Field Guide to
Optical Fabrication

Ray Williamson

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John E. Greivenkamp, Series Editor

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Introduction to the Series

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Introduction

Most *Field Guides* address a particular subset of physics and/or mathematics and, as such, can be treated in a linear exposition of theory from first principles. In contrast, optical fabrication consists of a collection of disparate crafts, technologies, and business decisions in the service of making *nearly* perfect physical instances of those geometric and physical theories. I have attempted to organize the subject matter in ways that make sense to me: What the designer needs to know before making final choices, how to specify the components before they are ordered, how conventional fabrication proceeds for representative components, alternative and emerging methods, how the manufacturer plans the work, product evaluation, and calculations used.

This *Field Guide* is intended to serve several audiences, and introduce each to the other. I hope to provide designers and purchasers with some perspectives and appreciation for the craft and business, the shop manager with a concise reference, the optician with a wider overview than one is likely to get within any single company, and the optical community at large with some insight into this fascinating and dynamic enterprise.

Thanks are due to Oliver Fähnle for inputs to synchrospeed and fluid jet. I want to particularly acknowledge three influences, true masters in the field: Dick Sumner, Norm Brown, and Frank Cooke. Dick personified excellence in craft, a passionate curiosity, and a focus on effectiveness. Norm brought the light of science and engineering to the hidden mysteries of this once-black art with accessible clarity. Frank was an inspiration to all through his boundless creativity and zest. We are in transition between 20th Century craft and 21st Century technology, and the field will be hardly recognizable in twenty years.

This *Field Guide* is dedicated to my wife, Lore Eargle, in recognition of her encouragement, patience, support, editing, and so much more.

Ray Williamson
August 2011

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Glossary of Symbols and Acronyms

AOI	Angle of incidence
AQL	Acceptance quality level
b	Bevel leg length radial to part diameter
BFS	Best-fit sphere
BK7	Schott glass type 517642
BRDF	Bidirectional reflectance distribution function
C	Curvature, 1/radius
°C	Degree Celsius
CA	Clear aperture
CGH	Computer-generated hologram
CMM	Coordinate measuring machine
CNC	Computer numerical control
C_p	Specific heat
CT	Center thickness
CTE	Linear coefficient of thermal expansion
D	Diopter, reciprocal meter, unit of focal power
D	Thermal diffusivity
deg	Degree, angular
dn/dT	Change of index with respect to temperature
DPTWF	Double-pass transmitted wavefront
e	Natural logarithm base, ~2.718281828
E	Young's modulus
EFL	Effective focal length
ET	Edge thickness
ETV	Edge thickness variation
°F	Degree Fahrenheit
FS	Fused silica
GPa	Gigapascals
h	Height of surface form error normal to surface
HF	Hydrofluoric acid
HIP	Hot isostatic pressing
H_K	Knoop hardness
IR	Infrared
K	Kelvin, absolute temperature units
k	Thermal conductivity
mrad	Milliradian
MRF	Magnetorheological finishing
MSDS	Material safety data sheet
n	Index of refraction

Glossary of Symbols and Acronyms

nm	Nanometer, 10^{-9} m
OPD	Optical path difference
OPL	Optical path length
PSD	Power spectral density
PV	Peak to valley
PVr	Peak to valley, robust (due to C. Evans)
r	Radial distance from axis
R	Radius of curvature
RMS	Root-mean-square
RSS	Root-sum-square
RWF	Reflected wavefront
s	Sag
SCOTS	Software-configurable optical test system
S-D	Scratch-dig (surface quality)
SFE	Surface form error
SPDT	Single-point diamond turning
SQ	Surface quality
SSD	Subsurface damage
t	Thickness
T	Temperature
t_c	Center thickness
t_e	Edge thickness
T_g	Glass transition temperature
TIR	Total internal reflection
TIS	Total integrated scatter
TWD	Transmitted wavefront distortion
TWF	Transmitted wavefront
UV	Ultraviolet
y	Radial distance from axis
z	distance along axis
α	Linear coefficient of thermal expansion
α	Prism angle, wedge, or tilt
α	Angular error from reference, as from 90 deg
δ	Beam deviation
θ_B	Brewster's angle
θ_C	Critical angle
κ	Conic constant
κ	Thermal diffusivity
λ	Wavelength

Glossary of Symbols and Acronyms

μm	micrometer, 10^{-6} m
μrad	Microradian, 10^{-6} rad
ν	Abbé number; reciprocal dispersion
ρ	Specific gravity
σ_f	Rupture strength
τ	Time
ϕ	Diameter
ϕ_{block}	Block diameter
ϕ_{eff}	Effective diameter including spacing

From Functional Desires to Component Tolerances

You can build a lot of things with Lego® pieces, but the good people who make them have no idea what you want to build—and telling them may not help. What you really want is for the pieces to reliably snap together, so you must specify **dimensions** and **tolerances**.

Typically, the optician knows little if anything about the final system (often for proprietary reasons), and the designer knows little about the processes involved in creating the components' shapes. It is wise to consult with fabricators prior to finalizing a design.

Functions desired in the system map poorly to parameters that can be measured in the optical shop. Understanding the relationships between **specification** versus function, tolerance versus performance, and configuration versus cost will affect overall success.

Figure, **surface quality**, **aspect ratio** (ϕ/t), **clear aperture**, and **centration** are strong and nonlinear determinants of difficulty and cost that do not directly correspond to system performance.[1]

While the designer may sometimes have a limited choice of materials, the wrong choice can change the outcome from predictable success to a high-risk gamble. These are some characteristics of troublesome materials:

- **hygroscopic**
- easily cleaved
- exhibiting low **yield strength**
- toxic
- soft, or very hard
- stainable
- exhibiting high **thermal expansion**
- exhibiting low **thermal diffusivity**
- exhibiting high ***dn* / *dT***

Materials having a combination of these characteristics are especially problematic.

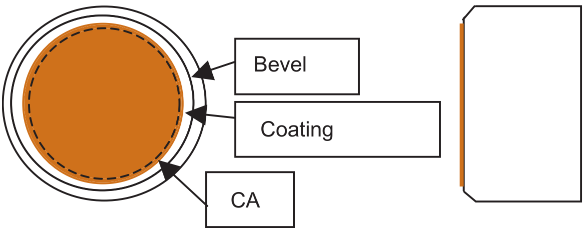
Clear Aperture

Clear aperture (CA) or free aperture is that area inside which all optically functional tolerances and specifications apply.

The manufacturing process inevitably creates a lower-quality surface near the edge than at the center. The edge may have low surface quality, figure, or **chips**. Light encountering boundaries may be scattered, diffracted, or vignetted.

In general, allow for a zone between the edge and the CA with purely mechanical specifications. An 80–85% diameter CA is a good starting point. Weight or **packaging** considerations may force a larger CA. When specifying CA in excess of 90%, double check for **bevel** and **coating** margin interference.

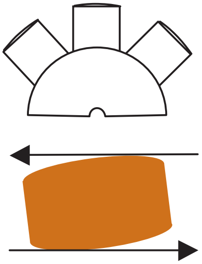
When specifying coated aperture, keep in mind both minimum and maximum size. A guideline for part diameters of 10–100 mm is for the tooling lip to extend 1 mm inside the bevel. If a wider coating-free perimeter is required, this should be specified. Also, coatings shift performance near the tooling lip; thus, the coated aperture should exceed the optical CA by at least 1 mm.



One exception to this allowance is the unbeveled, internally reflecting **roof edge** of some **prisms**, which is always a troublesome and fragile area. Any relief allowed on roof edges will be rewarded by substantial reductions in difficulty, lead time, and cost.

To maintain **Gaussian** and near-Gaussian coherent beams, the CA must be at least 1.5 times the $1/e^2$ point.

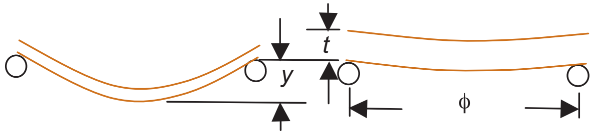
Thickness versus Stability and Ease of Fabrication



In general, thicker parts are easier to fabricate than thin parts. Exceptions include thick-edged strongly convex lenses (due to sparse **block** packing) and tall flat parts to be **double-lapped** (due to a tendency to rock between the laps).

Increased **thickness** provides a broader path for extraction of process heat and greater stiffness to resist **stresses** from machining, **blocking**, and **handling**. A common rule of thumb is that the "knee of the curve" is found at an **aspect ratio** (ϕ/t) of 8:1 for precision optics.

When supported at its edge, a disc of a given diameter deflects in proportion to the pressure applied, and with the inverse cube of its thickness.



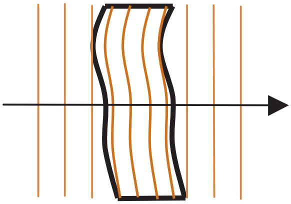
Several methods are employed to minimize stress while supporting thin parts during fabrication, some of which are included here:

- **Pitch buttons** can be used where forces are low and **angle tolerances** are above a few arcminutes.
- Electrician's tape applied to the backside before **wax blocking** reduces stress and allows better angle and thickness control.
- **Optical contacting** allows subarcsecond angle tolerances and submicron thickness control by coupling the thin part to a stiff substrate.
- **Double-sided processing** entirely removes the need for blocking and can produce highly parallel and uniform parts. However, the resulting parts may not be flat.

Flatness versus Transmitted Wavefront

Before the advent of practical commercial **interferometers**, it was far easier to compare both surfaces of a window to a reference flat than to measure its **transmitted wavefront distortion (TWD or TWF)**. However, it has never been easy to make and keep both sides of a thin section flat.

Parts bend due to blocking or coating stresses, stress relief from **polishing** a formerly ground surface (see **Twyman effect**), and even simply supporting the part while testing or **mounting**.



Windows are used in transmission, thin sections bend, and bending has a negligible effect on TWD, *especially* in thin sections. TWD is the preferred specification for windows unless the quality of a surface reflection is a functional requirement.

While solid **etalons** must be of highly uniform thickness, they can tolerate far more bending than variation in thickness. TWD is the more relevant specification for windows and solid etalons, especially for thin ones.

The finite **radius** of a lens is always allowed a radius tolerance, often amounting to many **fringes**. But when the radius is infinity, no radius tolerance is given. Typically, a **plano** surface is specified by figure, meaning total **peak-to-valley (PV) surface form error**, thereby setting a much tighter tolerance on **curvature**.

Considerable cost and effort can be saved by allowing plano lens surfaces a reasonable power tolerance similar to that allowed on **spherical** surfaces. As stated by W. J. Smith, "...if a uniform tolerance is to be established for all radii in a system, the uniform tolerance should be on curvature, not on radius."[2]

Scale Factors for Surface and Wavefront

All opticians know that a **fringe** is a half-wave. But all physicists know that constructive interference occurs when two interfering waves are in phase, which can happen only once per wavelength.

So who is right? The whole truth is:

> One fringe spacing at the **plane of interference** represents one full wavelength of **optical path difference (OPD)** between the interfering beams. The question you need to ask is, "What paths did the beams travel?"

On a test plate or in most commercial interferometers, the test beam travels *to* the surface *and back*, or *through* the optic *and back*, thus taking twice the optical path length of either the surface deviation or single-pass **transmitted wavefront distortion (TWF or TWD)**. In these most common cases, one fringe corresponds to $\lambda/2$ of *surface form error* or of single-pass TWF *seen in double pass*. However, other configurations have different scale factors:

- **reflected wavefront (RWF)** specs
- single-pass TWF specs
- multiple passes of the optic
- non-normal incidence
- internal reflections
- single-pass interferometers

In one extreme example, the **total internal reflection (TIR)** surfaces of a laser slab are functionally encountered internally (where the wavelengths are shortened by $1/n$) at non-normal incidence, multiple times in the same **orientation**, for each pass of the slab.
Guidelines:

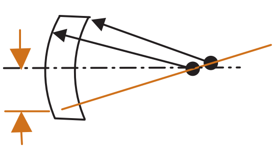
- Never specify fringes without also specifying the test configuration.
- If not normal incidence, specify a test's **angle of incidence (AOI)**.
- Consult the Equation Summary for appropriate **scale factors**.

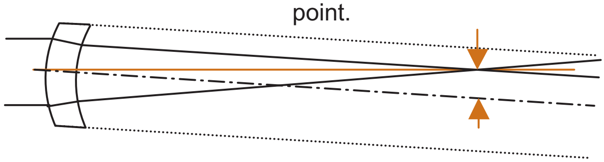
Wedge in Nearly Concentric Optics

Wedge between **plane** surfaces may be adjusted across an entire block of parts. Wedge (or **decenter**) between differently curved surfaces on a block can be minimized at one exact thickness and then eliminated by **centering** during a final **edging** operation.

However, wedge between nearly concentric surfaces cannot be removed by edging and centering—it must be adjusted by individual processing. Achieving tight wedge tolerances on nearly concentric optics is expensive and time consuming.

- The **optical axis** is the line that contains both **centers of curvature**.
- The **mechanical axis** is the line formed by collapsing the lens barrel cylinder.
- Authoritative sources are vague concerning where to measure the displacement between them—focal point, center of lens, or someplace else?
- In any case, when the **radii** are nearly concentric and long relative to the part diameter, a very small physical wedge results in a large decenter.





Left: lens with small wedge, decenter measured at lens.

Below: lens with no wedge but slight barrel tilt, decenter measured at focal point.

Wedge or **beam deviation** angle are preferable to centration tolerances in this type of optic. These parameters are more easily measured in the shop and more closely related to optical performance than centration is.

Surface Quality versus Performance

Surface quality (SQ) generally refers to **scratch-dig (S-D)** specifications. In the US, this includes MIL-PRF-13830b (formerly MIL-O-13830a), MIL-C-48497a, and MIL-F-48616, the latter two both officially inactive and applying only to coating defects. While MIL-PRF-13830b addresses "gray," stain, **bubbles**, **inclusions**, and **voids** and **spatter**, it only *grades* S-D. Statistical surface parameters including **root-mean-square (RMS) roughness**, **slope error**, **ripple**, and **lay** are not covered in these standards.

SQ does affect performance in terms of laser damage threshold, absorption, scatter, **polarization**, and diffraction. However, no reliable guideline exists that matches an SQ cause with a performance effect.

While MIL-PRF **digs** can be physically measured, **scratches** are only compared for "similar visibility" to "standard" scratches under prescribed lighting conditions by unaided eye. Scratches of similar appearance in the test method may have widely different profiles that look different in other conditions. These "standard" scratches vary substantially from set to set and supplier to supplier. Also, precision optics suppliers and their customers often deviate from the standards' prescribed methods by applying magnification and increasing illumination. Finally, no "5-2," "0-0," or "**laser quality**" standards exist.

Due to inherent subjectivity at each end, suppliers avoid disputes by invariably over-rejecting and overpricing.

Designers selecting an SQ specification should consider wavelength (scatter varies as $1/\lambda^4$), coherence, polarization, beam diameter, distance from focal plane, incident **power**, multiple passes, and the budget.

ANSI/OEOSC OP1.002 is a recent extension of, and improvement to, MIL-PRF that includes dimensioned scratches with visibilities <#10. **ISO 10110-7** is entirely based on areal and linear dimensions of defects.

"Difficult" and Preferred Materials

For various reasons the designer's options may be limited to a few, or even one, material. Chief among the factors to consider are the difficulty and cost of making the part.

There are hundreds of substrate materials. This list includes only a notable subset.

Material	Cost	Issues
BK7 glass	Low	Preferred, moderate **CTE**
Fused silica	Moderate	Preferred, low CTE, works more slowly than BK7
Si	Low	Preferred, poor **SPDT**
High-index glass	High	Stains, high CTE, scratches
Crystal quartz	Moderate	Critical axis orientation, moderate CTE
CaF_2	Moderate	Easily **fractured** and scratched
Sapphire	High	Extremely slow working, "brushy" surface quality
IR: ZnSe, ZnS, GaAs, CdTe, etc.	High	Some toxicity, special slurries. **Polycrystalline** is tougher and stronger.
AlON	High	Slow working, orange peel surface
Metals	Variable	Poor results from standard glass shop practices
Plastics	Low	Soft, **ductile**, **birefringent**, extreme CTE, sensitive to solvents
LiF, NaCl, etc.	Variable	Soft, stains, scratches, hygroscopic, cleavable (except polycrystalline)

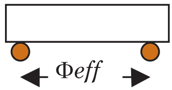
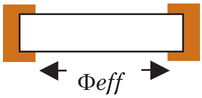
Some optical shops have unconventional machinery such as **single-point diamond turning (SPDT)** or **magnetorheological finishing (MRF®)**, or have developed niche specialties in processing particular materials. Consult the experts.

Pressure-Bearing Window Thickness

A window serves less as an optical element than as a mechanical barrier between liquid and gas, hot and cold, vacuum and pressure, or toxic and benign environments. When used to safely maintain a pressure differential, the thickness of the window must be sufficient to withstand the stresses.

Simply supported windows are those supported against pressure by a circular ring, the way a manhole cover is supported. Clamped windows are those for which the entire edge is embedded in rigid material. Material strength here is *not* **Young's modulus**, but is rather whichever is lower: yield strength or rupture strength.

Minimum Thickness

Mounting	Image	Minimum Thickness
Simply supported		$t_f^{ss} = 0.55\Phi\sqrt{SF/\sigma_f}$
Clamped		$t_f = 0.433\Phi\sqrt{SF/\sigma_f}$ where **SF** is the "**safety factor**," and σ_f is the "strength" of the material

The typical "safety factor" is 4. Note that this is inside the radical, which means that a window half as thick has an SF of 1. "Safety factor" is enclosed in quotes because it does not consider material fatigue, scratches, thermal loading, or the consequences of failure. If catastrophic failure could hurl sharp shards toward someone or drown people, leak noxious contents, or suck body parts through a porthole, go for a higher safety factor.

Specifications Checklist

Although not complete for all cases, this list covers the most common optical component **specifications**. In many situations, some of the specifications may be ignored, or defaults may be used.

- Configuration (with tolerances): radii, physical dimensions, CA, angle/parallelism, centration (including relevant **datums**), bevel dimensions and angle, flat bevel (width/**sag**/tilt), edge finish, **marking**.
- **Prisms**: pyramidal error, beam path, beam displacement and deviation, base angle, roof edge chips, wavefront, **polarization**.
- **Aspheres**: base radius with tolerance, conic and polynomial coefficients, **best-fit sphere** reference, **sag** table reference, sag error tolerance, slope errors versus bandwidth, wavefront per specified test, both tilt and decenter.
- Optical path: CA, surface figure and/or transmitted/reflected wavefront, power, **irregularity** [**PV (peak-to-valley)** or **robust (PVr)** or RMS], ripple **(mid-spatial-frequencies)**, slope error, S-D, surface roughness (with frequency cutoffs), absorption/optical density versus λ.
- Coatings: **apertures** (maximum coated, minimum for full performance), reflection, transmission, absorption, phase shift (all per wavelength band/polarization/AOI), adhesion, abrasion, fungus, humidity, salt spray (citing specific paragraphs of applicable standards), damage threshold (continuous wave or pulsed with pulse length and duty cycle).
- **Environmental**: abrasion, fungus, humidity, salt spray (typically under "coatings"), use and **storage** temperature range, thermal shock, pressure differential, vibration G-loading, **cleaning** methods.

Realistic Tolerances

The designer performs a **tolerance** analysis to determine the sensitivity of each parameter of a design's performance, as well as its cost and manufacturability.

Not all toleranced values follow a bell curve; in order to avoid the irrecoverable loss of going under thickness, for example, opticians strive to achieve all other specs at the top of the thickness tolerance. By the same logic, a combination of materials that polish quickly and have tight figure and SQ tolerances and narrow thickness tolerance explodes costs.

All costs are process dependent. Processes are proprietary and evolving, and each shop has its particular strengths. Ask suppliers for their true pinch points and capabilities.

The table gives relative cost factors due to various tolerances, to be multiplied by a base cost.

	Willey and Durham[3]	Nelson, Youngworth, and Aikens[1]
Diameter tol.	$1+3.16/(\#\ \mu m)$	
Lens wedge	$1+0.5/(\#\ \text{arcmin})$	$0.6\ (\#\ mm)^{-0.2}$
Curvature (power) tolerance	$1+1/(\#\ \text{fringes})$	$1.2\ (\#\ \mu m)^{-0.4}$
Irregularity	$1+.25/(\#\ \text{fringes})$	$(\#\ \mu m)^{-0.2}$
Aspect ratio	$1+0.0003(\phi/t)^3$	
CT (center thickness) tolerance	$1+12.64/(\#\ \mu m)$	
S-D per MIL-PRF	$1 + 10/S + 5/D$	$2[(S/10)+(D/5)]^{-0.2}$
Schott stain class	$1+0.01(SC)^3$	
BK7 = 1	**Pyrex**® = 1.25	**FS** = 1.4
ZnSe = 1.6	**MgF_2** = 3	**Al_2O_3** = 8

An important discontinuity in price is found at a ratio of R/ϕ_{eff} somewhere below ~0.87–1.1, where the block quantity drops from 3 to 1.

Designing Aspheres for Manufacturability

Aspheres are attractive; a single aspheric surface can perform the work of several spherical surfaces, saving length, mass, coatings, and cost of materials. With new manufacturing and testing technology, their costs have shrunk from 10–20 times that of a sphere to perhaps 2–4 times. If molded, the premium is smaller. Critical factors remain and are changing with technology:

Convex aspheres were more difficult to test with conventional interferometry, requiring a reference surface larger than the asphere. **Stitching interferometry** now allows **subaperture tests** to be combined into a high-resolution, full-aperture image for both concave and convex. Stitching errors are being reduced through improved instrumentation. But certain machines such as MRF® cannot polish very short concave radii. (Recall that concave molded optics have convex masters.)

Local changes in curvature must be kept below the **Nyquist limit** in all zones of conventional or stitched interferograms. That limit depends on the supplier's instrumentation. A recently introduced sparse-array, sub-Nyquist interferometer addresses this issue.

Stitching interferometry does not handle inflections (as in Schmidt plates) gracefully. Contact **profilometry** is insensitive to inflection but produces only line scans.

Subaperture polishing machines produce some degree of **mid-spatial-frequency error** or ripple, the effect of which must be carefully considered in the design.

The likelihood of inadvertent human error can be reduced by providing several points of a sag table so that the supplier can verify the interpretation of the units and signs of your aspheric equation.

Finally, consider using the Forbes Qbfs equation,[4] which increases the visibility of manufacturability issues.

$$s = \frac{C_{bfs} r^2}{1 + \sqrt{1 - C_{bfs}^2 r^2}} + \frac{u^2 \left(1 - u^2\right)}{\sqrt{1 - C_{bfs}^2 r^2}} \sum_{m=0}^{M} a_m Q_m \left(u^2\right)$$

where $u = \frac{r}{r_{\max}}$.

What Kind of Shop Is It?

Just as there are many kinds of food preparation businesses, there are many kinds of optical manufacturers. The layout, equipment, and metrics for efficiency and excellence are different for a donut shop and a pizza parlor—and certainly for a wedding cake specialist, diner, five-star restaurant, and candy factory.

While some firms thrive on a single-line flow with few variations, others are more like the restaurant with an ever-changing mix of custom-produced small orders criss-crossing the workplace in different sequences.

No one company can be best at everything (and those who attempt it fail). Well-run companies know their limits as well as their specialties, and either buy from, or direct business to, their strategic partners for the rest.

When looking for optics suppliers, consider the following specialties and capabilities (which are not necessarily mutually exclusive):

- aspheres
- assemblies
- build to print
- catalog
- coatings
- crystals
- cylinders
- defense and aerospace
- design and build
- extreme precision
- flatwork
- high power
- high production
- imaging
- IR
- laser cavity optics
- massive
- metals
- micro
- molding
- MRF®
- polarization
- prisms
- prototype and craft
- quick turn
- **reticles**
- SPDT

Finally, an increasingly vexing decision must be made: domestic or foreign manufacturer? And if a company has a domestic address, are the parts really manufactured there, or offshore?

Stages of Conventional Fabrication

The stages of conventional fabrication include:

Shaping (establishing configuration): Shaping may be spread throughout fabrication. For example, finished surfaces may be divided into multiple parts by **dicing** or **coring**; or wedge may be removed by centering and edging.

Grinding: Approaching dimensional tolerances, smoothing surfaces to accept a polish.

Polishing: Removing grinding damage, making surfaces specular.

Figuring: Final polishing to meet optical tolerances.

Coating: Depositing thin films on specular surfaces to modify reflection, absorption, polarization, and other properties possibly including abrasion and corrosion resistance, conductivity, hydrophobicity/hydrophillicity, coefficient of friction, and solderability. Coating is the only additive stage of conventional optical manufacturing.

Cementing: Connecting components with an **adhesive**. Cements for multi-element prisms and lenses are transparent and nominally match the indices of the elements to reduce reflections of uncoated buried surfaces. Design of buried coatings must consider the cement index.

Mounting: Connecting and aligning components to a mechanical structure. This may include clamping, gluing, and stacking.

Inspection: Incoming, in-process, and final inspections establish product conformance and maintain process control. Parameters inspected may include mechanical, surface defects, form, roughness, spectral characteristics, angles, and centration.

Documentation: This is integral to fabrication, critical for troubleshooting, often a customer requirement, and a cost. Inspect and report only what is necessary to ensure quality. Exact, as-built thickness and radius data can help designers adjust optimum assembly spacing.

Shop Safety

The optical shop presents a number of personal **safety** hazards, overcome through safety training, protective gear, approved procedures, situational awareness, and a responsible attitude. Hazards can be classified as:

- electrical
- thermal burns
- slips and falls
- cuts
- mechanical
- radiation
- chemical
- eye injuries
- lifting and dropping

Management responsibility: Collect and make available MSDS sheets; provide emergency showers, first-aid kits, and protective gear; conduct and monitor training; maintain emergency response team and phone numbers.

Electrical hazards: Fabrication machinery runs at 110–440 VAC and has wet metal surfaces and exposed power cords. Shop floors are often wet. Some coating machinery runs at tens of kV. Lasers—even small HeNe lasers—may harbor >10,000 VDC at high capacitance.

- Avoid using knives, razor blades, wrenches and screwdrivers near live cords.
- Route power cords overhead.
- Follow lockout procedures.
- Wear rubber-soled shoes.

Chemical hazards: Methanol, acetone, NO_3, HCl, H_2SO_4, H_3PO_4, NH_4OH, KOH, NaOH, chlorine bleach, **pitch**, terpenes, limonenes, pitch vapors, and **epoxy** resins are common. Potentially toxic substrates include Be, ZnSe, CdSe, GaAs, and AMTIR®. Issues include reactions, combustion byproducts, ingestion, inhalation, contact, and absorption. Chronic inhalation of glass dust can cause silicosis.

- Never add water to acid.
- Never combine chlorine bleach with ammonia.
- If it has an odor, don't breathe it.
- Use approved respirators, eye protection, gloves, and aprons as appropriate.
- Supply and maintain emergency showers.
- Remove gloves or cots and wash hands before eating.
- **Hydrofluoric acid (HF)** requires special training, isolation, and protection.

Shop Safety (cont.)

Mechanical hazards include pinch points and ejecta. Rotating and reciprocating machine parts can capture hands, clothing, jewelry, or hair. Machine crashes can rapidly eject parts.

- Tie back long hair and avoid wearing loose clothing and jewelry.
- Provide panic buttons and safety interlocks and know where they are.
- Shield operators from high-speed machinery.

Slips, falls, lifting, and drops: Clutter and floors wet with oily coolant increase risks.

- Maintain clean, slip-resistant floors and wide, unobstructed corridors.
- Use proper lifting procedures.

Cuts: Razor blades are everywhere, and freshly cut or broken glass is common.

- Handle and dispose of blades with care.
- Clean up broken glass with wet towels or mops.

Thermal burns: Hot plates, buckets of hot pitch and wax, and lit propane torches present burn hazards.

Eye injuries: Chemical splashes, flying objects, and broken glass are common. Light hazards include high-intensity **UV** for curing cements, and various lasers.

- Use machine shields.
- Wear appropriate eye protection and have eye wash stations available.

Radiation hazards: **X-ray diffractometers** are used for orienting crystal axes. **ThF_4** is a common thin-film coating material, hazardous mainly through inhalation.

- Designated personnel should wear dosimeters.
- Those handling ThF_4 should employ appropriate respirators, and cleaning chambers where ThF_4 was used should have HEPA vacuum cleaners.
- Dispose of contaminated waste appropriately.

Blocking Layout

Just as muffins are baked by the tray, simultaneously processing a batch of parts affixed to a single base increases efficiency, separates the parts from direct machine contact, and enhances stability through a larger footprint. In the optics shop, that base is called a block.

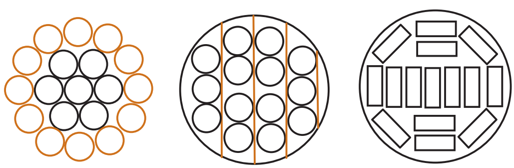
Factors for good **block layout** include:

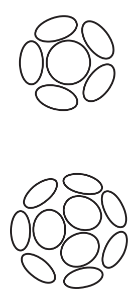
- Symmetry
- Close packing (but not touching)
- Nearly circular edge profile

Block capacity for spherical parts is limited by edge slope, which should not, as a general rule, exceed 60 deg. Thickness, radius, and diameter determine optimal layout. The layout may have one centered part, a first-row triad, or a first-row quad.

Block capacity for plane surfaces is limited only by machine size and production goals. Typical layout for circular parts is with one part centered and six surrounding it, surrounded by circular rows of twelve, eighteen, etc.

Blocks accommodating **wedged** parts are usually made with straight-milled ramps, thus the outer rows cannot be made circular. The slot positions and block diameter should be planned for good layout factors as explained above.





Top views (left to right):
Plano layout with colored row circularized.
Wedge ramps.
Rectangular plano parts arranged for best edge, symmetry, and uniform packing.
Spherical blocks: centered.
Spherical blocks: triad.

Blocking Methods

There are several ways to affix components to a block. The choice depends on several factors: bond stress, angle and thickness control, part configuration, production volume, delivery time, and budget.

Recipes for **blocking wax** combine waxes and resins to achieve a desired melting point. Wax blocking is performed by heating the components and block, coating the block and/or components with melted wax as an adhesive layer, and pressing parts to the block. When cool, the bond is very strong, thin (~10–20 μm), stable, and water tight, but stressed. Parts are removed by reheating.

Blocking pitch contains fillers to limit cold flow. If kept in a hot pot, the fillers will settle out. Thick layers (~2–10 mm) allow stress relief over time. Buttons (small dots) of blocking pitch are spaced evenly about the heated parts. The parts are arranged against a reference surface, and the heated block is floated onto them over temporary spacers to achieve the desired thickness. Pitch buttons do flow, so thickness and angle are poorly controlled. Parts are removed by freezing the pitch, which makes it brittle and easy to chip off.

Contacting is done by bringing two extremely clean and smooth surfaces into such proximity that van der Waals forces pull them together. Other than a water-sealing bead around the edge, no adhesive is used. With no adhesive and no bond line, stress is practically eliminated, angles held to ≪1 arcsec, and thickness to <0.1 μm. Unfortunately, contacting is an acquired skill. The technique is almost never used for curved surfaces.

Plaster blocking is used for awkward part configurations in lower quantities. The parts are coated with wax and arranged against a reference surface, then buried in plaster to achieve a rigid, low-stress block. Parts are removed by breaking the plaster.

UV adhesive can be used for holding optics to blocking tools. Although there is some shrinkage of the adhesive because the bond is formed at room temperature, the stress is lower than that of wax blocking. The adhesive does not flow like pitch

Blocking Methods (cont.)

and can be used with a greater variety of configurations than contacting. The parts can be individually adjusted with great precision prior to cure. Small bond areas are deblocked by soaking in acetone; larger areas are immersed in a hot furfuryl alcohol deblocking agent.

Transfer blocking is a combination technique wherein a wax block of flat parts is polished on one side, then the finished side of the entire block is UV cemented to a second block, forming a sandwich, and the first waxed backer is removed by heating to work the second side. All parts are coplanar on the first side while working the second side, allowing precise parallelism without needing to contact each individual piece.

Vacuum is sufficient to hold larger sections in hard contact to a fixture. Where applicable (as in **milling**, **curve generating**, and **CNC polishing**), the workpiece can be precisely located to **datum** points and fixed or released in seconds without adding materials that must be subsequently cleaned off. The stress of unbalanced atmospheric pressure is minimized by proper design of the chuck. Porous chucks and backing tape are used for precision dicing. Alternatively, a precision chuck may be designed with the intention to pre-stress an optic so that an easily produced flat springs back to a desired shape such as a Schmidt plate upon release.

Mechanical clamps also fix or release parts cleanly in seconds and are used for angles, bevels, and stacking **rods**.

Eutectic metallic alloys, used primarily in **ophthalmics**, melt as low as 47 °C and are used somewhat like pitch buttons. While almost completely recoverable, there is some stress, and the alloys may contain toxic elements.

Pitch Pickup Blocking

Since **spot tools** are expensive, and to work parts one at a time is inefficient, small to moderate quantities of lenses are often made with temporary tooling such as the **pitch pickup blocking method**, in which spherical surfaces can be blocked by individually generating or grinding them, sticking pitch to their back sides, wringing them directly against their grinding tool, sinking a hot backer into the pitch to a predetermined depth, then removing the parts and backer. Because it uses the surface to be worked as a reference (unlike the spot tool, which uses the edge of the opposite side and thus demands a specific thickness), this method also allows rework of scratched parts.

The pitch should be a few millimeters thick at its thinnest point and relatively equal in the inner and outer zones.

Accurately calculating the backer tool radius is a bit more complicated than described in the available literature. Taking convex radii and convex sags (and all thicknesses) as positive, R_1 as the radius being blocked and R_2 as the opposing radius, if $R_1 + R_2 - t_c > 0$, then

$R_{pick\,up} = \sqrt{(R_1 - t_c + h_2)^2 + \left(\frac{\phi_{eff}}{2}\right)^2} - t_{least\,pitch}$, while if

$R_1 + R_2 - t_c < 0$, then

$$R_{pick\,up} = R_1 - t_c - t_{least\,pitch}$$

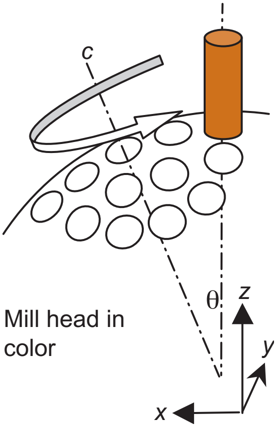
These expressions work for both concave and convex tools.

Since pitch flows over time, it is good practice to press the block onto its test plate for overnight breaks in work.

Spot Blocks

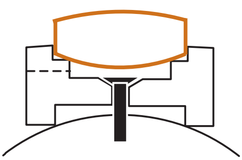
Monolithic hard tools offer the advantages of easy blocking, repeatable accuracy, and simple cleanup. Their disadvantages include inflexibility, cost, and inventory.

Spot tools have precision-machined seats that contact each optic only against its face edge, leaving its clear apertures untouched. An edge slot allows wax and hot air to escape. Every seat must be tangent to one sphere that is coincident with each lens's center of curvature at its finished thickness. Even biconvex lenses can thereby be fabricated to nominal centration without hand grinding and pitch blocking.



Monolithic spot tools are machined on a five-axis mill. Errors along the y axis cause uncorrectable wedge in all parts. x- or θ-axis errors cause relative wedge in that row. Z-axis errors affect that part's thickness. Burrs on seats affect thickness and wedge. Fortunately, there are simple diagnostic tools using only ground glass coupons, dial gauge, and pencil.[5] Each tool has an ideal part thickness, and accepts but one diameter.

With seating plugs turned on a lathe for standard diameters and affixed temporarily to baseplates of a desired radius, modular spot tools[6] are simple to manufacture and test, and they reduce cost and inventory, and increase flexibility. The plugs can be individually inspected, refined, or replaced.

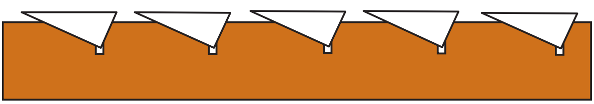


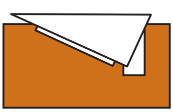
Wedge Tools

Parts with a specified angle, including wedged windows and prisms, are blocked against an equivalent wedge on hard tooling—either wax blocked on a single machined metal plate or contacted on wedged glass **bars** attached to a parallel plate. **Wax blocking** can repeat angles to 1–3 arcmin, while contacting can repeat to 0.2 arcsec, depending on part size.

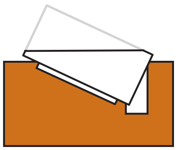
Wedged slots and relief cuts are milled full width and repeated across the block. While the slots should be arranged to allow the *top* side of the parts to make a symmetrical block, the slots themselves are cut asymmetrically in one mill setup; creating a dihedral tool invites angle errors that cannot be corrected later.

Relief cuts are necessary to remove the inevitable fillet on the outer edge of an end-mill cut. Flatness and angle of the slots should be checked before production.



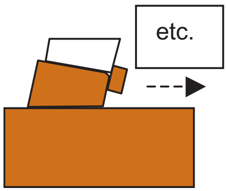


It may be desirable to make additional cuts to avoid touching a finished clear aperture to the tool.



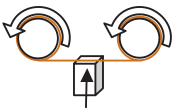
Because acute angles are fragile (and sharp!) it is a good plan to leave original faces from the **blanks** as bevels, when possible.

Glass bars, polished flat on the top side, are finely adjusted for wedge before being glued to a channeled glass plate. Limit bars are glued to the lower edge.

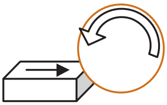


Sawing

It may be desirable to slice off blanks from a long core, create a new face on a crystal oriented with respect to its axes, slice off a portion of a large blank, or separate prisms initially made in a long bar. Optical shops use the following types of **saws**:



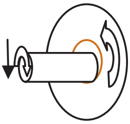
The **wire saw** passes a thin, taut wire across the workpiece in a continuous or reciprocating path. The wire is embedded with **diamonds** or fed with **free abrasives**. The wire's low lateral inertia allows delicate materials to be sawn without chipping. Its fine **kerf** width makes it desirable for small, valuable crystals.

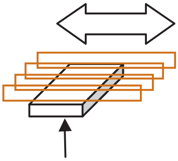


The **cutoff saw** is essentially a hand-operated tile saw, used for rough hacking. Its undamped massive head can produce chipped surfaces. If its blade intersects the workpiece surface close to tangency, it can grab the workpiece (and operator!), causing damage and injury.

Precision saws have a stiff machine base and well-balanced disc blades, and can produce finely finished cuts with angular accuracy of a few arcminutes and dimensional tolerances of a few microns with limited depth.

The **ID saw** (inner-diameter) has the cutting surface on the inside of a thin annular blade that is stretched like a drum. Parts are inserted in the annulus and brought outward, resulting in narrow kerf and straight, deep cuts.





Gang saws come in two types: Parallel rotating wheels in a precision saw, or reciprocating parallel straight blades (like a hacksaw), for making multiple simultaneous cuts.

Milling

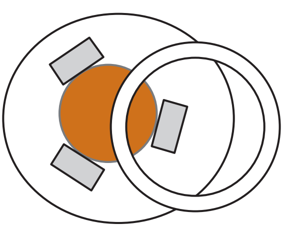
In optics shop talk, the term **milling** has the limited meaning of planarization, reducing thickness, and creating flat lands, on a machine built for just that purpose. A prime example is the **Blanchard**.

The standard machinist's mill of **Bridgeport** type, by contrast, can also be utilized for coring, drilling, and edging relatively simple perimeters.

A third category is the CNC machining center, which allows for programmed tool path and tool changes for complex and repetitive operations.

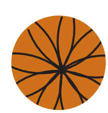
The Blanchard type mill is composed of a rotating work table on a vertical axis, an annular tool on a separate vertical axis with a downfeed slide, and a recirculating coolant feed to the work area. The axis of the work table intersects the abrasive zone of the tool.

The work table is an electromagnetic chuck. Workpieces are clamped or blocked to ferrous fixtures, or ferrous chocks are clamped around nonmagnetic parts. Downfeed rate, work table rotation rate, and stop height are the only adjustable parameters, apart from the seldom-used alignment bolts to keep the axes parallel. A **double-rosette pattern** of tool marks on the work indicates proper alignment.



Left: Top view of the Blanchard mill with the workpiece in color.

Right: Double-rosette marks.



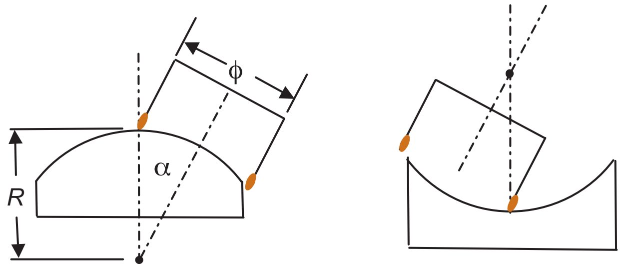
The annular tool may be resin-, bronze-, or steel-bonded diamond of varying grit sizes according to the expected mix of materials to be worked. Its face may be interrupted to enhance coolant flow against large sheets.

Curve Generating

The purpose of **curve generating** is to sculpt the lens curvature onto blanks in one machine operation. Traditional curve generation is followed by grinding before polishing, but newer generators produce a finish ready for polishing.

Spherical curve generators comprise a rotating vertical work axis with upfeed to a machine stop, a tool head containing a **fixed-abrasive ring tool**, and coolant flood. The tool head is tilted and laterally translated as shown below. Aspheric curve generators, by contrast, are available in a variety of new configurations, generally with nearly point tool contact along a CNC-generated path.

When properly adjusted, the ring tool axis intersects the work axis at the sphere's center of curvature, and the work axis intersects the rim of the ring tool. Misadjustments create nonspherical curves. The double-rosette pattern of tool marks with no central nub shows proper alignment.



Convex (left) and concave (right) generating geometries.

$$\sin\alpha = \phi/(2R)$$

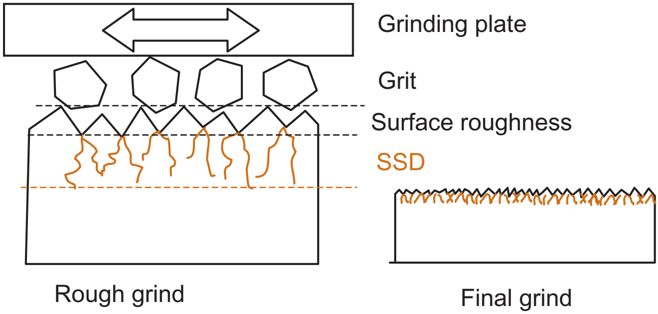
As the ring tool wears, it seats to fit the curve being generated. When the head is adjusted to a different angle for a new radius, the tool re-seats over the course of several lenses, thus changing its effective diameter and therefore the radius it cuts. Lens radius must be monitored throughout a production run, and head angles and lateral offset adjusted as necessary.

Free-Abrasive Grinding

The purposes of grinding are

- to achieve a fine, smooth surface capable of taking a polish,
- to adjust the radius of curvature and wedge, and
- to decrease thickness to approach the final part dimensions.

Free abrasives are uniformly graded grit particles applied in a thin liquid slurry between a grinding plate and the workpiece. Sliding motions cause the grit to roll, creating small fractures in brittle materials. (Ductile materials do not fracture; they work-harden.) Microscopic chips are separated from the workpiece into the slurry, which is periodically refreshed by drip or brush.



Remaining fractures are known as **subsurface damage (SSD)** and can safely be assumed to be less than 1.4× the grit size. It is good practice to remove 2× the previous grit size.

The surface is refined with 2 or 3 stages of finer abrasives, Typical grit stages are 30 µm, 15 µm, and 9 µm; or 20 µm, 12 µm, and 5 µm. Each stage should remove material to the depth of the previous SSD until the surface is fine enough for polishing.

Preston's law: For a given grit and material,

$$\text{removal} \propto \text{pressure} \times \text{time} \times \text{speed}$$

Abrasive Types and Grades

Abrasives are graded by grain size to obtain a uniform finish that is free of pits and scratches. There are several grading methods. Higher **mesh grades** correspond to finer grits, as with sandpaper grades. Letter grades, of historical interest only, correspond to settling time of emery and garnet in water. Since mesh and grit values can vary in size from vendor to vendor, it is best to specify the actual micron size of the abrasive needed.

Alumina, or aluminum oxide (Al_2O_3), is graded by average grain size in microns. Commercial alumina is white, of relatively narrow size distribution, and has a hexagonal platelet shape that produces a uniform scratch-free grind.

Industrial diamond, both natural (single crystal) and synthetic (polycrystalline) is gray. Due to its extraordinary hardness, diamond must be kept carefully segregated from other abrasives. It is graded in microns.

Alumina is the preferred "free" or "loose" abrasive except for certain crystals and very hard materials. Diamond is the preferred abrasive for use in matrix bonds.

Silicon carbide (SiC), also known as **Carborundum**™, is a black, shiny powder consisting of jagged irregular pieces with sharp corners. It is graded by mesh sieves.

Because of different methods and criteria for grading, correspondence tables in the literature do not completely agree. The following is only a rough guideline:

$$80 \text{ mesh} = 180\ \mu\text{m}$$
$$180 \text{ mesh} = 90\ \mu\text{m}$$
$$240 \text{ mesh} = 60\ \mu\text{m} = \text{F}$$
$$300 \text{ mesh} = 45\ \mu\text{m} = \text{FF}$$
$$320 \text{ mesh} = 35\ \mu\text{m}$$
$$380 \text{ mesh} = 25\ \mu\text{m} = \text{FFF} = \text{W0}$$
$$600 \text{ mesh} = 18\ \mu\text{m} = \text{FFFF} = \text{W3}$$

Fixed-Abrasive Lapping

In free-abrasive grinding, the abrasive grains roll. In **fixed-abrasive tooling**, the abrasive particles are held in place by, and distributed throughout, a softer solid matrix of resin, bronze, or steel. The abrasive, typically diamond, is much more efficiently used and the process is cleaner, although SSD can be a higher multiple of surface roughness than free abrasives. The cutting action is somewhat different and produces distinct patterns (a "lay") on the workpiece.

Fixed abrasives are plated or bonded to rings, wheels, blades, etc., and are also sold as pellets for gluing to existing plane or spherical tooling.

The workpiece scours the matrix of the tool as the abrasive grains wear so that they continue to stand proud of the matrix until they are eventually ejected, exposing fresh abrasive. This reciprocal wear relationship can ideally maintain efficient cutting action for a long time.

Improper parameters can compromise this relationship. When the matrix is too soft, the tool wears out quickly. When the matrix is too hard for the workpiece, the abrasive grains flatten to the level of the matrix, grinding turns to burnishing, the smooth glazed surfaces of both workpiece and tool drag across each other with no room for coolant, and frictional heating can fracture the work. Lapping with too little pressure can result in the same burnishing action and, paradoxically, lead to higher loads.

New tool | After use or dressing | Glazed, needs dressing

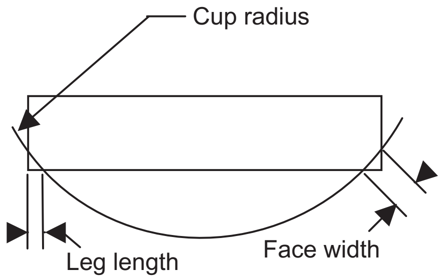
When machine loads increase or the lapping rate decreases, dress the tool briefly against a grinding stick to expose fresh abrasive.

Beveling

Bevels perform the following functions:

- protect optics from chips and fractures during handling and assembly,
- improve surface quality and figure control during polishing,
- facilitate cleaning,
- can indicate orientation, and
- provide seating and sealing surfaces.

Circular elements are typically beveled to nominally 45 deg by lapping their edges against a rotating spherical cup wheel of radius $R = (\phi - b)/\sqrt{2}$.



Noncircular or massive optics require different techniques.

Rebeveling during fabrication is often preferable to making a larger bevel at the outset; producing a bevel by hand takes time proportional to its *volume*, not its width.

Decentered bevels can cause element tilt when used as a mounting surface:

$$\alpha = (b_{\mathrm{max}} - b_{\mathrm{min}})/2R$$

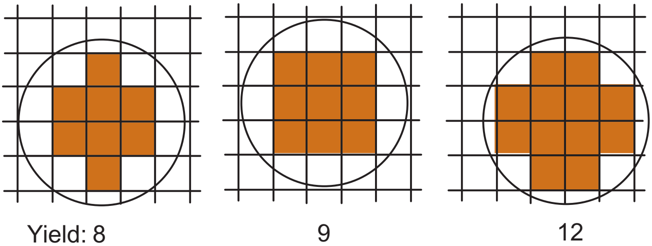
where b_{max} and b_{min} are minimum and maximum leg lengths of the bevel measured radially, R is the radius of curvature of the surface with the bevel, and α is in units of radians.

If a bevel is to be used as a precision mounting or sealing surface, it should be so noted on the print. If not, overspecifying a simple protective bevel adds needlessly to cost.

Dicing

Dicing is essentially repetitive sawing in two directions. It is frequently desirable to purchase material in sheet form and dice it into many smaller pieces. It is easier to block, polish, figure, clean, and coat one large wafer than many small parts. The dicing operation can be the last step.

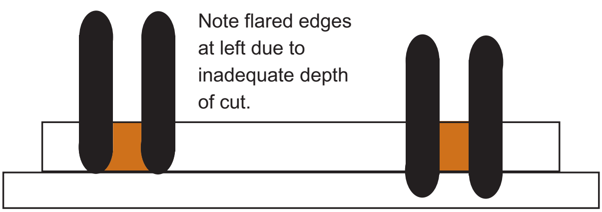
To dice rectangles from a circle, the parts may be face centered, corner centered, or edge centered in either dimension. Careful planning maximizes yield.



Note: Corner centering is not always best.

To minimize yield loss to kerf width on small parts, narrow blades are used. These are inherently more flexible and fragile. Proper blade alignment, support, balance, coolant flow, and feed rate are critical. A square cover piece helps guide off-center cuts.

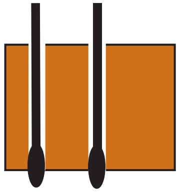
As the blade wears, its outer edge becomes rounded. As a result, the bottom of the cut is not square. To achieve a plane, orthogonal edge on the diced part, the blade must cut well below the workpiece into a support piece and must be periodically dressed.



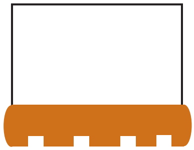
Coring and Drilling

Both **coring** and **drilling** plunge-cut the material on a mill using a rotating hollow cylindrical tool faced with abrasive on its leading edge. The distinction between coring and drilling lies in whether the material of interest is inside or outside of the cylindrical tool.

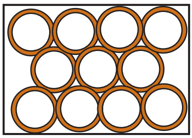
In most cases the tool is faced with diamond bonded in a metal matrix. Coolant is fed to the interior through a rotating coupling and passes to the outside either through a castellated cutting edge or by repeatedly backing the tool out partway.



Cross section of core drill entering backer



Castellation detail



Layout top view

To avoid the cost and delay of purchasing such a tool for a small quantity of odd diameters, a section of brass or steel tubing may be used. Free abrasive is fed to the tube from the top by periodically pulling the tool out completely.

When the core is long and narrow, torque and vibration can cause the core to snap apart. **Blowout** occurs at the exit face unless it is firmly affixed to a stiff backer (usually with blocking wax). If chipping on the entrance must be avoided, a cover plate is also used.

A hexagonal pattern does not necessarily achieve maximum material yield during coring. Separation must be adequate to avoid nicking adjacent cores with the outer diameter of the core drill.

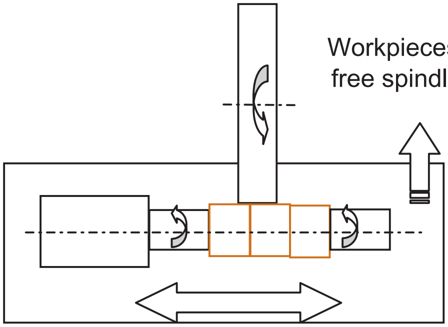
Edging

The purposes of **edging** are to

- make blanks and diced parts round,
- achieve the desired diameter, and
- achieve the desired edge finish.

Sheet material may be diced into squares and then edged round. Bulk material may be cored and the cores edged to final diameter before slicing to thickness. Molded blanks may be edged into tolerance. Parts with exacting figure requirements may be polished at a larger diameter, then edged to remove rolloff.

Edging machines have a bonded diamond wheel turning at high speed and a low-speed rotating **spindle** to hold the workpiece (or stack) on a two-axis base. Parts are held on the spindle with wax or by vacuum. There may also be a live spindle opposed to the drive spindle to clamp and stabilize the work. The workpiece(s) and spindle(s) are slowly passed across the wheel at ~1 Hz as the reciprocating slide is fed toward the wheel in small increments on each pass.



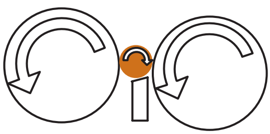
The reciprocating motion spans all workpieces and maintains the abrasive wheel as a true cylinder. Machine stops set the reciprocation stroke and finish diameter.

Some newer edging machines include an automated carousel feed and angled beveling tools.

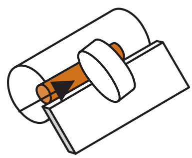
Centerless Edging

Standard edging machines cannot make long narrow cylinders such as **gradient index lenses** and **laser rods** because the edging wheel causes large torques against a small mounting surface at the spindle(s). **Centerless edging** is the solution.

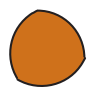
The rod lies tangent along its full length against a rotating, hard-rubber cylinder called a support wheel. The support wheel rotation brings the rod against a thin, full-length, stationary work rest, causing the rod to roll against the work rest. A narrow edging wheel contacts the rod opposite the support wheel. The edging wheel is set at an angle of several degrees to the support wheel.



Support / work rest / grinder



Feed direction



Three-lobe pattern

The rod is introduced to the machine at one end. The angle between the support wheel and grinding wheel causes the rod to "walk" down its length and exit on the opposite end.

It is important to set the geometry to avoid **lobing**. The most common patterns are three lobe and five lobe. Note that lobing cannot be detected by measuring the "diameter" with a **micrometer**! Some laser rods made from monocrystals with **anisotropic grinding** rates are prone to lobing or oval cross sections even at classically "correct" geometries. Alternating passes with the rod flipped end-to-end minimizes this issue.

If the grinding wheel angle is incorrectly set, or if the rod is carelessly introduced to the machine, the diameter may not be constant across the full length.

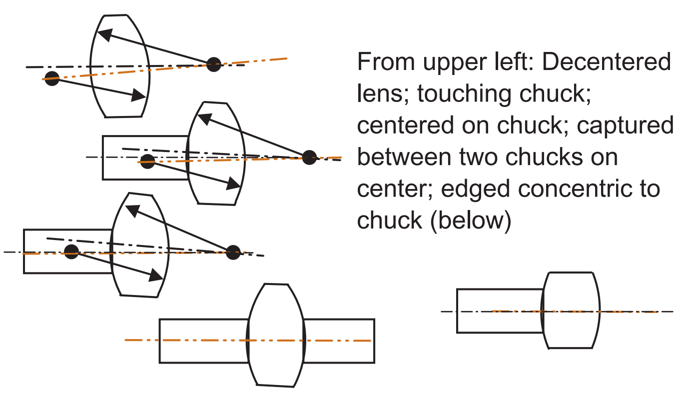
Centering

In a centered lens the optical axis (defined as the line connecting the two centers of curvature) coincides with the mechanical axis (defined as the centerline of the edge cylinder). Because lenses tend to become somewhat decentered during fabrication (especially in multiple blocks), they are often started at a greater diameter; the eccentricity is then individually removed.

The process of **centering** consists of aligning the optical axis to the spindle axis of an edging machine, and then edging the barrel concentrically. The alignment is accomplished by one of these methods:

- One surface of the lens is coated with hot wax and placed in contact with a precision chuck while the lens is adjusted laterally so that its opposite side does not wobble during rotation, as indicated by a feeler gauge.
- As above, but wobble is shown by a reflected beam from the opposing side.
- As above, but wobble is shown by a beam transmitted through the lens and (hollow) spindle.
- The lens is squeezed between two concentric precision chucks. Mechanical forces automatically center lenses having *sufficient* focal power.

Several terms are used to describe lens asymmetry. Conversions are in the Equation Summary. Caution: tilt and decenter are distinct from each other for aspheres.



From upper left: Decentered lens; touching chuck; centered on chuck; captured between two chucks on center; edged concentric to chuck (below)

Fractures, Chips, and Stoning

When working with brittle materials, fractures and chips are common occurrences.

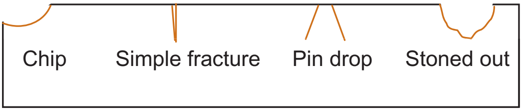
A **fracture** is a physical separation of material with a narrow subsurface leading edge. Because the critical crack length in glass is a few microns, any visible fracture is likely to eventually propagate to failure, and must be mitigated.

A **chip** is a fracture that has entirely re-exited the surface leaving no subsurface crack. Chips may be permitted within specified tolerances in noncritical areas. However, they can interfere with sealing, and their smooth surfaces can cause undesirable glints.

A **pin drop** is a conchoidal or shell-shaped fracture usually resulting from the impact of a heavy object such as a machine spindle.

Stoning is the practice of dulling the surface of a chip, or digging out and broadening the leading edge of a fracture. It is so called because it is often done with a hand-held abrasive stick. A dental or hobby drill, diamond rasp, or air-abrasive tool can also be used for stoning.

Fractures deepen during fabrication, so they must be dealt with when discovered. The outcome is often more drastic than anticipated for three reasons: (1) the depth of a fracture is greater than it appears according to the index, (2) the dull finish of a stoned-out relief interferes with visibility, and (3) the fracture may propagate ahead of the stoning tool.



Marking: Spot Bevels, Dots, Arrows, etc.

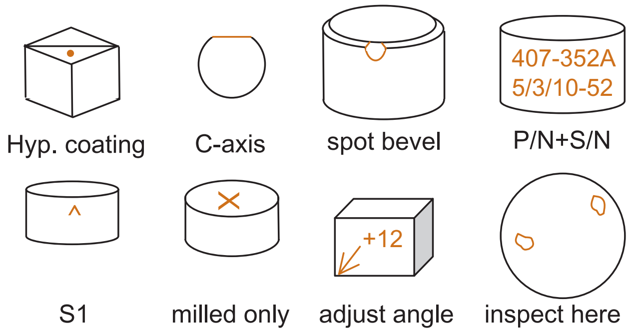
Marking, whether temporary or permanent, is used for identifying and serializing parts and to discriminate among:

- sides,
- parts,
- degrees of finish, and
- azimuth orientations.

Marks help in many aspects of optical fabrication: to isolate defects in process, to bring attention to areas for inspection and repair, to more easily discriminate ground versus lapped surfaces or one radius from another, to select which side is to receive a particular coating, to bin by measurement, to orient to wedge, to identify crystal axis, or to maintain lot identity. Such markings may be temporary, applied with pencil, dye, or marker.

Permanent markings are helpful to the end user to serialize parts, orient wedge or axis, and discriminate between radii or coatings. Methods of application include pencil, marker pen, epoxy ink, grinding, chemical or laser etch, abrasive jet, and engraving by a diamond-tipped scriber or dental drill.

Spot bevels are permanent localized flat spots on the optic's perimeter. **Arrows** can be as minimal as a caret (ˆ). Text can be written on the part. Even a simple **dot** can convey important information.



Polishing

The purposes of **polishing** are to:

- create a specularly smooth surface,
- fine adjust radius, figure, and angle,
- approach precise dimension,
- remove subsurface damage,
- mechanically strengthen the surface, and
- remove skin stress.

Polishing mechanisms are still not perfectly understood. Active and continuing research has identified elements of abrasion, flow, electrostatic forces, and chemical reactions. For the purposes of this field guide, polishing can be thought of as a molecular-level removal of material that, unlike grinding, does not generate fractures.

Conventional polishing proceeds by "charging" a compliant lap with polishing slurry and rubbing it against the surface of the optic. Solid particles in the slurry adhere to the tool and slide (not roll) against the surface.

The lap consists of a compliant layer typically of pitch (wood rosin, tar, or synthetic), polyurethane, or a micropore fiber on a stiff substrate. The slurry consists of an aqueous suspension typically of **ceria** (for glass) or alumina (for metals and crystals). Other compliant laps and slurry recipes are used for special circumstances; for example, diamond in oil on tin.

Both the optic and lap can slowly change shape during polishing according to the distribution of forces and summation of paths between optic and lap. It is up to the optician to adjust and maintain "strokes" so that they closely fit and approach the desired figure.

Newer, primarily subaperture methods of polishing include magnetorheological finishing (MRF®), **fluid jet**, **ultraform finishing (UFF)** utilizing a ribbon, and the "**precessions**" or **bonnet method**. Each of these requires specialized and relatively expensive machinery.

Polishing Compounds

Optics are polished in a slurry consisting of abrasive particles, a fluid carrier, and optional additives including suspension agents, lubricants, detergents, biocides, and **pH** modifiers.

- **Cerium oxide (CeO_2, ceria)** has been the most widely used compound for glass in the last half century, whether pure or in combination with other rare earths. It is softer than most glass and friable (easily crumbled). It is available in premixed suspensions and dry powder. Particle size for various grades range from 0.3 to 3.0 μm. CeO_2 is suspended in water and has a natural pH of around 8, but has been used from pH 4 to pH 9.5. Recent trade issues are forcing the use of alternatives. **Zirconium oxide (ZrO_2, zirconia)** can be a substitute for CeO_2.
- Synthetic or natural diamond is frequently used for crystals, semiconductors, ceramics, and metals. Its durability makes it more economical than one might expect, but its hardness can make it a pesky contaminant. Particle sizes range down to 0.05 μm; recently, nanodiamonds have become of interest. Diamond is available in dry powder, paste, and oil suspension.
- **Aluminum oxide (Al_2O_3, alumina)** is used primarily for crystals, metals, semiconductors, and plastics. With a flat platelet shape and narrow size distribution, Al_2O_3 produces high-quality surfaces. It most commonly comes in dry powder form and requires a suspension agent to prevent caking.
- **Colloidal silica (SiO_2)** is used for crystals, metals, semiconductors, and ceramics. Its nanoscale size (1–60 nm) translates to high surface area and negligible subsurface damage. SiO_2 is available in a basic fluid at pH ~9.5 and remains in suspension indefinitely if not frozen.

Concentration (by **Baumé** scale), pH, and additives are strong determinants of polishing rate, surface quality, subsurface damage, and ease of cleanup.

Pitch Laps: Channels and Figure Control

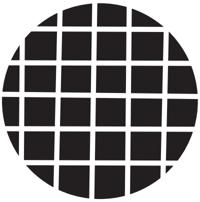
For centuries **pitch laps** have been used to polish optics, due to these unique properties of pitch:

- Its viscosity drops rapidly with heat.
- It has high room-temperature viscosity.
- It has a brittle response to rapid loading.
- It is incompressible.
- It embeds polishing compounds.

Hot pitch is poured onto a rigid base, and when warm, is pressed against a reference shape. When cooled, channels are cut in the lap with a razor blade or saw. The channels form conduits for the slurry to polish and cool the work, and to give the pitch somewhere to flow.

Its glacial flow rate allows the lap to slowly adjust its shape to forces applied to it by the workpieces, just as the workpieces are polished in response to the forces applied to them by the lap. The lap's incompressibility keeps the lap from expanding rapidly into the gaps between and around the workpieces and causing rolled edges.

Much art is needed to achieve this balance of forces. The optician chooses the pitch viscosity, channel pattern, relative size of the lap and workpiece, and machine stroke and speed settings so that the lap and workpiece maintain close contact while mutually changing shape to the desired figure.



Typical pattern.
Note: decenter is deliberate and desirable.

Cross section.
Channel in center has closed up and must be recut to maintain local pitch flow.

Polishing Pads

Pads were once considered fit for ophthalmic use only, but this attitude has changed. Compared to pitch, pads are easier to affix to a backer, are more consistent, require less maintenance, and offer a variety of surface textures. Unlike pitch, they rebound elastically and so are prone to round off corners, roll edges, and emphasize grain structure. The wide range of available pads, sometimes used before or after pitch, allows many useful approaches.

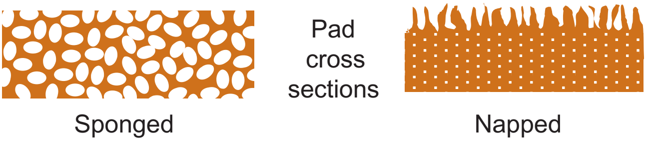
Foam pads are **elastomeric** with closed-cell bubbles with top surfaces that are broken open, retaining coolant and compounds. They come in a range of hardness, either filled with abrasives or not, and are available pre-grooved. They are durable and can polish much faster than pitch with consistent figure. They may be periodically dressed with bound abrasives or metal brushes and are widely used in CNC polishing.

Fiber pads include woven and nonwoven forms, such as felt.

Napped pads, whether fiber or engineered poromeric, have thin free-standing stalks on their surface that act like a brush to soften contact. They are especially useful for polishing soft materials and for quick removal of sleeks, contamination, and stains without affecting figure.

Smooth plastic pads maintain the best figure on small parts but do not retain polishing compounds and coolant across larger diameters.

Combination processes include high-speed polishing with a sponge pad followed by figuring on pitch, or sleek removal with a napped pad.

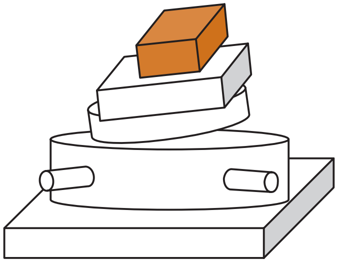


Crystal Shaping and Orientation

Anisotropic crystals have many uses in optics due to their electro-optic, gain, transmissive, nonlinear, or birefringent properties. Due to their asymmetries, axis orientation is critical. Further, some crystals are prone to internal defects such as inclusions, **veils**, and twinning, requiring an initial inspection and zonal allocation.

Axes may be determined by reference to natural growth faces (where available), by extinction between crossed polarizers, or by x-ray diffractometry. Once the orientation is established and fixed on tooling, a reference face is machined.

Optical crystals can be extremely soft or hard, easily cleaved, and/or subject to thermal shock. Depending on the properties of the material, initial format, desired angles, and final configuration, a wire saw, core drill, or surface grinder is used for initial shaping. Directional references must be maintained throughout the sequence of fabrication by use of fixturing, surface marking, or distinct dimensions.



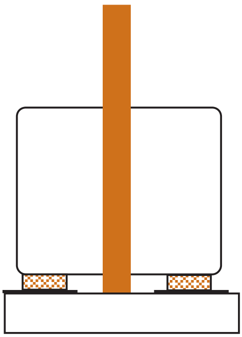
Nonlinear crystal oriented on goniometer atop backing glass, ready for wire sawing or surface grinding

Biaxial crystals must be oriented to each axis. The prescribed optical path through nonlinear crystals is often at a substantial angle to an axis (perhaps 23.5 deg, for example), and the incident angle is not necessarily normal. Clearly, the opticians working on such materials should have special training and experience with them.

Crystal Lapping

Single crystals, in general, are fabricated into small pieces having flat or long-radius surfaces. Their small dimensions necessitate outrigger feet with similar lapping rate to expand the block size to stabilize them during lapping. (Note: The lapping rate may depend on the orientation of the crystal.)

As contrasted to the usual guidelines for close-packed blocks, crystal blocks are sparsely populated. In cases of doped materials, the outriggers can be less expensive undoped stock.



A Nd:YAG laser rod, for example, is set into a heated, waxed bore in the center of a steel block, one end of the rod protruding to contact a reference plate while the undoped outrigger feet stand on shim material.

When the wax sets, the rod face stands proud of the feet; then is quickly ground coplanar and all are polished parallel to the opposite end of the rod. The reference plate may have a radius, or the rod bore may be angled. Of course, blocks can be configured to work multiple production pieces.

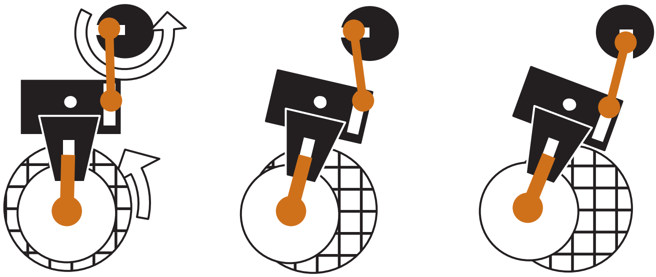
Lap channels, if any, must be narrower than the part dimension. Ground glass is used to lap harder materials; tin, lead, or mylar films for softer materials. Diamond, alumina, and colloidal silica are the standard abrasives.

The work has been done on **planetary machines** or by hand. MRF® could prove useful assuming edge effects can be controlled.

Smooth bevels are of critical importance for scratch avoidance; small apertures, multiple passes, and high-power coherent light make for extreme surface-quality demands.

Overarm Spindle Machine

The following describes a workpiece on top, but this configuration can be reversed. **Overarm spindle machines** consist of a lower axle that rotates and drives the lap, and an eccentric arm extending a spindle pin that oscillates laterally over the lower axle. The workpiece spins freely about this pin as it is stroked across the lap. Adjustments include lateral and forward offset of the pin midpoint, length of eccentric stroke, frequency of stroke, and RPM of the lap.



Warning: If the pin directly passes over the axle, all of the forces suddenly reverse, and the spindle jumps.

The lap is shaped by the workpiece and vice versa. In grinding, the lap is much harder; in pitch polishing, the lap is much softer. Since the lap is larger than the workpiece (again, on top for the moment), the workpiece must swing to the side to cover the entire lap and avoid digging a rut. Relative speed at any point between workpiece and lap are functions of eccentric RPM, lap RPM, and lateral offset. During overhang, the pressure between workpiece and lap at any instant varies across their contact zones. Of course, no work is done in those regions and times in which the workpiece and lap are not in contact with the other.

The optician has no closed-form solutions for these functions; only an intuitive feel and a few guidelines. Although nominally only spheres mate in free rotation and translation, convergence to the desired figure is iterative at best and asymptotically more difficult under $\lambda/8$. This is scientific craft at its best.

Stick Lens Fabrication

Steeply curved lenses must be worked singly. Small-steep lenses are waxed to a **dop stick**, which is used to hold and orient the lens against the lap, either by hand or machine.

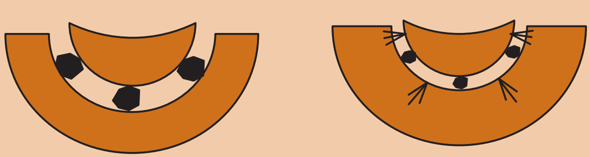
Stick machines generally have six or more rotating spindles and reciprocating arms ganged together in identical motion. The overarm motion is an arc concentric with the lap's center of curvature. The stick and lens may freely rotate or be driven counter to the lap.

The top end of the dop stick should be well above the center of curvature.

During handwork, a single stick is moved in an orbital pattern over the rotating spindles, and the optician periodically lets the stick slip a bit, reducing **astigmatism**.

Because these lenses are steep and their radii are short, standoff between lap and lens due to abrasive grain size must be considered; grinding is performed with different radius laps for each abrasive grade.

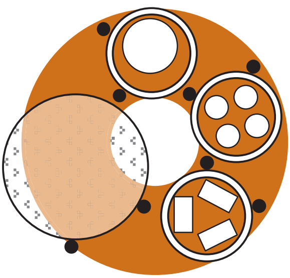
To maintain equal removal across entire surface at successive abrasive grains, the lap radius has to chase the shrinking lens.



Planetary Lapping

Also known as ring laps, **annular polishers**, or **continuous polishers (CPs)**, **planetary machines** are usually run at a constant pace all day while flat parts are introduced to and removed from the lap and constrained within **carriers** rotating inside one to three **work rings**.

Advantages of CPs include a stable thermal environment, minimal operator intervention, full contact, and relative insensitivity to part shape, including rectangles.



In this top view, the three annuli are work rings containing four small rounds, one large round, and three rectangles, respectively. The large circle on the left is the **conditioner plate**. The small black circles are fixed roller wheels that keep the conditioner and work rings from rotating with the lap.

The conditioner plate (or bruiser) is much larger and heavier than the optics being worked and therefore is the dominant factor in maintaining figure control. It effectively “steamrolls” the lap while the lap polishes the conditioner.

The conditioner overhangs the lap both inboard and outboard, shown in the diagram as the uncolored hatched areas. When the conditioner is adjusted outward, the unbalanced forces cause the lap to wear more rapidly on its outside and thus become more convex, and conversely when the conditioner is moved inward. With the proper balance, the figure remains constant, and the parts are polished to match.

Such adjustments are small—a percent or less of the lap diameter. The figure is periodically monitored with a test piece and can be maintained for days.

Double-Sided Lapping

The strengths of **double-sided machines** include:

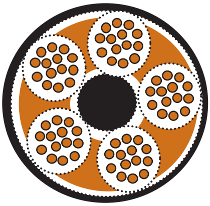
- nearly automatic **parallelism** to <1 arcsec,
- nearly automatic transmitted wavefront to $<\lambda/10$,
- thickness uniformity within a lot to $\ll 1$ μm,
- no blocking or deblocking time or cleaning,
- no blocking stresses or nonuniformity, and
- capability to work two sides simultaneously.

Limitations of double-sided machines include:

- Lot size must match machine capacity.
- Part configuration *must* be plane parallel.
- Parts must have aspect ratio (ϕ/t) > ~3:1 to achieve good figure.

Waveplates, windows, reticles, wafers, filters, and solid etalons are good candidates for double-sided machines.

Double-sided machines include two annular laps, a surrounding **ring gear** and central **sun gear**, and toothed carrier plates fitting between the ring and sun gears, which are perforated with cutouts for workpieces.

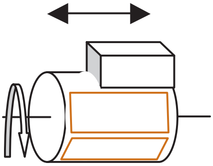


Top view: Lower lap in color, ring and sun gear in black, carriers in white. Upper lap (matching lower) is removed. Parts should be periodically flipped over and shuffled to maintain uniformity.

There are several families of machines with different relative motions among their components. A few examples are: (1) Sun and ring gears counter-rotate to cause the carriers to spin against stationary laps as the workpieces trace epicyclic orbits. (2) Sun and ring gears rotate to drive the carriers around the lower lap while the upper lap rotates at twice the carrier speed. (3) Top and bottom laps counter-rotate while gears spin the carriers.

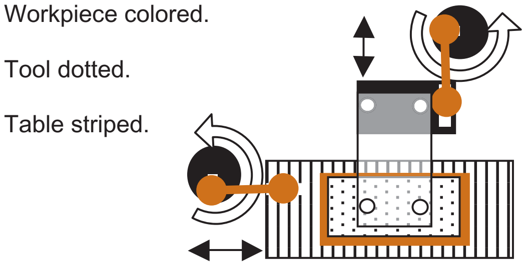
Cylindrical and Toric Lapping

To produce non–rotationally symmetric surfaces, one must constrain the rotation of lap against workpiece in order to control astigmatism in rotationally symmetric parts. There are two main branches of conventional machine for these optics: the **rotating barrel** and the ***x–y* Lissajous type**.



The rotating barrel is a cylinder or **torus** with workpieces arrayed around it. A mating tool is brought into contact and oscillated axially while the barrel rotates. The ratio of tool length to barrel length and the tool's overlap beyond the barrel ends affect the curvature along the axis. The radius about the rotation axis becomes more convex with time. Angular coverage of the tool around the rotation should be large to maintain circular cross-sections. While this type of machine produces better figure, it requires spot tooling and multiple parts per setup.

The Lissajous type is analogous to an overarm machine, but tool overlap and size are controlled independently on each axis. Single parts can be run without special tooling.



Surface form is monitored with radius gauge, test plate, and interferometer. Spherical and flat test plates and interferometer references produce line profiles. A **computer-generated hologram (CGH)** added to an interferometer creates a full-aperture test.

Intrashop Transportation and Storage

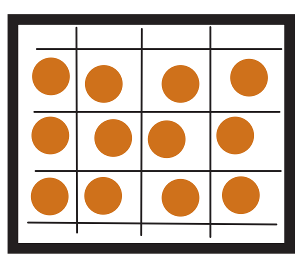
Best manufacturing practice mimimizes **transportation** and **storage** because of the potential for loss and damage. However, parts must be moved and stored, during which they must be protected from loss, spillage, mixing, and contact with each other.

Instructions for transportation and storage:

- Always place parts and tools in trays—even individual parts. Line the trays with soft and nonstaining material such as unbleached paper towels, lens tissue, cushioned shelf paper, or felt. Change the liners frequently. The trays can be labeled, shelved, and stacked. Use tray lids for more protection.
- Place dividers between parts in a tray to avoid collisions. Interlocking slotted cardboard works well.
- When holding a tray and going through doors, hold the tray in both hands, lead with your shoulder, and let the tray follow you. To avoid collisions, do not cut corners in hallways (whether holding a tray or not!)—go wide and turn late. Install and use corner mirrors.
- Transport heavy or multiple trays and tools on a cart.

Side view tray divider

Top view of tray with parts and dividers



In-Process Cleaning

The goal of **in-process cleaning** is to remove contaminants to an acceptable degree. It helps to know which contaminants are involved, what constitutes acceptable cleanliness at each stage, and what actions compromise the quality of the part at this stage.

Optics and tools must be cleaned numerous times during fabrication to remove the following:

- abrasives,
- adhesives,
- blocking wax,
- fingerprints,
- pitch,
- polishing compounds,
- rust stains,
- swarf,
- water spots, etc.

Dirty parts cannot be blocked or accurately measured. Abrasives must not be allowed to cross-contaminate. Fingerprints and water spots are corrosive.

Accomplish in-process cleaning with subsets of the following:

- brushing with detergent or solvent,
- pressurized air,
- solvent rinse, wipe, or soak,
- ultrasonic immersion,
- vapor degreasing or dewatering, or
- water rinse.

Small particulates are especially adherent, and require surfactants and mechanical contact for removal. Phosphoric acid removes rust and polishing compound stains. Appropriate solvents remove pitch, wax, oil, and adhesives. Each agent used in the course of cleaning becomes a new contaminant to be removed. Each step should dissolve or suspend the contaminant, and be dissolved in the next step.

Cleaning for Thin-Film Coating

In-process cleaning only removes contaminants to the degree that they do not damage the parts or interfere with inspection. By contrast, precoat cleaning must remove everything to a pristine surface. Otherwise, lint and dust cause shadows and voids in the coating, and even partial monolayers reduce adherence of the coating to the substrate.

In the small shop, precoat cleaning is done by simply wiping the surfaces with a lens tissue moistened with reagent grade or spectrophotometric grade acetone or methanol, often called "**drop and drag**," as the final step. Prior steps may include solvent soak, cotton ball wipe with detergent in water, or ultrasonic immersion, as necessary.

Budget permitting, a semi-automated cleaning line is used. This can consist of a series of ultrasonically agitated soaks in solvents and detergent, several stages of de-ionized (DI) water, and a drying station. Drying methods include air knife, alcohol vapor, or spin dryer.

Carrier design is critical for automated cleaning line success. The carriers must hold parts securely while not contacting polished faces and must drain fully, be compatible with temperatures and solvents used, and be easily loaded and unloaded.

Two informal tests are used to judge cleanliness. The first is called "**breath fog**." Steam (or breath) should fog the surface uniformly and not form large drops. The second is **water break**, in which DI water that is dripped on the surface should sheet, not bead or clump.

Clean surfaces are very chemically attractive and rapidly become recontaminated. Therefore, all precoat cleaning should be accomplished in a clean room, preferably directly across from the coating chamber and immediately before the chamber is to be loaded.

Thin-Film Coating

The purpose of coating is to change the surface characteristics in terms of reflection, absorption, polarization, and other properties. Coating is the only additive stage of standard optical manufacturing.

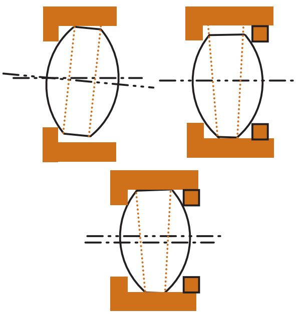
The customer designs a lens system and specifies dimensions and materials for its component substrates, but must specify performance characteristics for the coatings and leave thin-film design to each shop.

Thin-film coatings require atomically clean surfaces for proper adherence. The substrates are placed in planetary rotation fixtures high in a vacuum chamber above the various materials to be applied. The chamber is evacuated so that the mean free path of an evaporant particle exceeds the distance between source and substrate; the substrates are usually heated to improve adherence and uniform growth. A source material is slowly vaporized by resistive heating, e-beam, or ion sputtering, and freezes on the substrates. Alternating layers of various materials are deposited to exacting optical thickness and monitored in-process.

Coating and fabrication are separated within a shop because coating needs a clean environment, while the shop is full of abrasives and coolant, and because scheduling priorities, machinery, and knowledge bases for each are completely different. Some shops only fabricate; some only coat. Opticians often move from shaping to polishing, or from flatwork to aspheres, but it is rare to switch between coating and fabrication.

Coatings are applied to finished surfaces so almost all of the work value and allotted schedule are invested before the parts reach the thin-films department. Since most coatings are harder than the substrate to which they're applied, it may be impossible to remove a coating and still maintain the substrate within tolerance. A "blown run" can change deliveries from "tomorrow" to "twelve weeks."

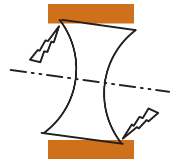
Assembly



Multiple-lens systems are held to accurate alignment and spacing by mounting in cells and stacking in barrels. Centration is only achieved through consistency between element **datum** systems and cell datum systems.

A loose diametral fit allows decenter. Either axial force applied by retainers against strongly-curved surfaces, or lateral hand-adjustment within the cell using setting screws before potting, restores centration.

Lenses can tilt and bind when dropped in a barrel. Once stuck, pressing on the trailing side may worsen the situation. Two quick fixes are (a) heat the barrel to expand it all around; (b) compress the barrel across the diameter perpendicular to the tilt, causing it to go elliptical with long axis along the tilt. Take care that the lens doesn't bind farther. Yoder suggests that a spherical edge profile allows near-interference fits.[7,8]



Due to gravity and the sequence of differing diameters, what looks good on paper or CAD may not be stackable in practice. The optomechanical design must include the assembly sequence and method. And after assembly, athermalization during shipping (or at least controlled stresses due to differential expansion) is critical for intact arrival and field performance. Finally, tolerances—like lenses—stack.

Optomechanical design and lens assembly are a rich study outside the scope of this *Field Guide*. See texts by Yoder[7,8] or Ahmad[9] for guidance.

Packaging for Shipping

We can assume that the shipping container will be dropped, tossed, and experience −40 ° to +50 °C temperatures. Impact forces at a given **G-load**—and, therefore, appropriate **packaging**—depend strongly on the mass of the component. Customers (especially the DOD, see MIL-STD-130) may further specify packaging, marking, and serialization.

For *very small parts*, choose among the following methods:

- Suspend parts between polyethylene membranes in a "trampoline" box.
- Stick parts to a proprietary gel layer in a styrene box.
- Set parts by edge contact in vacuum-formed PETG clamshells that fit in styrene boxes.
- Contact the parts on their edges to custom-molded high-density foam containers.
- Wrap parts individually in lens tissue, nested tightly between layers of styrofoam or open-cell foam in an inner box.
- Drop parts singly in a cotton, microfiber, or Tyvek envelope, nested in an inner box.

Encase everything in bubble wrap and float the wrapped parts in popcorn within a cardboard box.

For *larger parts* of up to ~100 g, do as above, but with cushioning materials between parts.

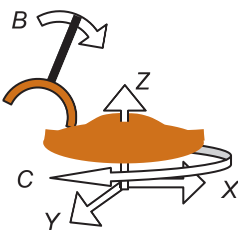
For *large parts*: Specially designed frames encase the part, contacting it by its edge (or integral mounting points). The frame is bagged, and the bag is purged, sealed, and suspended within custom-cut or expandable foam in the center of a rigid shipping container.

For *thermally sensitive parts*, include thermoelectric controllers within an insulated shipping container. Manufacturers of sensitive, costly, or unique items have occasionally sent a representative to fly with the parts in a carry-on bag. One may imagine that this practice has become increasingly difficult to explain to the TSA.

CNC with Spindle-Mounted Tools

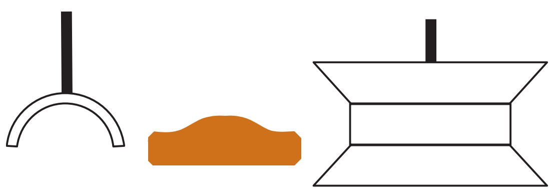
The versatility of computer numerical control (CNC) enables a great variety of machine configurations and actions, with new ones constantly emerging. Their impact on production speed, precision, and the set of shapes that may be practically realized has been revolutionary.

There are several branches in the genealogy of **CNC machines**. This page addresses the branch with **spindle-mounted tools**. Fluid-jet, MRF®, belt, bonnet, and SPDT are other branches. Each has its own page.



Common motions include X, Y, and Z as with standard mills, plus C for workpiece rotation, and B for tool head tilt about Y.

Some have two spindles laterally separated on the same head, each specialized to different functions. One generates a curve and the other edges and bevels; or one deterministically grinds and the other polishes.



Some have one tool head and a rack with a selection of tools robotically interchangeable at programmed instructions; these tools are typically for shaping. Some may also have workpiece pick and place racks or a carousel, allowing uninterrupted work.

One machine has a dual-action tool with a ring and central puck and is actuated pneumatically to sequentially grind and polish in the same spindle.

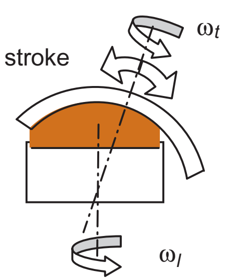
CNC Synchrospeed Polisher

In traditional overarm machines, the upper piece is free to rotate and tilt about an oscillating central pin, and sectors of both tool and workpiece are out of contact during at least part of the stroke. The relative velocity and pressure distributions require the intuition and art of experienced opticians to approach and maintain a desired figure.

By contrast, in the **CNC overarm machine**, both tool (always on top) and lens are driven in rotation strictly about their respective axes, the tool axis is always directed at the lens center of curvature, and the entire lens is in full contact with the polishing tool during the full stroke. This results in equal pressure across the lens at all times. If we assume a relatively flat lens, and control the axes' rotation so that at all times

$$\omega_l = \omega_t \cos\theta$$

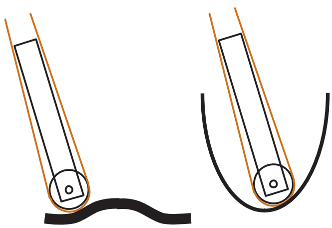
where ω_l = rotation rate of lens, ω_t = rotation rate of tool, and θ = inclination angle between the axes, then the relative speed between tool and lens is nearly constant across the lens for all points in the stroke, varying globally with the lateral offset. Thus according to Preston's law, equal work is done across the lens, and the original generated sphere is maintained.



The rigid tool, ~2× the diameter of the lens, is faced with a plastic pad. Using high pressures and rotation rates of ~1000 RPM, polishing time from a high-quality modern generator is only a few minutes. The lens is supported in back by a pressurized bladder to minimize sagging, and force-fed slurry is refrigerated to minimize heat distortion. Although not optimal, with special tooling such machines can approach hemispherical curves.

CNC Belt Style Machine

The tool head is an elastomeric wheel with a driven belt wrapped around it. The interchangeable belts contain bound particles of diamond, zirconia, ceria, or alumina, or are uncharged for slurry feed. The wheel is a toroid with diameter ranging upward from 8 mm, and durometer ratings from 30 to 80 Shore D. It is a full five-axis machine with the wheel's rotational axis perpendicular to and offset from the workpiece axis.

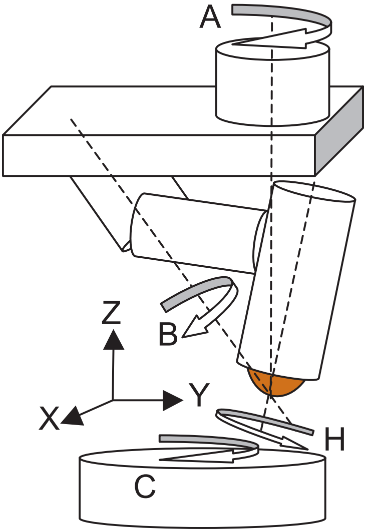


- Small and interchangeable wheels allow sharp inflections and short concave radii.
- The long arm is capable of reaching deep into concave ogives such as advanced-missile cones.
- Various wheel hardness and abrasive styles enable its use on soft crystals and hard ceramics.
- Rapid volumetric removal is possible with aggressive belts.
- With the relatively small and simple contact patch, free-form shapes can be created.

On-board metrology is by confocal, white light, chromatic imaging. The effective removal function of the tool is mapped by measuring a test dimple. A dwell program is created by convolving this removal function with the difference between the interim workpiece shape and the desired shape.

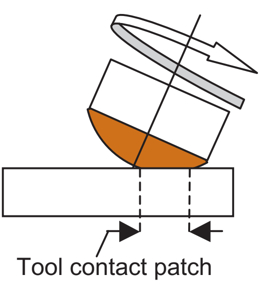
This type of machine is currently capable of surface form error in the range of $\lambda/2$ to $\lambda/4$ visible in some configurations. It can be followed by MRF® or fluid-jet for a finer finish.

CNC Bonnet Polisher



A spherical fluid-filled **bonnet**, covered with a polishing pad fed by abrasive slurry, is moved across the workpiece along seven axes: The standard X, Y, Z, plus tool head inclinations A and B, workpiece rotation C, and tool rotation H.

The bonnet's contact patch size is a function of Z, fluid pressure, and bonnet size, and can vary two orders of magnitude. The force against the workpiece decreases toward the edge of the contact patch. Local relative tool speed at the workpiece is a function of the radial distance from the tool axis H. With $H \parallel C$, the removal function is "W" shaped. When the contact patch does not include the center of rotation of the tool, the removal function is nearly spherical. **Precession** about axis A eliminates directional lay.



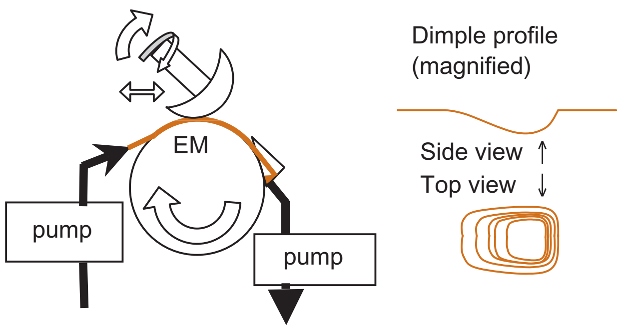
Motions include spiral, raster, and labyrinthine patterns. The latter randomizes periodicity and orientation of mid-spatial-frequency slopes.

The bonnet can be covered with diamond-charged pads or pellets for aggressive removal, or replaced with a fluid jet to produce highly sloped steps.

Magnetorheological Finishing (MRF®)

Magnetorheological fluid is a liquid that stiffens when exposed to a magnetic field. In an MRF® machine, a stream of this fluid is captured on a rapidly rotating wheel by a localized electromagnet, and then released. Abrasive particles are held in suspension within the fluid. The contact patch of the stiffened zone against the workpiece acts as a subaperture polishing tool.

To determine the removal profile, the workpiece is briefly held in place against the stiffened zone. An interferogram of the resulting dimple is then fed into proprietary software that plans the path and dwell for the workpiece across the contact zone to achieve the desired removal. The work path may be spiral or raster.



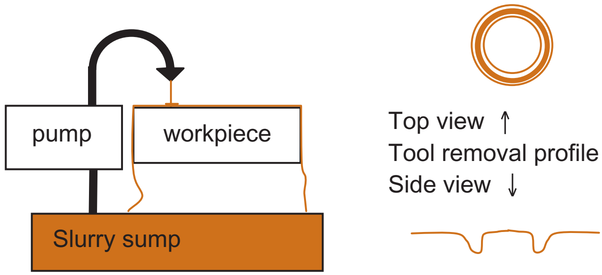
A notable feature of MRF® is that polishing is driven by shear forces—the pressure term of Preston's equation in conventional polishing is of little consequence. When coupled with on-machine interferometry and CNC control, this feature enables rapid convergence on any desired figure or transmitted wavefront from any (prepolished) starting shape. Subsurface damage is essentially eliminated, resulting in a high laser damage threshold. Print through is minimized.

These highly desirable features are partially offset by high initial machine cost, consumables cost, limited workpiece area, slow removal rate, some ripple, and concave radii limited by the diameter of the wheel.

Fluid Jet Polishing (FJP)

As with MRF®, in **fluid jet polishing (FJP)** a stream of abrasive particles suspended in fluid is passed across the workpiece in a pattern that is prescribed by the effective tool profile and the desired removal profile. Removal is due to the kinetic energy of abrasive particles in water-based slurry pumped through a nozzle directly against the workpiece. Slurry concentrations are ~5–10%, nozzle diameters <1 mm, standoff distances of millimeters to centimeters, and pressures <15 bar.

When directed against a ground surface, FJP can reduce the roughness over tenfold for all but the hardest materials. When directed against conventionally polished surfaces, a roughness of 1-nm RMS can be maintained while removing substantial material. FJP produces lower mid-spatial-frequency structure than MRF®.



The effective tool profile depends on the diameter of the nozzle and the angle of incidence. Because material removal occurs with lateral movement of the abrasive, at normal incidence, there is a dead spot in the center. As a result, dwell function calculations are more complex than for MRF®. The tool profile is typically ~3× the nozzle diameter. Nozzles can be easily changed, so the process can be targeted to the spatial frequencies of interest. The smallest reported spots are 0.3 mm FWHM.

The technique is applicable to a wide variety of materials, and difficult configurations including steep concave parts, conformal surfaces, and free-form shapes. Machinery costs are about half those of MRF®, and the slurry is much less expensive.

Single-Point Diamond Turning (SPDT)

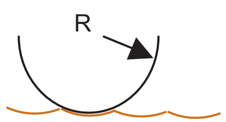
A specular surface is created, track by track, by ductile cutting with a single small bit. This bit is similar in shape to a lathe bit, but with a tip fashioned from a highly polished single-crystal natural diamond. The surfaces thus produced have a distinct "lay."

Depths of cut range from tens of micrometers to tens of nanometers, so workpieces must be precision machined prior to mounting on the **SPDT** machine and usually receive multiple cuts. Perhaps surprisingly, multiple pieces can be processed simultaneously, and interrupted cuts are allowed.

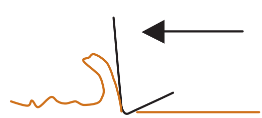
Two main configurations are **fly cutter** and lathe. SPDT is ideal for producing aspheres (including torics and axicons) and working with soft materials. Slow- and fast-tool servo oscillations in Z enable production of free-form shapes such as off-axis aspheres, arrays, and diffractive optics.

SPDT machines are characterized by extreme stiffness, motion control in the nanometer range, and machine-wide temperature control of $\ll 0.1°C$. These conditions are realized with air bearings, hydrostatic slide ways, interferometric feedback, PZT controls, and environmental isolation.

Pure Al, Cu, Ge, ZnSe, ZnS, GaAs, and many plastics are excellent choices for materials. Silicon optics display an azimuthally variable roughness. Ferrous metals and alloys containing carbon destroy the tool tip. Applications to glass and other brittle materials are limited by the shallow depth of ductile cuts.



Surface cross-section viewed along tool path (cusping exaggerated)

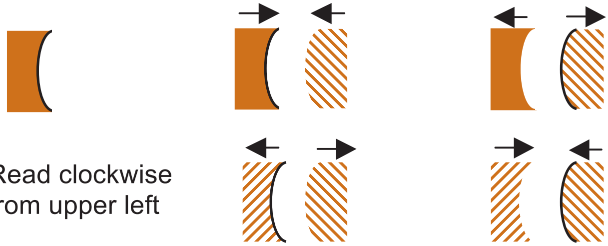


Surface cross-section viewed across tool path showing chip formation

Replication

Replication is an *additive* approach to surface finishing that involves these steps:

1. The master surface is coated with a release agent followed by a layer of epoxy, then sandwiched to a negative submaster.
2. The master surface is removed, leaving the submaster's epoxy surface as a mate to the master.
3. The submaster is coated with a release agent.
4. The replica substrate is machined to a near match to the master surface, coated with epoxy, and pressed into the submaster.
5. After cure, the replica is separated, leaving the submaster ready for repeated pressings.



Read clockwise from upper left

Alternatively, the submaster can be replaced with a directly produced negative master. This variant is particularly helpful where the finished part (and by extension its original master) is a convex asphere that would be difficult to test directly. Thin-film coatings can be applied to the submaster.

Advantageous features of replication include:

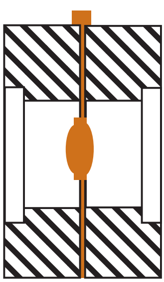
- flexible choice of substrates merits, including weight, stiffness, cost, machined features, and shaping techniques,
- integrated mounting and alignment features,
- low costs for complex surface shapes,
- ability to create aspheric, free-form, and diffractive surfaces in quantity, and
- ability to duplicate existing surfaces.

Resulting surfaces are relatively soft and cannot handle high powers.

Plastic Injection Molding

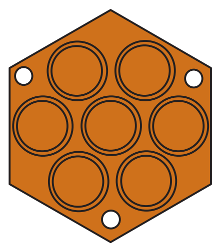
Once used only for mechanical parts and low-quality magnifiers, **injection molding** can now produce optics to 1λ accuracy in high volumes at low cost. Aspheres, prismatic elements, and arrays can be produced. Integral mounting and alignment features can be incorporated, and due to the properties of plastics, snap-together assemblies can be created.

Pellets of thermoplastic material are melted and pumped through sprues into a heated mold cavity containing optically polished inserts, then cooled. The cavity parts are then separated, and the entire tree is removed. Extraneous tags are removed at a convenient point in the process, sometimes by the end user.



Mold with inserts and sprues

Multilens component with mounting points



Plastics offer high impact resistance and low specific gravity (0.2–0.5× other optical materials.) Due to plastics' high coefficients of expansion, shrinkage in the mold must be considered in the cavity design to minimize distortions. Due to high viscosity and chain molecules, **birefringence** is prominent. Careful material selection, cavity margin and sprue design, and process development help minimize these concerns.

High initial tooling costs contrasted with low material and labor costs make injection molding competitive only for quantities exceeding many hundreds, and prices reduce asymptotically up to the hundreds of thousands.

Thermoset Casting and Compression Molding

Thermoset casting simultaneously establishes the material's structure and its surface finish. A liquid monomer is mixed with a catalyst and sandwiched in a glass mold where it is heated and cured to a cross-linked polymer. In contrast to thermoplastics, which can be repeatedly melted and resolidified, thermoset plastics cannot be reheated to a liquid without dissociation.

This technique is utilized in mass-produced ophthalmic lens blanks. Standard combinations of base curves and bifocal segments are integral to the molds and are cast into the blank on its outer surface.

CR-39® (allyl diglycol carbonate) shrinks about 14% upon cure, so nearly uniform thickness is necessary to preserve shape when casting. The blanks are produced with extra thickness; any necessary power and cylinder are applied to the side opposite the bifocal, and the frame-border is machined in the optician's lab by conventional grinding and polishing or diamond turning.

Compression molding is able to replicate fine detail and high spatial frequencies such as Fresnel lenses, diffractive optics, and reticles by heating a premeasured gob or plate of polymer or glass to its softening point and pressing it between two mold masters.

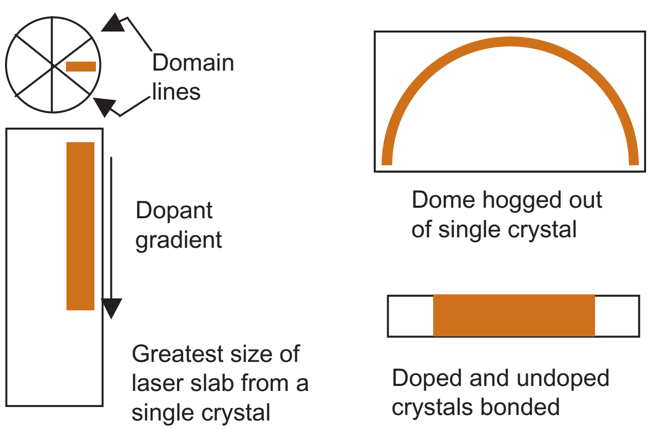
Glass manufacturers have created families of glass with low **transition temperatures (T_g)**, specifically designed for compression molding. Still, there is thermal contraction upon cooling below T_g, so the final result does not exactly match the mold. Precision molders model this in advance and adjust the mold surfaces to compensate. The optics are slowly **annealed** after molding.

Hot Pressing

Some ceramics and semiconductors are either unavailable in the desired size, or shaping to the desired configuration would require extensive removal of expensive and hard material. Near-net shape blanks of high quality can be created through combinations of **hot pressing**, **sintering**, and **hot isostatic pressing (HIP)**. Such blanks eliminate the birefringence, index, and dopant gradients, and exceed the strength, dimension, and dopant limits of single crystals, while reducing waste.

The process begins with fine-grain starting materials. The grains are fused together under high pressure (1–3 kBar) and temperature (up to 2000° C). Large laser slabs, domes of AlON and spinel, and combinations impractical to realize through crystal growth have been produced. Alternatively, singly grown crystals can be joined by diffusion bonding.

Bulk scattering is a function of grain size and **densification**, and therefore is a function of process parameters. Usually these materials are somewhat hazy in the visible but acceptable in the IR. Surface scattering is also a function of grain size, densification, and differential grain polishing rates.



Raw Material and Forms of Supply

Before planning how to finish, one must choose where to start. Raw materials are available in a number of forms:

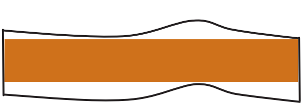
- Glass **blocks** have one face machined and five as cast.
- Glass **strips** are loaves with cut or broken ends, available either fine annealed or coarse annealed; the latter is only for hot reprocessing such as molding.
- Glass **plates** are fully machined rectangles or cylinders with beveled edges. These can be ordered with at least one dimension that is just enough above final tolerance to allow for processing with minimum work or material loss.
- Glass **rods** are long cylinders suitable for slicing.
- **Prism blanks** are available cut and machined or molded.
- Lightweight mirror **castings** have an open-cell honeycomb back surface and can be ordered pre-slumped to approximate the desired first surface shape.
- Crystal **boules** are the as-grown form of a single crystal. Their shape depends on the growth process, crystal form, and seed shape. Their faces are often rounded and not suitable for orientation.
- Crystal **wafers** or **bars** are sliced from the raw crystal in a particular orientation, with parallel opposing machined faces.
- **Polycrystalline** sheet is available in raw loaf or with machined faces.
- Metals are available in many forms: cast, sawn, machined, forged, or sintered.
- **Hot-press** glass and **sintered** glass, metal, composites, and crystals may be ordered in many forms.

Exotic glasses and crystals may only be available in limited dimensions.

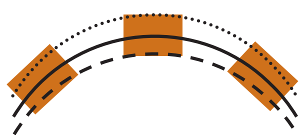
Starting Material Dimensions

When planning a job, one must ensure that the starting material stock dimensions are capable of yielding the final dimensions.

- Sheet material may have surface defects or a warp. Remember that warp affects both sides.
- Molded blanks have skin stress that must be removed.
- Sawn surfaces are not strictly plane.
- Curve-generated surfaces are not exactly spherical, and may need radius adjustment.
- Cores usually need fine edging.
- All shaping and lapping operations leave subsurface damage that must be fully removed by polishing.
- To achieve surface figure, it may be necessary to polish opposing sides for stress relief before reworking one or both sides to a lesser thickness.
- Plan for adequate removal across the block: When grinding a spherical surface, grinding depth is proportional to the cosine of the angle between the local surface normal and the block axis.
- Plan for wedge variability in lenses mounted in a block: It may be necessary to start them over diameter and center after polishing.
- If possible, plan to finish with enough thickness to rework in case of rejection for surface quality, figure, or coating.



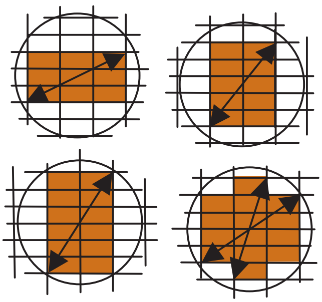
Maximum available plane material from warped sheet (exaggerated)



Each colored lens blank starts at same size. Initial removal is greatest, final removal least, and wedge is constantly changing on outer parts of block at constant radius.

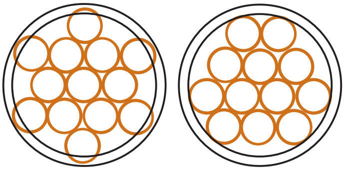
Yield from Dicing and Coring

Finding the best **yield** of rectangles from a circle requires several trial calculations but returns substantial reward for expected yields of <30 per parent blank.



Compare the usable area of the parent to the pattern diagonals (counting the saw kerfs) for each of four pattern centers: corner, vertical face edge, horizontal face edge, and part center. The best arrangement is dimension dependent. The sketch here shows yields of 9, 10, 12, and 14, depending on the starting position.

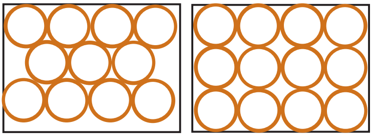
A square cover piece guides the saw to make square cuts on round pieces.



A similar approach works for coring from a circular parent with only two options: hexagonal with one part or three parts in the center.

Note that for the larger parent circle, the pattern on the left yields one more part (13 versus 12), while for the smaller parent the left yields only 7 versus 12 on the right.

When coring from a rectangular plate, a close-packed hexagonal pattern is not always best.



Efficient Production and Optimum Quantities

Scheduling the custom optical shop can be a complex task due to concurrent processing of many orders in different quantities and configurations through multiple work centers in different sequences. **Queue** time often exceeds 90% of total order time.

- Exploit commonalities between part types by making quantities of partially completed blanks (standard diameters, thickness, one side polished plane, etc.) ahead of time, in most efficient quantities, for later differentiation.
- Create dedicated setups and tooling wherever they will increase efficiency.
- Simplify recurring setups.
- Make all needed tools available at every station.
- Fill coating chambers whenever possible, often with different part types, and even at the expense of queuing parts for a run.
- Minimize bottlenecks by matching machine capacity to lot size and work flow.

Optimum quantities depend on part configurations and stage of production. Block size for plano optics is limited by machine capacity and convenient weight. Block quantity for spherical surfaces is limited by the included angle, which is a function of part diameter, thickness, and radius, so the limit may be different for opposing sides. A few guidelines follow:

- Blocks should be symmetrical, and densely packed, and should not exceed the 120-deg included angle limit.
- Match machine capacities to lot sizes and keep them running, not with larger lots, but with smaller, more flexible machines.
- Run planetary polishers as long as possible for stability, and route work to keep them full.
- Plan lot quantities to complete the order despite reasonably expected yield losses.

Planning for Yield Losses

Glass breaks. Scratches can't be filled in. Coatings are subject to random spatter. Bubbles and inclusions are easier to see after polishing. Tolerances may challenge process capability. These problems are likely to surface late in manufacture, and delivery schedules seldom accommodate a second run.

An example may serve best: An order is for 10 mirrors, but the best block geometry for obtaining good figure is 7 pieces. Make 2 blocks of 7. You *may* have 40% overage. If so, you can (1) offer them at a discount, (2) stock them for the next order, (3) donate them to a grateful grad student who could become a CEO, or (4) rework one side into a similar part, recouping partial material and labor.

Another example is as follows: You find a scratch that cannot be removed without taking all under thickness, a bubble in another piece, and coating spatter marred a third. You have fulfilled the order with one spare. You still have recoverable material and labor in the other three. This took less time and labor than struggling to figure one block of 10 or 2 blocks of 5. It avoided the risk of coming up short. And your customer may break one and be grateful you have another of his custom parts on hand!

How, then, should we calculate the yield for the second scenario? Is it 79% (11 good out of 14 made)? Or 110% (11 good out of 10 ordered)? Or maybe even 180% (due to the labor savings in process efficiency plus labor applied toward reworked parts)? Reported yield is not the best indicator of efficiency. Do not punish prudent planners.

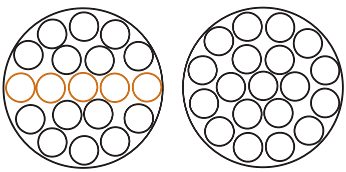
Do investigate the root causes of those rejects. At least you will not need to explain them in front of a customer whose order, due tomorrow, would take another month.

Rare or costly materials, or single-part CNC machines, can change this strategy.

Block Capacity: Flat

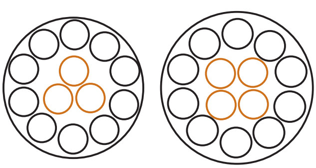
Flat or plano **block capacity** is limited by weight and machine dimensions. For safety and liability reasons a shop may choose to restrict the weight a person must lift to 10 kg or so; or provide hoists and cranes.

Planetary and double-side machines have limited room in their work stations; mills and generators have limited clearance; overarm machines are limited by stroke length and interference with adjacent axles, and the cost of interferometers rises exponentially with aperture.



A quick method to determine flat block pattern is to lay out parts across a block diameter with ϕ/10 spacing between and count how many fit; then use the table below.

Shortcut: 0.763(# across)^2. Good to 1 piece out of 200!



The best packing could have one, three, four, or even five parts in the inner zone. Subsequent zones should be spaced in circles.

Beyond a count of perhaps seven across, the central pattern makes vanishingly little difference for hand blocking.

# across	Center pattern	Total #
3	1,6	7
4.15	3,9	12
4.24	3,10	13
4.41	4,10	14
4.7	5,11	16
5	1,6	19
6.15	3,9	28
6.24	3,10	29
6.41	4,10	30
6.7	5,11	33
7	1,6	37
8.15	3,9	50
8.24	3,10	51
8.41	4,10	53

Wedge Tool Capacity

Parts blocked in wedge slots do not naturally conform to a circular layout. As with dicing and coring, planning the layout results in better distribution and higher capacity.

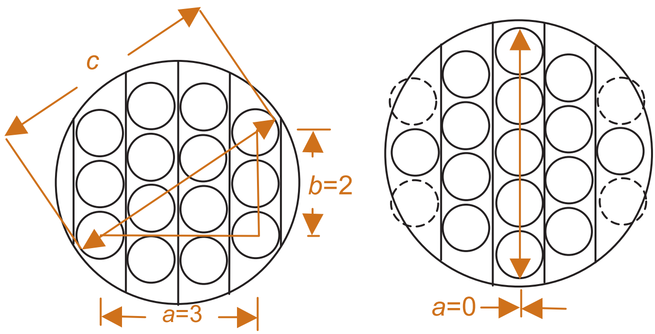
To obtain the part count for trial layouts, sum the number of parts fitting in each column:

ϕ_{eff} = column width = vertical part spacing

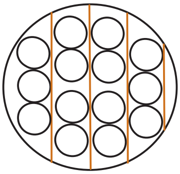
a = # column spacings across a centered zone of interest

b = # part spacings vertically

$$c = \phi_{eff} \times \left(\sqrt{a^2 + b^2} + 1\right) \leq \text{tool diameter}$$



The tool, when loaded with workpieces, must balance on the areal center of the workpieces as well as on the spindle pin, which may need to be decentered.

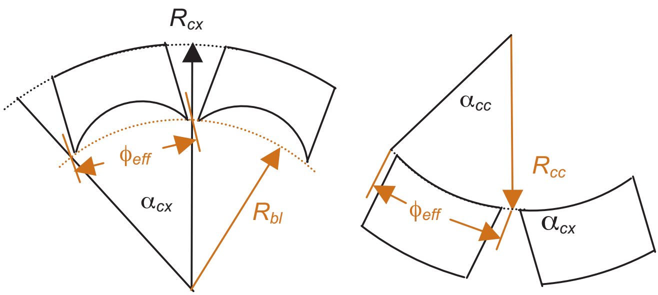


Once the slot layout is chosen, the optician may choose to space the parts within the slots to make a smoother outer perimeter.

Prism bars are more conveniently made in equal lengths in square tools and polished on a planetary machine.

Block Capacity: Radius

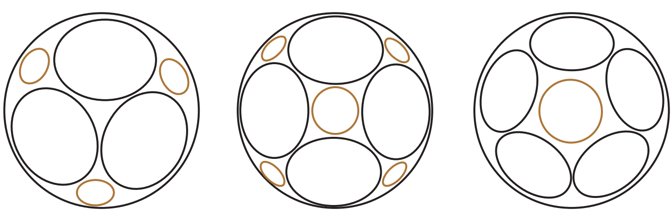
Conventional fabrication becomes more difficult as the edge slope exceeds ~60 deg. For parts with $R \gg \phi$, the number of parts to fill a given angle can be estimated through their effective diameter, including their separation. Take R as the radius of the surface if concave, and of the blocking tool if convex.



It should be clear from the above that thick lenses with steep convex radii can only be worked singly.

According to Karow,[10] $N \approx 6R^2(1 - cos\alpha)/\phi_{eff}$. While this is a decent approximation for $R \gg \phi_{eff}$, it does not suggest the best packing for steeper lenses.

As with flat blocks, the best packing to fill the desired slope may start with 1, 3, 4, or 5 pieces on center. The edge profile of blocks with *only* 3 or 4 pieces, and the empty center of blocks *starting* with 4 or 5 pieces, make for poor figure control. Small **dummy** pieces can be placed strategically between the production parts.



Dummy fillers shown in color

Scheduling for Coating

A coating chamber can be thought of as an airliner:

- Chamber setup and run time are substantial and independent of the fill ratio.
- Everything in the run receives the same treatment.
- Popular runs are scheduled more frequently.
- When the door closes, it stays closed.
- There are only so many chambers available, and so many hours in a month.

A simple 1–3 layer antireflection run takes 4 hr end to end and is run frequently. More complicated designs can run well into the next day and then not again for some time. If a run is started without filling the chamber, that unused capacity is lost forever.

Queuing parts from different orders to share a full run is the best use of expensive and limited chamber time. While parts needing slightly different spectral tuning can be coated concurrently at different heights, substrate indices must be compatible with the design. Thus a simple air-spaced doublet may need four runs.

Having both small and large chambers improves flexibility (but the chambers respond differently and need different sets of spare parts).

Adequate time must be scheduled for test runs to be performed after repairs, and before coating actual parts with a new design.

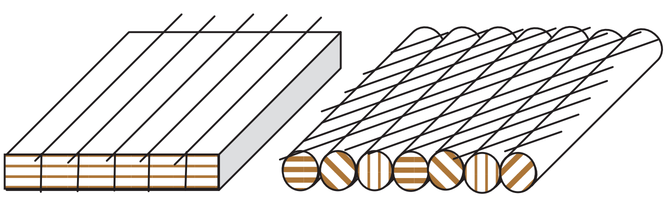
A popular superstition is that splitting lots among runs reduces the risks associated with a "blown run." While it increases the probability of *some* parts being good (which should already be high) it also *multiplies* the risks of some parts being bad, as well as delaying order completion and reducing production capacity. If the need is to get at least one prototype of a new design for testing, then splitting lots may be a good idea, but for production it is illogical.

Directional Inhomogeneity

Smooth **index gradients**, localized inhomogeneities, **striae**, and periodic layering affect the performance of transmissive optics in different ways. Glass consisting of several ingredients must be processed carefully to avoid striae and localized variations. **Float glass** is prone to layering. Materials that are grown (including fused silica) and not melted or sintered are prone to layering and gradients.

> When possible, plan the fabrication sequence so that the optical path is perpendicular to inhomogeneities.

For an example of unfortunate planning, consider a seemingly efficient way to make **Brewster windows**: Sheet material is sliced (lumbered) into sticks, edged to cylinders, and sliced at a diagonal into ellipses that are blocked, ground, and polished. Depending on the orientation of the cylinders during slicing, the optical path lands at 0–33 deg to the layering. Multiple intracavity passes divided the laser's mode into a dotted line.



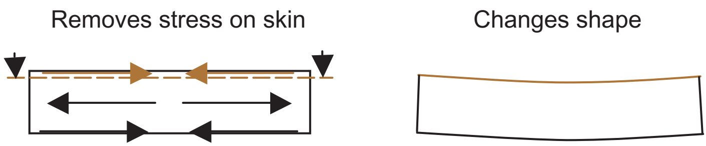
Stresses within Optical Components

Stress causes **strain**, affecting surface shape and, in extreme cases, part failure. Stress-induced birefringence can compromise polarization purity.

Internal stresses, frozen into glass when cooled from melt or when compression molded, are reduced by **annealing**. The degree of this stress is measured indirectly in terms of induced birefringence, $\Delta n_{\parallel} - \Delta n_{\perp}$, where the actual stress is proportional to its **stress-optic coefficients** as follows:

$$K_{\parallel} = (n_{\parallel} - n_0)/\sigma \qquad K_{\perp} = (n_{\perp} - n_0)/\sigma$$

Molded blanks are under compressive stress near the original melt's skin and under tensile stress inside. Machining the skin on only one side thus changes the stress distribution and bends the glass.



The Twyman effect: Grinding and lapping induce surface compressive stress, decreasing with abrasive size below 50 μm, reducing gradually over time, and being relieved by etching or polishing.

> When a thin section is ground on both sides and polished flat first on one side and then the other, the first side does not remain flat. Three-sided polishing is a solution.

Tempering, whether by thermal shock or chemical bath, intentionally induces large compressive surface stresses. Tempered glass resists scratches, fractures, and thermal shock but cannot be cut without danger of shattering.

Injection-molded optics, their molecules being large and production speed being paramount, are highly stressed and show substantial birefringence.

Stresses Applied to Optical Components

Throughout fabrication, coating, assembly, storage, and usage, optical components are exposed to a number of stresses.

In wax blocking, wax is melted in a layer between hot optics and backing plates made of some type of glass or metal. When the optics cool and shrink differentially to room temperature, they are stressed. Blocking wax shrinks by a large percentage after solidifying (the actual number is never published), and unlike pitch, wax does not flow. After polishing to figure, the parts are deblocked, the stresses are released, and the figure changes.

> A layer of electrician's tape or adhesive-backed shelf paper adjacent to the wax provides much stress relief.

An optic may slip easily into and out of a hot aluminum spot block seat that is too small at room temperature, but bind severely during cool processing. Because of small burrs and fillets, multiple seats, diameter variations, and the difficulty of getting a "diameter" measurement of lobed parts, this problem can be hard to pinpoint.

The work of surfacing generates frictional heat to the worked surface(s). In single-side processing this causes an axial thermal gradient; in double-side processing it causes a radial gradient.

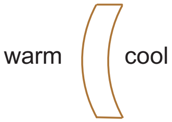
Thin film coatings are most often applied at 100–250 °C, and the various film materials have different expansion rates from the substrate. Film stresses can bend the surfaces or even cause the film to **delaminate**.

Rigid and large adhesive connections between materials of different expansion rates can stress optics beyond their strength, causing catastrophic failure. Thicker, smaller pads cause less stress, and flexures between separated pads avoid stress on the optic while maintaining alignment.

Thermal Settling Time

In the course of fabrication, optics are subjected to heat inputs from blocking, deblocking, polishing friction, or handling. Nonuniform temperature distributions cause physical distortion from localized thermal expansion and optical distortion due to dn/dT. Upon removal of the heat flux, conduction eventually restores equilibrium.

Polishing friction applied to one side causes an axial thermal gradient, bending the part. Finger heat incurred in handling causes localized hot spots that can affect both surface figure and transmitted wavefront. Tests performed before reaching equilibrium are not accurate.



$$\Delta s = \frac{\phi^2 \alpha \Delta T}{8t}$$

The time constant for an axial thermal gradient to decay to $1/e$ (<40%) of its initial value is given by

$$\tau = \rho C_p t^2 / k$$

Two time constants reduce the gradient almost eightfold. Three time constants reduce distortion by 95%. Tests performed even less than one time constant apart show whether the part is likely to approach the desired tolerance. With interferometer time at a premium, this is valuable information. The time constant for BK7 is nearly seven times as long as for FS, and its initial physical distortion is fourteen times as great.

A perhaps surprising result is that the entire Schott catalog, plus FS and crystal quartz, all fall within a factor of 3 on the figure of merit for transmissive OPD due to thermal differences:

$$OPD \cong t \Delta T \left(n\alpha + \frac{dn}{dT} \right)$$

Thermal Failure

Rapid changes or extremes in temperature adversely affect optical components in several ways, including fracture, delamination, loss of annealing, permanent shape change, and degradation of cement bonds. Certain shop practices that cause thermal changes can exceed the limits, especially when production pressure impinges.

Materials that are easily cleaved—those with high CTE (or different by axis) and low transition temperatures or yield strengths—are of particular concern.

Optics are heated for blocking with a torch or hot plate, then cooled, sometimes on a chilled plate. Providing heat distribution during heating as well as reduced rate of cooling is good practice. Cooling even a heated Pyrex® blocking plate directly against cool aluminum can fracture it.

> Brittle materials tend to break when a surface is in tension; this is most likely to occur during rapid cooling or localized heating.

Aluminum spot tool seats expand with heat more than any glass, so parts can be slipped into seats that are too small, and then be stressed to failure at room temperature.

Coating application temperatures must be kept below metal annealing, glass transition, or plastic softening temperatures. Some interesting physics is entailed here: The interior of the vacuum chamber is heated by IR quartz radiators. IR-transparent materials do not heat as rapidly as the tooling, which can expand and either drop the optics or catch and later bind them to fail. During cooling, the interiors of large optics stay hot while in edge contact with cool tooling. Upon rapid venting, large (and especially IR transmissive) optics suddenly sense cool gas on their skins.

> It's usually the biggest, most expensive part fabricated in years that "inexplicably" breaks during venting. A slow addition of air, to $\leq$ 0.1 bar, and patience are advised.

In-Process Inspection Points

The obvious purpose of inspection is to ensure that the finished product meets all specifications; however an equally important purpose is to minimize the impact of defects on the schedule and capacity of the shop.

Problems tend to surface late in the fabrication process. The later they are discovered, the greater the sunk costs and impact on schedule. While inspection never adds value, when well planned, it can save a great deal of time and cost.

The purposes of **in-process inspection** are to take early corrective action, minimize sunk costs, ensure adequate yield downstream, and to give early warning of developing problems to upstream manufacturing departments—*not* to find every defect. The **cost of inspections** should equal the consequential costs of missing the found defects, including opportunity costs, reputation, materials, rework, and more. Part-per-million metrics are not meaningful in custom optics production.

For example, prior to coating, a sample inspection of ten parts from a block of 100 for an order of 78 finds one scratch. That order can be filled with high confidence. Inspecting more parts at this point adds no value; any scratched parts will be culled during the necessary 100% inspection after coating. Say that that scratch is characteristic of scuffs from a micrometer. Now the response would be to go upstream immediately and talk to the person holding the micrometer before more product is damaged, but still pass the block.

If three from the sample of ten are scratched or the figure is poor, the block can be put back on the machine without loss. Many processes are iterative.

Inspections should be performed when they are easiest and most effective. The best time to inspect a dimension or an angle is when it is established. It is quicker to obtain an interferogram of one sheet than of 100 diced parts, and to measure angles on a prism bar compared to measuring every individual prism. It is *much* easier to adjust and correct wedge before the sheet is diced.

Dice After Coating?

Most hard dielectric coatings are scratch-, peel-, and water-resistant, so it is possible to coat large sheets and then **dice** them into smaller parts. This cannot be done with soft coatings. It is *much* easier to clean one hand-sized sheet than a few hundred tiny rectangles for these reasons:

- There are far fewer sharp edges to catch lens tissue.
- Cleaning tooling is simpler.
- Capillary drag-out in wet baths is less of a problem with fewer edges.
- Inspection and handling are easier.
- Chamber tooling is simpler; a few small tabs can be used to hold the sheet by its edge in the chamber leaving 100% clear aperture for the rest of the diced parts.

However, there are good reasons *not to dice after coating*:

- Dicing causes small chips and localized delamination of the coating. These can become sites for introduction of corrosives and creeping failure in a challenging environment.
- The Twyman effect causes raised edges. If 100% CA is required, it may be necessary to dice before polishing then suspend the parts in the chamber with double-stick Kapton® tape.
- The finished part may be designed for hard mounting against its coated face, offering opportunities to crush or scratch the coating at those points.
- Rough procedures such as dicing and subsequent cleaning are ill-advised for soft coatings.

Beamsplitter prism assemblies are a great candidate for slicing after coating. The halves are made in long bars on a wedge slot tool so that the angles are uniform along the bar. The bars can be sawn in half, marked and oriented as mates, coated, then cemented so that the set has very little beam deviation. Final slicing separates a number of practically identical assemblies.

Cements and Adhesives

For structural purposes the choice is typically between a **room-temperature-vulcanizing (RTV) elastomer** and a two-part **epoxy**.

RTV elastomers cure by atmospheric reaction so cannot be used in broad uninterrupted face bonds. They have low durometer values, fill large gaps, provide some strain relief and shock protection, but allow vibrational oscillation.

Two-part epoxies are mixed just before use with a limited pot life. Cure time is accelerated with heat. They are rigid, are applied in relatively thin bonds, maintain close mechanical tolerances, and have great strength, often exceeding that of the brittle materials to which they are bonded. The effective stiffness of a rigid adhesive depends on its aspect ratio (controlled by shims and bosses) and temperature (stiffness increases dramatically as temperature decreases). A good optomechanical design must include proper bond aspect ratio, CTEs, yield strengths, expected thermal range, and flexural properties of structural elements.

Two-part **optical cements** are transparent for use in the optical path. The two parts are mixed just before use, and thorough mixing is necessary to avoid **striae**. To avoid bubbles in the optical path, the mixing is done with a paddle beneath the surface. Then the mixture is placed in vacuum to expand any bubbles and force them to the top, where they break. Finally a dropper is inserted below the surface to transfer cement to the components, and spread by pressing them together with an orbital motion.

UV-cure optical cements are not limited by pot life, or subject to striae, and have fewer bubble problems. A partial cure increases viscosity for fine adjustments. These cements cannot cure between materials that do not transmit UV, and their containers must be protected from long exposure to fluorescent lamps.

Avoid **cyanoacrylates** near optical surfaces; they fog the surface and lessen the laser damage threshold.

Sampling Inspection and AQL

Inspection has costs and does not add quality, so it needs to be minimized. However, if a parameter or attribute is important, it must be inspected eventually, or else the consequences of not inspecting it must be deemed acceptable. Those consequences vary in criticality and can include

- death or injury,
- mission failure,
- system failure,
- repair or rework costs and delays, or
- continued production of scrap.

A great deal of work has gone into quantifying **acceptance quality levels (AQLs)** for each of the listed consequences. Charts are available in, for example, MIL-STD-105e. For each AQL and various lot size ranges, these charts specify the number of parts to be inspected within the lot, and the numbers of parts within that *sample* that, if found discrepant for the attribute of interest, would trigger acceptance or rejection of the *lot*. Any defect that is discovered at any point should be removed, but the costs and consequences of having some defects within the lot is deemed acceptable compared to the costs of inspecting 100% of every attribute.

Customers may specify AQLs for final inspection before shipment. The sample should be selected at random from the production lot. Internal planning and quality departments may also set AQLs as appropriate at in-process points to balance the costs of inspection against those of producing scrap. For inspection on the block, sampling is never random, so it must be representative. That means selecting parts from the outer row, the center, and a mid-zone.

For parameters that will be inspected again—SQ after coating for instance—100% inspection is wasteful. The goal should be to discover production problems before more defects are produced, and to ensure sufficient yield to complete the order after coating.

Cosmetic Surface Quality

The word '**cosmetic**' is chosen because scratches, digs, edge chips, bubbles, voids, spatter, and stain are not *directly* related to performance. Only scratches (long narrow imperfections) and digs (nominally circular imperfections, including voids and spatter) are graded, usually as a pair of numbers or letters, the first referring to scratches and the second to digs.

MIL-C-48497A and MIL-F-48616 are officially inactive and applied to coating defects. The first letter in each graded scratches by width (A = 5 μm, G = 120 μm), and the second graded digs by diameter (A = 50 μm, H = 1 mm).

MIL-PRF-13830b (formerly MIL-O-13830a) is the most common SQ standard in the US. The first number is a scratch grade, evaluated by comparing visual appearance to a "standard" scratch set under prescribed lighting conditions by the unaided eye. The second number × 10 μm is the maximum dig diameter. 10-5 is its finest specification, although not sufficient for intracavity laser optics. 80-50 is its coarsest and default specification. Because MIL-PRF scratches are subjectively weighed, there is much room for disagreement. SQ is the most common cause for rejection, and a major cost driver.

ANSI/OEOSC OP1.002-2009 contains nomenclature for both appearance grades (numbered as in MIL-PRF) and quantitative dimensions (by letter as in MIL-C and MIL-F). The latter are extended beyond MIL-PRF at the fine end to address the laser community.

Each standard has rules for binning and accumulation.

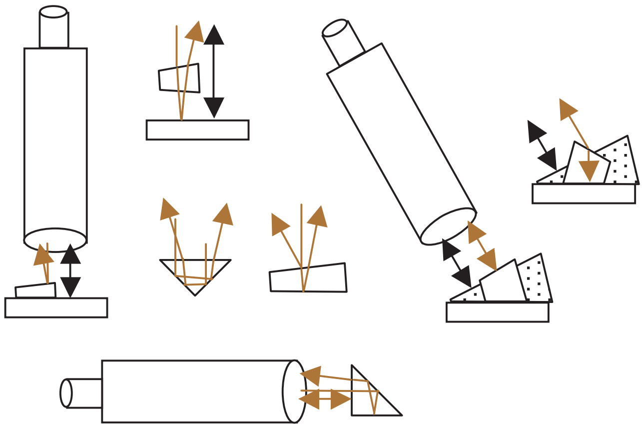
ISO 10110-7 is dimensionally quantitative. Its nomenclature lists in one line the number and size of short defects, of coating blemishes, of scratches longer than 2 mm by width, and of edge chips. Short defects enumerate digs and short scratches according to the square root of their areas.

Angle Testing with an Autocollimator

Protractors can verify physical angles to ~15 arcmin for angles >~10 deg. Interferometry can verify beam deviation to ~0.1 arcsec for angles <~2 arcmin. **Drop gauges** can compare heights to ~2 μm. The gaps are covered by autocollimation. Depending on focal length and detector (visual, CCTV, quad), **autocollimators** have resolutions from 30 to 0.05 arcsec over ranges from several degrees to several minutes.

Most autocollimators are mirror reading, meaning that they report the physical angle between first-surface reflections, rather than the (doubled) mirror deviation angle. Refractions and multiple reflections change the scale factor.

In operation, the autocollimator is oriented to the test or reference object, and the returns' positions are compared. There are two basic modes: self-comparison and reference comparison. For parallelism and small wedge, front and back surface returns are compared. For exterior submultiples of 180 deg (π rad), clockwise and counterclockwise returns are compared. For arbitrary angles, a reference artifact is needed.



This figure displays a small fraction of the tests and configurations possible with a single autocollimator.

Sag and Spherometers

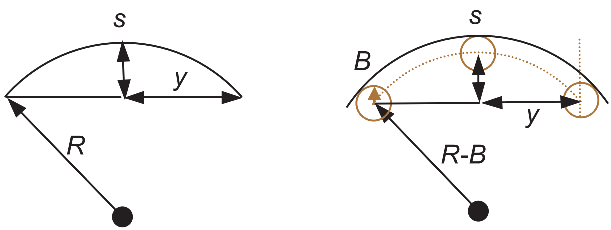
Sag (short for sagitta) is calculated by several formulae, each having its place.

Contact points or balls do not have to be equally spaced, and a narrow span can be useful. In any case, y is the half-span of the circle formed by the three points contacting a plane perpendicular to and centered on the probe gauge.

> When using a linear gauge with two pins and an in-line centered probe, rock the gauge to find the true reading.

Accurate for all spheres: $s = \left(\frac{y^2}{R}\right) \Big/ \left[1 + \sqrt{\left(1 - \frac{y^2}{R^2}\right)}\right]$

Note: A simpler version of this equation, $s = R - \sqrt{(R^2 - y^2)}$, assumes R to always be a positive number.



When using a **spherometer** with ball feet:

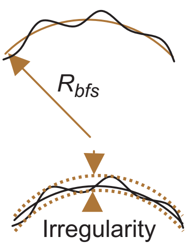
$$s = \left(\frac{y^2}{(R-B)}\right) \Big/ \left[1 + \sqrt{\left(1 - \frac{y^2}{(R-B)}\right)}\right]$$

where R is entered as positive for concave surfaces and negative for convex, and B is the half-diameter of the contact balls.

> An excellent approximation for shallow spheres with fewer chances for input error is
>
> $$s \cong \frac{y^2}{2R} \qquad \text{or} \qquad s \cong \frac{\phi^2}{8R}$$

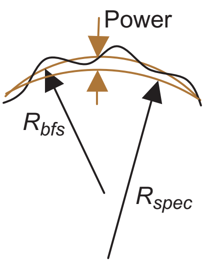
Radius, Irregularity, Power, and Figure

These terms are commonly used in the optical fabrication community, but the way they are used is not consistent from person to person. Consider these definitions as modest proposals and starting points for discussion. More complete and rigorous expositions are available in OEOSC OP1.004, ISO 14999-5 (in development), and ISO 10110-5.



Radius: radius of the RMS best-fit sphere to a surface or wavefront.

Irregularity: range of residual errors between best-fit sphere (or best-fit cylinder for cylindrical surfaces) and the surface or wavefront, which may be expressed as PV or RMS.



Power: difference between the *specified* sphere and the best-fit sphere. Cylindrical power is measured along its axis. Power should not be applied to aspheres. For noncircular areas, apertures must be carefully defined.

Cylinder or **saddle** (also known as astigmatism): Greatest power difference between two orthogonal sections of equal extent.

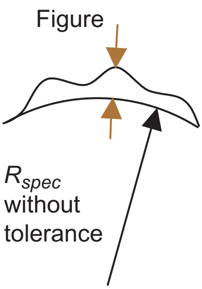
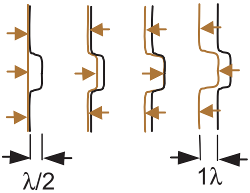


Figure: overall physical shape, as compared to specified geometric ideal. If no tolerance is given to the radius, then figure includes both power and irregularity. If the radius is separately toleranced, figure is equivalent to irregularity, but the best-fit sphere must also be within the radius tolerance.

Interferometry

Of the many types of interferometers, the Fizeau has become the standard in optical fabrication. Commercial instruments have made huge advances in the last few decades, including instruments for phase measurement, spherical references, fringe-counting distance measurement, and digital imaging, as well as analysis software. Angle and scale registration allow integration with deterministic machining. Stitching algorithms increase the limits on numerical aperture, dimension, and aspheric departure.

Still, the basics are unchanged and often misunderstood: Every optician "knows" that "a fringe is a half wave," which is neither right nor wrong, but incomplete. When a surface is distorted by λ/2, the test wavefront travels that physical distance *both* outbound and inbound, accumulating an OPD of 1λ at the plane of interference, which shows as 1 fringe spacing. The correct **scale factor** must be applied when using commercial interferometers.



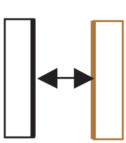
> One fringe spacing *always* represents one wave of optical path difference (OPD) at the plane of interference.
>
> A fringe does not "belong to" an optical component. It is only a phenomenon of interference between two waves that have traveled different paths.

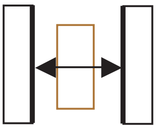
The importance of these fine points is that not *every* test setup encounters the surface (or refracted wavefront) twice at normal incidence before returning to the plane of interference. It is necessary to trace the paths, accumulate OPD at each encounter, then count fringes at one per wave of OPD.

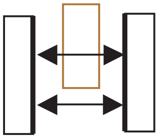
Although peak-to-valley (PV) measurements and specifications are still the most common and best understood, they are not well correlated with optical performance, because they do not account for slope or total affected area.

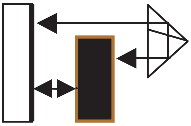
Interferometric Setups

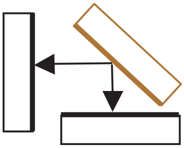
The following is a partial listing of common setups for Fizeau interferometers. Items under test are in color. The item on the left is the Fizeau transmission reference surface.

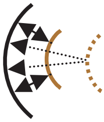

Surface

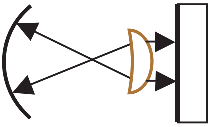

Transmitted wavefront

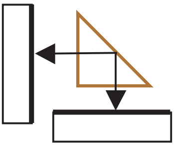

Beam deviation

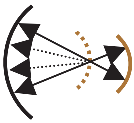

Wedge of opaque part using cube corner

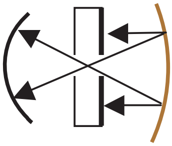

Oblique surface

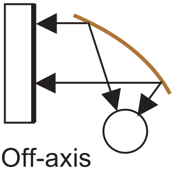

Convex surface + radius

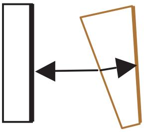

Lens TWF


Prism TWF


Concave surface + radius

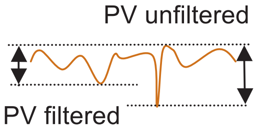

Parabolic null


Off-axis parabolic null

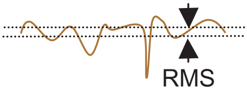

Reflected wavefront

PV, RMS, and PVr

Wavefront and surface form error are most commonly specified in the **peak-to-valley (PV)** form. PV is the difference between the greatest positive deviation and the greatest negative deviation from a desired function such as a best-fit sphere, or "flatness." It is familiar and easy to evaluate, but can be highly influenced by small areas of extreme value. In high-resolution digital interferometers, a few rogue pixels can multiply PV values severalfold, while having little effect on optical performance.



Look for the interferometer's **histogram** feature. If the major peak is narrow or skewed, look for outlying values and consider **filtering** or masking them.



RMS (root-mean-square) values are obtained by evaluating each pixel's deviation from the desired or best-fit value. Each pixel's deviation is squared, all are summed, and the square root of the sum is then divided by the number of pixels. While this result corresponds better with performance, it is not as intuitive and requires computation (integral-to-interferometer software).

For "typical" optical surfaces, PV is between 3 and 5× RMS. This relationship does not hold for structured surfaces such as those produced by SPDT.

PVr (peak to valley, robust) is the result obtained by computing the least-squares fit to a 36-term **Zernike** polynomial and adding to it 3× the RMS value of the residual error between that fit and the actual wavefront or surface. This procedure gives a result that "looks like" a PV value without its undesirable sensitivity to spurious pixels.

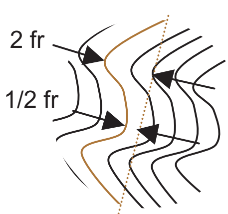
Fringe Patterns

Common fringe centers

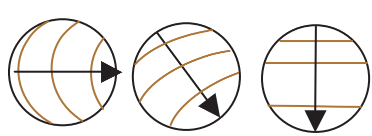
Interference fringes are read like topographic maps. A set of curved fringes whose centers are in the same direction indicates a relative radius or power difference between the interfering wavefronts. The sense of that difference (convex or concave) can be determined by pressing lightly on the component's mount. If shortening the path causes the fringes to converge toward their common center, the relative sense *of the wavefronts* is concave, and vice versa. (TWD through a convex part yields a concave wavefront.)

When using test plates, the sense of curvature is most dependably determined by pressing on a point orthogonal to the fringe system tilt. If the system center swings toward the pressure, the fit is relatively convex; if away, it is relatively concave.

Fringe patterns can show both senses in different areas. Fringes are enumerated by counting the number of *different* fringes crossed by a straight line across the region of interest.

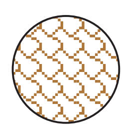


Fringe patterns for nonspherical surfaces change shape with tilt.



Cylinder, axis horizontal, arrows show tilt

Multiple interfering waves confound interpretation; therefore, it is important to quench nonessential beams.

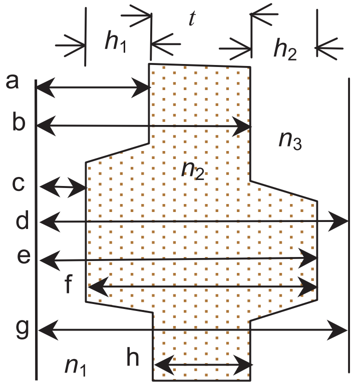


Fringe Scale Factors

A fringe or fringe spacing refers to a wavefront or surface distortion causing an OPD equivalent to that between adjacent fringes; it does not refer to any one fringe, or to lateral spacings on the interferogram.

One fringe spacing *always* represents one wave of OPD at the plane of interference.

Following are the **scale factors** between various errors and their resulting OPDs after a round-trip path, as in a Fizeau. n_1 is index before object, n_3 is index after object (both usually = 1), and n_2 is index within object. Increasing thickness is positive on both sides.



a–c) 1st surface reflection:

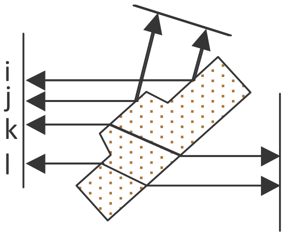
$$OPD = 2n_1h_1$$

d–g) Double-pass transmitted wavefront (DPTWF):

$$OPD = 2[(n_2 - n_1)h_1 + (n_2 - n_3)h_2]$$

e–b) 2nd surface reflection: $OPD = 2[(n_2 - n_1)h_1 + n_2h_2]$

f–h) internal fringes: $OPD = 2n_2(h_1 + h_2)$



For oblique incidence, air is assumed to be on either side, and the error on one (either) side.

j–i) oblique 1st surface reflection: $OPD = 4h\cos(\alpha)$

k–l) oblique DPTWF:

$$OPD = 2h\left[\sqrt{(n^2 - \sin^2\alpha)} - \cos\alpha\right]$$

Conics and Aspheres

In the past, the rule was that an **asphere** could do the work of ~3 spherical elements, at 10–20× the cost. Using the new deterministic machinery, the cost differential is more like 2×. But tests designed for spheres cannot adequately evaluate aspheres without modification. Prolate ellipsoids, paraboloids, and hyperboloids can be tested by placing a sphere or flat at the appropriate conjugate to create a geometric null test. Oblate ellipsoids and polynomial or free-form aspheres need special tests.

> Designers should include two to three points from a sag table on the print. Fabricators should check the aspheric equation against the sag table to verify all signs and unit scales.
>
> Slope is more important than sag for aspheres.

A **null lens** or mirror system based on independently verifiable spherical surfaces can be designed to compensate for the aspheric shape, enabling testing with an ordinary interferometer. The Hubble mishap underscores the hazards of using a null lens.

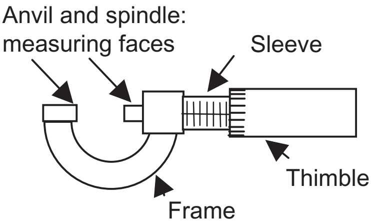
A computer-generated hologram (CGH) diffracts the test beam. Because it is generated lithographically and contains fiducial features for alignment, it is safer than null lenses where applicable.

Shack-Hartmann wavefront sensors measure, rather than null, the local slopes.

Profilometers are a family of instruments that measure surface height at a point that is translated along a line. Contact (stylus) and noncontact (optical or capacitive) types take one or more scans of the surface.

Stitching interferometers combine multiple images from subapertures, making the fringe count of each more manageable, thereby increasing the allowable range of departure without loss of resolution. They are integral to some CNC machines. A recent development is the **sparse-array phase-measuring interferometer**, which combines sub-Nyquist sampling with an internal software reference.

Dimensional and Geometric Measurement

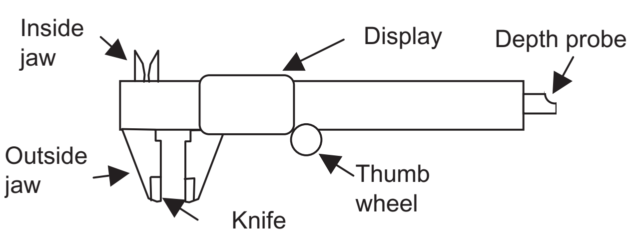


Anvil micrometers are the basic tool for linear measurement. Minimum calibration consists of checking the reported thickness of several different **gauge blocks** across the micrometer's full range of measurement, with values that let the thimble and spindle fall in different orientations to check for cyclic errors. A more complete calibration uses parallel optical flats, again landing at several orientations, to check parallelism of its measuring faces by Newton's fringes.

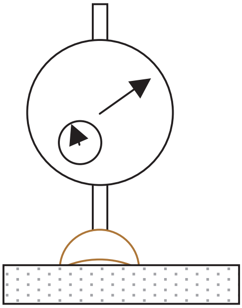
The zero position should be checked periodically. Because of thermal expansion, the frame should not be held longer than necessary. Concave surfaces can be checked with ball ends.

When using lens tissue over the test piece to protect surfaces, check the offset with the lens tissue around a gauge block; the offset will be different if the two sheets of lens tissue are adjacent, especially with ball ends.

Calipers are quicker and more versatile than micrometers, but highly skill dependent and less accurate. Their jaws are easily bent. Contact the outer jaws as close to the main scale as practical and with as little force as possible. When measuring holes, the inside jaws must be aligned carefully in pitch, yaw, roll, and lateral translation in order to obtain the maximum reading.

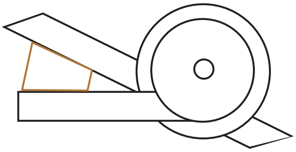


Dimensional and Geometric Measurement (cont.)

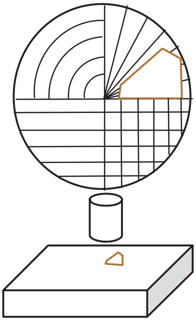


Drop gauge, as colloquially known, is a hard-mounted linear probe contact gauge used to measure small excursions of the gauge pin or to compare two arbitrary positions. With potential accuracy to 0.5 μm, this type of gauge is useful for measuring wedge, height, and center thickness.

Bevel protractors can measure angles whose sides can each contact the blades, a limit depending on both angle and thickness. With skill, coordination, and patience, accuracy of 5 arcmin is possible.



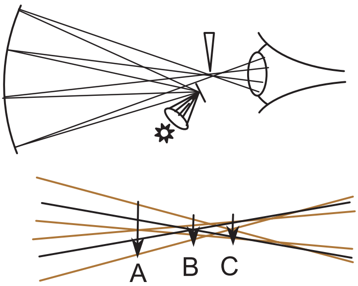
The **optical comparator** (or shadowgraph) projects a magnified image of an object onto a screen through a telecentric image system. The object is moved on a calibrated stage from one feature to another to coincide with markings on the screen. A variety of screen patterns is available; each can be rotated. Angles, centers, spacings, and vertices removed by beveling can be found.



Vision systems apply automatic feature recognition. Edges, circle centers, diameters, etc. and their relationships are identified in accordance with geometric dimensioning and tolerancing (GD&T) rules.

CMM (coordinate measuring machine) systems physically touch the object at key points under robotic control.

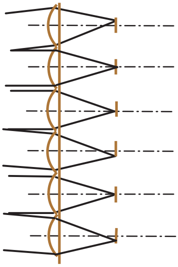
Slope Evaluation Methods



The **Foucault knife-edge test** is the classic **slope evaluation** method, in which the caustic is intercepted by a blade directly in front of the eye. It is surprisingly sensitive and requires no expensive gear. While only qualitative for high- and mid-spatial-frequency slopes, quantitative measures of transverse and lateral aberrations are obtained.

The **wire test** is a variant replacing the knife edge with a thin wire, allowing better location of the radial zones corresponding to each longitudinal focus. The **Ronchi ruling** replaces the knife edge with a ruled grating illuminated by a diffuse source. It produces a full-aperture fringe-like image. While purely qualitative, its image is easier to acquire than the knife edge.

The **Hartmann screen** is a full-size perforated mask placed at the aperture, creating multiple subapertures. The spots' positions through focus map local slopes.



The Shack-Hartmann wavefront sensor replaces the screen with a small lenslet array placed near focus that gathers all of the light. The spots are focused onto a CCD array that gives both slope and irradiance information at a rate of multiple hertz. Unlike interferometers, this sensor has no moving parts and no need for coherent light, and is relatively insensitve to vibration.

Roughness refers to spatial frequencies in the approximate range of ~5/µm to 5/mm, and waviness or ripple refers to spatial frequencies from ~5/mm to 0.2/mm.

BRDF and **TIS** are measures of scatter, the combined result of integrated surface roughness, isolated surface imperfections, and internal scatter.

Slope Evaluation Methods (cont.)

Several commercial instruments based on **Mirau** or **Michelson interferometry** can resolve heights <1 nm and include software to report maximum height variations and slope versus period statistics or **power spectral density (PSD)** over a millimeter aperture.

Commercial Fizeau interferometers also report slope statistics. Their spatial resolution is limited to tens of microns at best.

Stylus contact profilometers take a linear scan. The probe radius affects resolution and scan shape. Radii down to 0.2 μm are available, at which size stylus forces can easily exceed material yield strength, leaving sleeks. Calibration and vibration isolation are critical.

The **atomic force microscope (AFM)** has probe radii on the order of nanometers and can measure heights to 0.04 nm (atomic radii). It scans an area... slowly.

The **electron microscope** offers lateral resolution of ~1 nm and extreme depth of focus, but height information is only qualitative without taking several images at different tilts. Samples must have conductive surfaces.

> Spatial frequency bandwidth is a necessary part of surface roughness or slope error specifications; instrument transfer function is a necessary caveat to measurements. No single instrument covers the entire bandwidth of importance.

SCOTS (software-configurable optical test system[11]) is a sort of reverse Hartmann test in which the screen pattern is generated on a computer monitor. A pixel on the screen is imaged by a camera as originating from a location on the mirror at which the camera and aperture are at equal angles to the local surface normal. Local slope is thus mapped across the mirror; surface form is obtained by integration. Because the entire screen can be illuminated with rapidly changing patterns, the method is quick. And now with cameras integrated into laptops and pads, the hardware is inexpensive. SCOTS is applicable to convex, concave, and free-from surfaces.

Slope Tolerancing

TWF and **RWF** are expressed in terms of OPD, or phase. For diffraction-limited performance, phase must be maintained within $<\lambda/4$. However, for larger budgets, it is slope error that directly causes image blur.

Slope errors depend on the shape of the wavefront, not on its phase. While TWF and RWF values are independent of the ripple's spatial frequency, slope errors are directly proportional to it.

Slope errors can be measured directly or calculated from interferograms. Direct slope measurement methods are insensitive to phase and may be quicker and less expensive than using interferometry.

Harvey,[12,13] Murphy,[14] Youngworth[15] and others have brought attention to the importance of mid-spatial-frequency slope errors (ripple). System error budgeting is simple because each element's true contribution can be allocated in an RSS (root-sum-square) series.

Conventional optical fabrication with full-size pitch laps generally produces surfaces with low degrees of ripple. This is not guaranteed with subaperture methods such as MRF®, fluid jet, bonnet, or SPDT. As such machines become more common, and slope-measuring instruments become more familiar, and aspheric departures increase, we can expect to see more slope tolerancing on prints in the shop.

The choice of spatial-frequency bandwidth is always relevant and must be matched to the measuring instruments' capabilities.

Material Properties of Interest in the Shop

Optical designers needs to know index, Abbe number, specific gravity, birefringence, transmissive range, and possibly pumping and gain characteristics. The optician has different concerns. While opticians may have little choice when it comes to materials, they will need to know the material properties that determine how to work with them.

- **Index** n is necessary to set scale factors for autocollimation and interferometric tests. Crystals can have multiple indices.
- **Young's modulus** E determines resistance to bending under applied forces and is proportional to lapping rate.
- **Knoop hardness** H_K correlates to resistance to handling damage, and slower lapping rate.
- **Fracture toughness** K_{Ic}, as the name implies, is a measure of how much work it takes to fracture a material. K_{Ic} is inversely proportional to lapping rate.
- **Coefficient of thermal expansion** α is critical to proper fit in coating fixtures and spot tools. Crystal axes can differ in their CTE, some even having opposite signs.
- Low **thermal conductivity** k maintains gradients that cause distortions.
- **Thermal capacity** C_p predicts cooling time in air.
- **Thermal diffusivity** D or κ, which equals $k/\rho C_p$, predicts distortions due to nonuniform thermal loads, and cooling or heating time in a given environment.
- The degree of **stain, acid, and alkali resistance** (Schott **FR**, **SR**, and **AR** classes) constrains cleaning and handling methods. Lower alkali resistance is correlated to faster lapping.

Material Properties Table

Material	E, GPa	Chem. Resist.	T_g or M.P.	Toxic?
FS	73	Best	1075	No
BK7	82	Excellent	557	No
SF6	55	Poor	423	(Contains lead)
Pyrex®	63	Excellent	510	No
Zerodur®	91	Good	700	No
Crystal quartz	97 76.5	Excellent	~1680	No
CaF_2	76	Medium	1360	No
MgF_2	282	Poor	1950	No
YAG	300	Excellent	1940	No
YLF	85	Medium	819	No
YVO_4	310	Good	~1900	Yes?
$KNbO_3$		Poor	220	No
Al_2O_3	400	Best	2040	No
Si	131	Good	1412	No
Ge	150	Poor	937	No
GaAs	83	Poor	1240	Yes
ZnS	74	Poor	1700	Yes
ZnSe	67.2	Poor	1525	Yes
PMMA	1.8–3	Poor	85	No
Polycarbonate	2.2–2.6	Good	120	No
Polystyrene	3–3.5	Medium	80	No
Epoxy	2–20	Varies	50–160	Yes
UV cure adhesive	3–10	Poor	50–130	Yes
Aluminum	62.8	Medium	660	No
Copper	117	Very poor	1083	No
Beryllium	287	Medium	1287	YES!
Stainless steel	200	Good	~1510	No
SiC	455	Good	2730	No
Water	N/A	N/A	0	No

Optical Properties Table

Material	Trans. µm	n (varies)	ν	dn/dT $\times 10^{-6}$
FS	0.17–2.0	1.47	67.8	10
BK7	0.33–2.0	1.517	64.2	2.8
SF6	0.38–2.0	1.805	25.4	9.7
Pyrex®	0.42–2.2	1.473		
Zerodur®	0.5–20	1.539	56.2	
Crystal quartz	~0.2–3.0	1.555, 1.546		−6.5 −5.5
CaF_2	0.14–7.0	1.434	95	−11
MgF_2	~0.15–6	1.378, 1.39	105	
YAG		1.835	52.6	
YLF	0.18–6.7	1.456	93.5	
YVO_4	0.4–3.8	2.20, 2.30	19	3.9–8.5
$KNbO_3$	0.4–4.7	2.28, 2.24, 2.17		
Al_2O_3	0.15–7.5	1.770 1.762		13.6, 14.7
Si	1.5–6.5	3.43		160
Ge	2–15	4.005		408
GaAs		3.27		
ZnS	0.5–12	2.368		43
ZnSe	0.5–22	2.63	84	64
PMMA	"vis"	1.491	57.2	−8.5
Polycarbonate	"vis"	1.585	34.0	−13
Polystyrene	"vis"	1.590	30.8	−12
Epoxy	–	1.56	–	–
UV cure adhesive	0.4–2.0	1.48–1.55	~30	−183
Aluminum	–	–	–	–
Copper	–	–	–	–
Beryllium	–	–	–	–
Stainless steel	–	–	–	–
SiC	–	–	–	–
Water	0.25–1.1	1.333	55.8	−133 at 20 °C

Thermal Properties Table

Material	$\alpha \times 10^{-6}$	k, W/m K	Cp, J/kg K	T_g or M.P.
FS	0.52	1.38	180	1075
BK7	8.3	1.114	858	557
SF6	9.0	0.673	389	423
Pyrex®	3.3	1.13	1050	510
Zerodur®	0.05	1.64	821	700
Crystal quartz	7.97 13.37	10.7 6.21	787	~1680
CaF_2	16.7	10	844	1360
MgF_2	7.7, 8.2	12.9	590	1950
YAG				1940
YLF	8.3, 13.3	6.3	790	819
YVO_4	3.1, 7.2	5.2		~1900
$KNbO_3$	5.0, 1.4			220
Al_2O_3	5.0, 5.6	25–33	753	2040
Si	2.6	156	710	1412
Ge	5.9	59.9	322	937
GaAs	5.7	35	325	1240
ZnS	7.85	4?	470	1700
ZnSe	7.57	18	356	1525
PMMA	67.4	~5		85
Polycarbonate	68	4.7		120
Polystyrene	60–80	2.4–3.3		80
Epoxy	250–400			50–160
UV cure adhesive	90–120			50–130
Aluminum	22.5	167	896	660
Copper	16.5	391	385	1083
Beryllium	11.3	216	1925	1287
Stainless steel	8.5–15	16–25	500	~1510
SiC	2.4	198	650	2730
Water	200 at 20 °C	0.6	4182	0

Physical Properties Table

Material	E, GPa	ρ	H_K kg/mm^2	Chem. Resist.	Toxic?
FS	73	2.2	500	Best	No
BK7	82	2.51	610	Excellent	No
SF6	55	5.18	370	Poor	Lead
Pyrex®	63	2.23	418	Excellent	No
Zerodur®	91	2.53	620	Good	No
Crystal quartz	97 76.5	2.65	741	Excellent	No
CaF_2	76	3.18	~170	Medium	No
MgF_2	282	4.55	415	Poor	No
YAG	300		~1220	Excellent	No
YLF	85	3.99	300	Medium	No
YVO_4	310	4.24	480	Good	Yes?
$KNbO_3$		4.62		Poor	No
Al_2O_3	400	3.97	2250	Best	No
Si	131	2.33	1150	Good	No
Ge	150	5.32	780	Poor	No
GaAs	83	5.32	~730	Poor	Yes
ZnS	74		~200	Poor	Yes
ZnSe	67.2	5.27	~110	Poor	Yes
PMMA	1.8–3	1.18		Poor	No
Polycarbonate	2.2–2.6	1.25		Good	No
Polystyrene	3–3.5	1.05		Medium	No
Epoxy	2–20	0.8–1.6		Varies	Yes
UV cure adhesive	3–10	1.05–1.2		Poor	Yes
Aluminum	62.8	2.70	120	Medium	No
Copper	117	8.94	~60	Very poor	No
Beryllium	287	1.85	150	Medium	YES!
Stainless steel	200	8		Good	No
SiC	455	3.2	2480	Good	No
Water	N/A	1	N/A	N/A	No

Equation Summary

Quantities and yields, plane surfaces

Block quantity versus diameters, parallel block:

$$\#\text{ parts} = 0.763\left(\frac{\phi_{block}}{\phi_{eff}}\right)^2$$

Quantity per rail versus diameters, wedge bar block:

$$\phi_{block} \geq \phi_{eff} \times \left(\sqrt{a^2+b^2}+1\right)$$

a = # column *spacings* across a centered zone of interest.
b = # part *spacings* vertically.

Maximum coring yield, hex pack:

$$\#\text{ parts} \leq 1.153\frac{Area_{blank}}{\phi_{eff}^2} = 0.906\left(\frac{\phi_{blank}}{\phi_{eff}}\right)^2$$

Maximum coring yield, square pack:

$$\#\text{ parts} \leq \frac{Area_{blank}}{\phi_{eff}^2} = 0.785\left(\frac{\phi_{blank}}{\phi_{eff}}\right)^2$$

Spherical curves

Lensmaker's formula, thin lens:

$$1/EFL = (n-1)\left(\frac{1}{R_1}-\frac{1}{R_2}\right)$$

Lensmaker's formula, thick lens:

$$1/EFL = (n-1)\left(\frac{1}{R_1}-\frac{1}{R_2}\right)+\frac{(n-1)^2\,t_c}{nR_1R_2}$$

Diopter power (ophthalmic) per surface:

$$D = \frac{1\text{ m}}{EFL}$$

Bevel cup-tool radius for 45-deg bevel:

$$R = \frac{(\phi - b)}{\sqrt{2}}$$

Equation Summary

Bevel cup-tool radius for bevel at α to surface normal:

$$R = \frac{(\phi - b)}{(2\sin\alpha)}$$

Element tilt as a result of using decentered bevel as a mounting surface:

$$\alpha = \frac{(b_{\max} - b_{\min})}{2R}$$

Sag, excellent approximation for $R > \phi$:

$$s = \frac{\phi^2}{8R}$$

for $R = \phi$, error = 7.2% less than exact formula
for $R = 2\phi$, error = 1.6% less than exact formula
for $R = 3\phi$, error = 0.7% less than exact formula

Sag, exact:

$$s = \left(\frac{y^2}{R}\right) \Bigg/ \left[1 + \sqrt{\left(1 - \frac{y^2}{R^2}\right)}\right]$$

Sag reported on ball-circle spherometer:

$$s = \left[\frac{y^2}{(R-B)}\right] \Bigg/ \left[1 + \sqrt{\left(1 - \frac{y^2}{(R-B)}\right)}\right]$$

R is positive for concave, B is half-diameter of balls, and y is half-span of ball circle as it contacts a plane.

Fringe power difference versus radius change:

$$\#\ \text{fringes} = \frac{\phi^2 \Delta R}{(4R^2\lambda)}$$

Approximate spherical block capacity, edge angle α:

$$N \approx 6R^2\left(1 - \frac{\cos\alpha}{\phi_{eff}}\right)$$

Equation Summary

Generator head angle:

$$\alpha = \arcsin\left(\frac{\phi_{wheel}}{2R_{surface}}\right)$$

Wedge in lenses whose centers are at radial distance *r* from the tool axis caused by grinding to nonideal thickness:

$$\alpha = \sin^{-1}\left(\frac{r\Delta z}{R^2}\right)$$

Change in thickness required to remove wedge:

$$\Delta z = \frac{R^2(ETV)}{\phi r}$$

Slope angle at edge of spherical blocks containing 3 or 4 pieces:

$$\theta_3 = \sin^{-1}\left(\frac{\phi_{eff}}{\sqrt{3}R}\right) + \sin^{-1}\left(\frac{\phi_{eff}}{2R}\right)$$

$$\theta_4 = \sin^{-1}\left(\frac{\phi_{eff}}{\sqrt{2}R}\right) + \sin^{-1}\left(\frac{\phi_{eff}}{2R}\right)$$

Radius of pitch pickup tool, convex radii and convex sags positive, all thicknesses positive, R_1 being blocked and R_2 being picked up:

$$\text{if } R_1 + R_2 - t_c > 0$$

$$\text{then } R_{pickup} = \sqrt{(R_1 - t_c + s_2)^2 + \left(\frac{\phi_{eff}}{2}\right)^2} - t_{least\_pitch}$$

$$\text{if } R_1 + R_2 - t_c < 0$$

$$\text{then } R_{pickup} = R_1 - t_c - t_{least\_pitch}$$

Lens volume, cylindrical edge, with or without flat bevels:

$$V = \pi\left[s_1^2\left(R_1 - \frac{s_1}{3}\right) + s_2^2\left(R_2 - \frac{s_2}{3}\right) + \frac{\phi^2 t_e}{4}\right]$$

Lens volume, conical edge:

$$V = \pi\left[s_1^2\left(R_1 - \frac{s_1}{3}\right) + s_2^2\left(R_2 - \frac{s_2}{3}\right) + \frac{t_e\left(\phi_1^2 + \phi_2^2 + \phi_1\phi_2\right)}{12}\right]$$

Equation Summary

Aspheric curves

Rotationally symmetric asphere equation:

$$s = \frac{Cr^2}{1 + \left[1 - (1 + \kappa)C^2 r^2\right]^{1/2}} + A_1 r^2 + A^2 r^4 + A_3 r^6 + A_4 r^8 + \cdots$$

Qbfs equation:

$$s = \frac{C_{bfs} r^2}{1 + \sqrt{1 - C_{bfs}^2 r^2}} + \frac{u^2 \left(1 - u^2\right)}{\sqrt{1 - C_{bfs}^2 r^2}} \sum_{m=0}^{M} a_m Q_m \left(u^2\right)$$

$$\text{where } u = \frac{r}{r_{\max}}$$

Thermal and mechanical issues

Conversion, Celsius versus Fahrenheit:

$$°\mathrm{C} = \frac{5}{9}(°\mathrm{F} - 32) \qquad °\mathrm{F} = \frac{9}{5}(°\mathrm{C}) + 32$$

Conversion, Celsius versus Kelvin:

$$°\mathrm{C} = \mathrm{K} - 273.15$$

Temperature intervals (relative sizes):

$$1\ \mathrm{K} = 1\ °\mathrm{C} = 1.8\ °\mathrm{F}$$

Radius change due to axial thermal gradient:

$$\frac{\Delta R}{R} = \alpha \Delta T \qquad R = \frac{t}{(\alpha \Delta T)}$$

Sag change due to axial thermal gradient:

$$\Delta s = \frac{\phi^2 \alpha \Delta T}{8t}$$

OPD change due to temperature change (not linear for large excursions):

$$OPD \cong t\Delta T \left(n\alpha + \frac{dn}{dT}\right)$$

$$OPD = t\Delta T \left(n\alpha + \frac{dn}{dT}\right) + t\Delta T^2 \frac{dndt}{dT^2}$$

Equation Summary

Settling time for gradients to decay to 1/*e*:

$$\tau = \frac{\rho C_p t^2}{k}$$

Settling time for gradients to decay to 10%:

$$\tau' = 2.3\frac{\rho C_p t^2}{k}$$

Bend under uniform pressure for plane parallel circular, simply supported and clamped:

$$s_{ss} \cong \frac{5Py^4}{4Et^3} \qquad s_c \cong \frac{0.176Py^4}{Et^3}$$

Bend under self-weight for plane parallel circular, simply supported on edge:

$$s_{ss} = \frac{0.176\rho y^4}{Et^2}$$

Minimum thickness, pressure-bearing window:

$$t_{ss} = 0.55\phi_{eff}\sqrt{P \bullet SF/\sigma_f} \qquad t_c = 0.433\phi_{eff}\sqrt{P \bullet SF/\sigma_f}$$

Angles

Snell's law:

$$n\sin\theta = n'\sin\theta'$$

Critical angle (internal), Brewster's angle (external):

$$\theta_C = \sin^{-1}\left(\frac{n}{n'}\right) \qquad \theta_B = \tan^{-1}\left(\frac{n'}{n}\right)$$

Beam deviation versus wedge, small angle, normal incidence:

$$\delta = (n-1)\alpha$$

Beam deviation versus wedge, 1st surface normal, exact:

$$\delta = \alpha - \sin^{-1}(n\sin\alpha)$$

External 90-deg "bank shot" reflections:

$$\delta_1 - \delta_2 = 4\alpha$$

Equation Summary

Internal "bank shot" reflections, 90, 60, and 45 deg:

$$\delta_1 - \delta_2 = 4n\alpha_{90} = 6n\alpha_{60} = 8n\alpha_{45}$$

First-surface versus second-surface reflections, small angles:

$$\delta_1 - \delta_2 = 2n\alpha$$

Centering

Beam deviation angle versus wedge:

$$\delta = (n-1)\alpha$$

Single radius of curvature decenter:

$$r = R\tan\alpha$$

Image decenter versus wedge angle:

$$r = (n-1)EFL\tan\alpha = EFL\tan\delta$$

Edge thickness variation or axial runout:

$$ETV = \phi\tan\alpha$$

Lateral displacement (to restore centration) of lens chucked on one side:

$$r = \frac{R_1 R_2 \tan\alpha}{R_1 - R_2 - t_c} = \frac{R_1 R_2 \tan\delta}{(n-1)(R_1 - R_2 - t_c)}$$

Element tilt as a result of using decentered bevel as a mounting surface:

$$\alpha = (b_{max} - b_{min})/2R$$

Fringe scale factors

Ratio of fringes to wavelengths of OPD:

1:1 at the plane of interference. *Always*.

Test plate fringes:

$$OPD = 2h \qquad \#\ \text{fringes} = \frac{2h}{\lambda}$$

Equation Summary

Internal fringes versus thickness variation:

$$OPD = 2n\Delta t = 2n(h_1 + h_2)$$

1st surface-reflected wavefront per reflection, AOI = 0, embedded in index n_1:

$$OPD = RWF = 2n_1 h \qquad \#\ \text{fringes} = \frac{h}{\lambda}$$

2nd surface-reflected wavefront per reflection, AOI = 0, embedded in index n_1:

$$OPD = 2[(n_2 - n_1)h_1 + n_2 h_2]$$

Single-pass transmitted wavefront, AOI = 0, embedded in indices n_1 and n_3:

$$OPD = (n_2 - n_1)h_1 + (n_2 - n_3)h_2$$

Reflected wavefront per pass, oblique incidence, embedded in index n_1:

$$OPD = 4n_1 h \cos(\alpha)$$

Single-pass transmitted wavefront, oblique incidence, in air:

$$OPD = 2h\left[\sqrt{\left(n^2 - \sin^2\alpha\right)} - \cos\alpha\right]$$

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