern photographic lenses, as seen in Figure 2-17 are made from several individual lenses. Assembly is almost always completed by hand, as seen in Figure 2-18 as the sensitive nature of lens alignment requires deliberate attention and the handling of lens components must be such that the utmost care is given in order to prevent damage of individual glass lenses. (10)

Figure 2-16: Canon EF 500mm f4L IS II USM Telephoto Lens. Telephoto lenses such as this are often made of many lenses, 10 or more, and thus require meticulous assembly. (Cost = $7,000) (15)
Figure 2-17: Cross-sectional view of the lens seen in Figure 2-16. The inclusion of more lens elements increases assembly costs significantly. (10)

Figure 2-18: Glass lenses are assembled into a lens barrel with protective gloves to minimize transfer of skin oils and other debris. (10)

Following a pre-assembly cleaning, individual glass lenses are mounted in lens barrels or sub-barrels, depending on the complexity of the lens system as seen in Figure 2-19. (10) Lenses are mechanically set into place using threaded retaining rings and the use of adhesive cement on the outer cylindrical edge is used to hold individual lenses in place. (10)
Many lens systems also require the cementing of individual glass lenses together with other lenses. This procedure is extremely delicate and is carried out in a dust-free room. (12) The lenses are cleaned right before application of the cement and joining. Lenses that are joined typically bring together a concave and convex lens; the concave lens is heated to the melting point of balsam – the cement to be used. (12) The concave lens is then held-adhesive side down to prevent dust collection and the balsam is spread over the surface. This process is repeated for the convex conjugate lens to be cemented; meanwhile the concave lens sits in a glass jar to protect from dust. The lenses are then brought together and compressed to squeeze out excess cement as well as air bubbles. The pressing is done in an oval-rotational pattern such the bubbles migrate out from the center of the lens. (12) Before the cement cools and hardens, the lenses must be aligned. Alignment can be done mechanically, making the outer cylindrical edges concentric using a V-block or optically, through methods similar to optical centring describe above in Section 2.2. (12) Optical alignment is superior in that it bypasses any errors associated with aligned mechanical/optical axes, as seen in Figure 2-20. (12)
Figure 2-20: Potential centering error within a optical system as a result of unequal lens diameters, a – Centring error within the system, b – optical axis of the convex lens, c – optical axis of the flint lens, d – diameter difference between the lenses. (12)

Once the internal lens-bearing components have been assembled together and inspected, exterior structural and ergonomic components are fitted on the outside of the barrel assembly, as seen in Figure 2-21. Other electronic and measurement devices are incorporated into the lens assembly including focusing indicators, focusing motors, focusing rings and image stabilization components.

Figure 2-21: Addition of exterior components to the lens barrel assembly (10)
After final assembly of all features, the lens is put through a final inspection before packaging and distribution. Optical and electronic components of the photographic lens are comprehensively inspected for performance and for the existence of optical deformities including intra-barrel dust and other debris. (12) Testing is mainly divided into two forms: axial ray testing and oblique ray testing. Axial ray testing involves imaging of a pin-holed collimator or a test object that can only appear sharp in the case that all photographic lenses are aligned optically as seen in Figure 2-22. (12) Oblique ray testing involves use of mirror to test for optical clarity through non-centered portions of the lens system. (12) Much non-adequate imaging arises from centering errors between different lenses in complicated mechanical assemblies. Such errors can be corrected by shifting only one lens component but the most efficient way to deal with such errors is to avoid them through meticulous assembly procedures and extremely precise tolerances. (12) Nevertheless, optical performance variation between lenses with the exact same design specification is often observed, especially in low-cost zoom lenses. (3)
Figure 2-22: Testing a completed optical system for axial imagery, a – Centering collet for mounting the lens to be tested, b – collimator objective, c – illumination for the collimator graticule, d – collimator graticule or pin hole, e – rotating ground glass disc, f – observation microscope, g – lens under test (complete photographic objective) (12)
Chapter 3

Technological Advances in Grinding

3.1 – Physics of Grinding

Grinding is an abrasive process that utilizes the characteristic roughness of the abrasive surface to gradually wear another surface to a specified dimension. Grinding is technically a cutting process in which relatively small individual grains cut into the working material and remove chip through a shearing process. (16) Unlike machining, grinding utilizes abrasive grains with irregular shapes that are randomly distributed along the tool surface. The rake angle is highly negative, as seen in Figure 3-1, such that chips undergo a great deal of plastic deformation before removal. For glass lenses, surface speeds tend to be much lower than for metals owing to the brittleness of the glass. (16)
Grinding, when controlled geometrically with use of precise tools and dynamically through constant application of force, can produce very smooth finishes with surface roughnesses on the order of nanometers (much less than the wavelength of light). (16) Grinding typically serves to remove very hard and/or brittle material that cannot be accomplished with ordinary machining and to provide excellent dimensional tolerance and/or surface finished for precision parts. (16)

For glasses, rough and fine grinding operations are typically carried out at slow surface speeds and depths of cut to prevent cracking and the formation of residual stresses. During finer grinding operations, a process known as lapping is used to give lenses their characteristic transparency and lustrous surface finish. (16) Lapping is a type of grinding where the abrasive is loose and not adhered to the grinding tool itself. The abrasive are typically introduced as a slurry (referred to as polishing rouge in Section 2.2) The tool, known as a lap, is made to conform to the surface of the lens, minus the diameter of the abrasive grains. Because the tool is smooth, its dimensions can be more precisely controlled and as long as the abrasive can be controlled too, excellent surface finish is attainable. (16)
3.2 – Commercial Advances in Grinding Technology

Table 3-1: Tolerances in optical production, circa 1988 (3)

<table>
<thead>
<tr>
<th>Physical quantity</th>
<th>Typical tolerance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Refractive index of glass</td>
<td>± 0.001</td>
</tr>
<tr>
<td>Abbe's Number</td>
<td>± 0.2</td>
</tr>
<tr>
<td>Element thickness</td>
<td>± 0.010 mm</td>
</tr>
<tr>
<td>Element curvature</td>
<td>± 0.030 mm</td>
</tr>
<tr>
<td>Element centring</td>
<td>± 0.004 mm</td>
</tr>
<tr>
<td>Spacing of elements</td>
<td>± 0.003 - 0.007 mm</td>
</tr>
<tr>
<td>Average surface roughness</td>
<td>± 0.1 - 0.03 μm</td>
</tr>
</tbody>
</table>

The essence of lens manufacturing as described in Chapter 2 has remained the same for the preceding 30 years. Many modifications have been made to save time, increased production rate and more precisely control machining and inspection operations. Unfortunately, many of these advances, especially those of the past decade are not readily available in textual or electronic sources due to proprietary concerns of major lens manufacturers (Canon, Nikon, Carl Zeiss, etc.). To properly gauge the advances in commercial production requires more intimate understanding than is allowed for sources such as Canon’s Virtual Lens Plant (cited throughout this paper). Such understanding must be gained through extensive knowledge of the industry as well as access to lens manufacturing plants and the nature of the technology located therein. Unfortunately, such access is beyond the scope of this paper but a presentation of some past patents will hopefully shed light on what sort of technologies lens manufacturers are developing. The values given for typical tolerances above in Table 3-1 help to give a sense of the absolute precision of lens manufacturing.

Canon has several issued patents in the United States pertaining to lens manufacturing. Three in particular pertain to the grinding/polishing process. The first, (17) describes a novel procedure for polishing and grinding optical components. The novelty is not in the grinding
process but rather in the transfer of components from a conveying position to a working position. This machine is likely utilized in mid to high-volume applications where automation is necessary for lowering costs. The apparatus, seen in Figure 3-2, uses air pressurization to convey lens to a spherical grinding tool for grinding/polishing procedures.

![Figure 3-2: Canon's grinding and polishing apparatus used to convey and grind spherical lenses through automation (17)](image)

Aside from lowering handling costs, Canon has also sought to reduce the number of grinding operations lenses must undergo and the time these steps take. Canon has developed a grinding method that allows for more regulated grinding of brittle materials. (18) By prescribing a proper applied load and depth of cut with an abrasive grinding wheel, this apparatus can cut into the glass in a manner that resembles ductile machining instead of brittle machining. The machine is really no different than a typical grinding apparatus except in its ability to maintain a
sub-critical load and stay in the ductile cutting region. Typically, grinding is carried out in the brittle regime with higher loads and deeper cuts that result in cracking or chipping on the surface of the glass. Ductile-regime cutting maintains a sufficiently small cutting depth and load as well as having the abrasive grains on the grinding tool trued (machined and smoothed to a precise roughness). Brittle and ductile-regime cutting are shown below in Figures 3-3 and 3-4. Being able to use ductile-regime cutting can allow for significantly more smoothing in a single grinding operation than is normally attained on a conventional brittle-cutting grinding tool. (18)

Figure 3-3: (left) Brittle cutting with abrasive grains cutting beyond the critical depth (right) ductile cutting with abrasive grains cutting short of the critical depth (18)
The final Canon patent involves active electronic control of applied polishing loads. Using active controls, the speed, position, rotational speed, vibration and grinding load can be monitored for the glass lens being machined. Such a tool could be useful in machining high-precision photographic lenses as well as remachining out-of-specification lenses. Although filed in 1990, it provides a view into the sophisticated control apparatuses that Canon is likely employing in its modern manufacturing processes. The apparatus can be seen in Figure 3-5. Additionally, the machine can record and store information about each individual lens’
machining parameters for later use. Such methods in data collection can only serve to better information Canon and other glass lens manufacturers of machining parameters and potential machining deformities.

Figure 3-5: Canon’s polishing apparatus with active control systems to monitor and direct machining parameters (19)

As the focus of Canon’s lens manufacturing procedures is cost-minimizing and production rate-maximizing, the progression of technology from scientific development to commercialization can take many years. In fact, many technologies which offer significant increases to dimensional tolerances may simply be too expensive and not worth the added effort for the purposes of photographic lenses. As seen in Figure 3-6, costs rise significantly as surface roughness declines. Since photographic lenses have already witnessed significant technological development, the pace of commercial innovation is to bring down the prices of many of these lenses (some costing upwards of $10,000). Yet even entry-level photographic lenses for digital
SLR cameras often cost in excess of $500. Cost and efficiency pressures seem to dominate the innovation in the lens manufacturing industry and not adequacy of machining processes.

Figure 3-6: Machining cost increases significantly as smoothness reaches the nano-scale (16)
3.3 – Scientific Advances in Grinding Technology

The progress of optical engineering and manufacturing technologies has allowed for optical engineers and makers of precision components to utilize a wide range of new optical tools. Through effective new means of tool design, tool compensation and novel finishing methods the grinding apparatuses of the future may break away from machines in conventional use. Also, new methods in aspheric lens manufacturing may enable a whole new class of conformational optical glass lenses.

Aspherical lenses are showing promise in scientific applications as grinding technologies have improved and are capable of being controlled to such a degree that deterministic spherical lenses no longer limit optical instruments to confined geometries. Photographic objectives still rely heavily on spherical lenses as their ease of production and general adequacy doesn’t provide sufficient incentive to invest heavily in developing commercially viable aspherics. These non-spherical optics will also include non-axisymmetric lenses for specialized purposes. (20)

Studies of tool design and glass machining parameters have led researchers to find optimum conditions for grinding and polishing optical glass lenses. Application of CNC machines as well as tool path compensation methods have been researched and have shown to increase profile accuracy and decrease surface roughness by 50%. Surface roughnesses, even for aspheric lenses, have been pushed down to the single nanometer scale – well below the wavelength of visible light. (20) Optimization of machining parameters (work spindle speed, wheel spindle speed, federate, etc.) have been tested out in recent years with different machining forms (parallel grinding, cross grinding) to minimize final surface roughness. (21)

Experimentation with new tool derivatives has led to interesting and beneficial results. High-frequency surface irregularities are common problems in aspheric lens production with
rigid tools. A study done with a semi-flexible multiple-segment ring tool, seen in Figure 3-7, was proven to eliminate such irregularities and produce optically consistent transmission patterns. (22)

Figure 3-7: Semi-rigid tooling applied to grinding (24)

Theoretical inquiries into integrated manufacturing systems for freeform optics have risen as a computational and theoretical means of avoiding costly trial-and-error optimization experiments, seen schematically in Figure 3-8. Such systems not only depend on precision of machine tools but also depend on advanced optics design, modeling, data collection and optimization of the machining process. Such systems claim to shorten development cycle time and provide means for determining final surface roughness and optimal cutting strategy. (23) Results from such proposed systems are promising with predicted values giving final surface roughnesses about 1-6 nanometers away from measured values at surface roughnesses of about 2 nanometers as seen in Figure 3-9. (23)
Technological gains are also being made in sensor feedback networks to rectify undesired shifts in machining parameters in order to maintain precision. Computer-aided machining (CAM) systems with error compensation, on-machine measurement and simulation capabilities have realized gains in accuracy for machining processes. For example, a CAM system developed at Xiamen University in China halved the surface form error of a half-meter diameter aspheric lens from 8.2 to 4.1 microns. Such a system was able to supply high-precision grinding
control for planar, inclined planar, spherical, axisymmetric aspherical, non-axisymmetric aspherical and off-axis aspherical surfaces. (24)

The friction associated with the grinding process can build up sufficient heat to affect dimensional stability of the workpiece. Studies into the application of ventilation helped to shed light on thermal drift as well as inquiries into temperature changes from human handling and whether or not cutting fluid should be applied as a mist or as a drip. (25) Models derived from the results of these experiments were the ultimate goal of the researchers. (25) Such parameters are especially important where multiple passes with different tools are required to cut given geometry features. Such parameters for a laboratory setting, including maximum deviation results are shown in Table 3-2.

| Table 3-2: Peak-to-valley errors induced as a result of thermally-significant parameters (25) |
|---------------------------------|-----------------|-----------------|
| Machine door                    | PV radial (μm) | PV axial (μm)  |
| Open                            | 0.2             | 0.3             |
| Closed                          | 0.1             | 0.1             |
| Laboratory door                 |                 |                 |
| Open                            | 0.05            | 0.20            |
| Closed                          | 0.05            | 0.25            |
| OMS mist                        |                 |                 |
| No spray mist                   | 0.2             | 0.3             |
| Spray mist on                   | 0.5             | 0.9             |
| Mist air only                   |                 |                 |
| Air off                         | 0.2             | 0.05            |
| Air enabled                     | 0.5             | 0.1             |
| OMS droplets                    |                 |                 |
| No OMS                          | 0.2             | 0.2             |
| OMS dripping                    | 0.2             | 0.3             |
In addition to optimizing standard grinding procedures the inclusion of novel grinding and polishing operations may have potential as alternative methods with different sets of advantages and drawbacks. Fluid-jet polishing (FJP) is showing promise as a way of removing very small amounts of material (as little as 1 nm/min) from brittle materials including optical glass. (26) FJP utilizes a low-pressure water jet with a given concentration of abrasives that is used to alter a glass surface in a predictable fashion. (26) FJP also avoids tool wear, workpiece cooling times and debris removal procedures. The FJP process can achieve very low surface roughness when used to cut a uniform channel in glass – an average surface roughness of 1.2 nm. Such roughness can be achieved since the FJP process removes material in the ductile regime and avoid the cracking and chipping that is characteristic of brittle grinding. (26) The depth of the FJP is generally accurate to about 5% but the degree with which this technology can be scaled still remains to be seen.

Another mode of fluid polishing holds even more promise: magnetorheological finishing (MRF). MRF utilizes the relative motion of an electromagnet, the magnetic polishing fluid and the workpiece. The magnet generates a non-uniform magnetic field that passes through the workpiece and polishing fluid. The magnetic field increases the viscosity of the polishing fluid as it passes through a flow constriction formed between the lens and a moving wall, seen in Figure 3-10. (28) At this moment, the fluid acts to grind away materials from the workpiece. Thus, a large grinding tool is unnecessary, tool grinding is avoided and the electro-magnetic nature of the process is very amendable to digital control. (28) MRF may also be used to finish aspherical lenses with changing curvature due to its flexibility. (28) Finishing results of MRF show promise: MRF was able to finish test pieces to within 300 nm of desired shape with a finished average roughness of 1 nm. (28)
Figure 3-10: MRF with process parameters (28)
Chapter 4

Conclusion

Photographic lens manufacturers have a great multitude of new technologies to select from in future design iterations of their production systems. While most of these processes may not at first be cost-effective, integration and optimization of these processes into commercial production systems will likely yield cost benefits to producers and consumers alike. The technologies presented here were mere glances of the technical precision and skill required to develop and implement such advanced processes. Proceeding work should delve into these technologies with greater detail and analyze which groups of optical devices will most benefit from their development.

Photographic lenses are marvels of engineering and the appreciation of their intensive production and rigorous inspection requirements should give all an appreciation for the optical images they enable.
Bibliography


