Specification and fabrication of spherical surfaces

Objectives

- Understand the methods of specifying radius tolerances
- Understand what is a sensible radius tolerance based on an ability to measure the radius
- Understand why the radius may be specified differently if using test plates as part of the manufacturing process
- Develop a sense for how loose a radius can be if there are compensators in the design
- Understand how radii are generated into surfaces

Overview

- Look at methods of tolerancing radii
- Measuring radii, spherometers and lens bench
- Measuring radii and figure with test plates
- Measuring radii of convex surfaces
- Fabrication of spherical surfaces
  - Control of radius during fabrication
  - Conflict between figure and finish

Tolerancing radii – Why it matters

Suppose for a hypothetical representative optical drawing there is a surface that shows the following:
Nominal Radius: 110.672mm
Radius Tolerance: +/- 0.111mm
Clear Aperture: 49mm
Power: 3 fringes at 632.8nm (Equivalent to 0.037mm over CA)

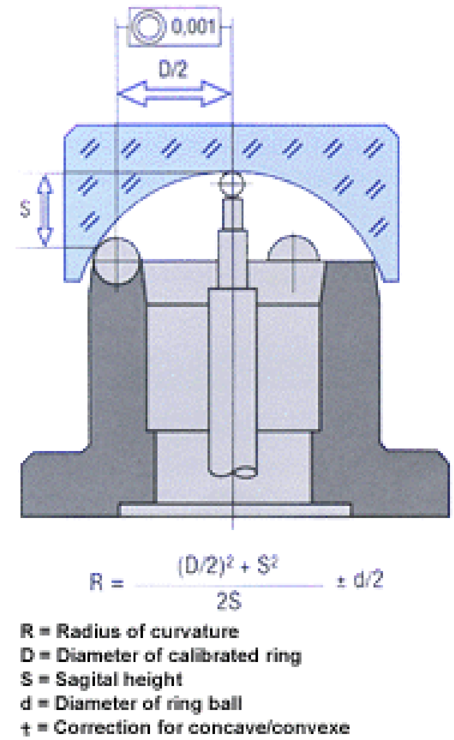
You have a test plate with a radius equal to the nominal radius.

What would the radius range of an in-tolerance part be?
a) +/- 0.037mm
b) +/- 0.111mm
c) +/- 0.148mm
d) Other (please explain)

What is the basis for your answer?

How are radii measured?

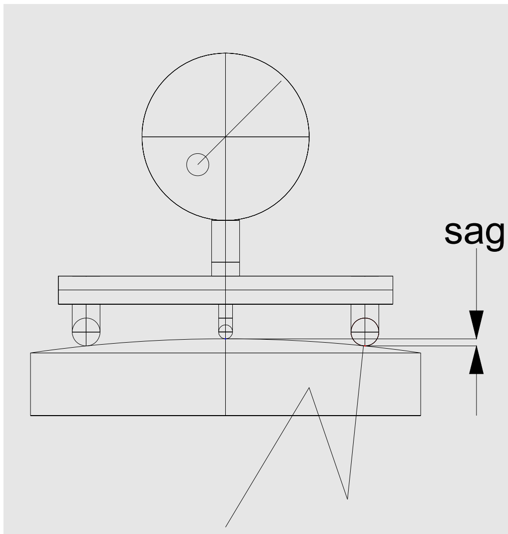
For ground surfaces a spherometer, mechanical device

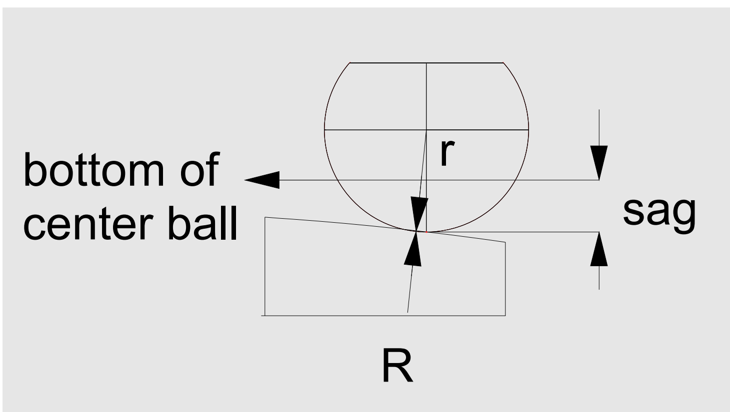


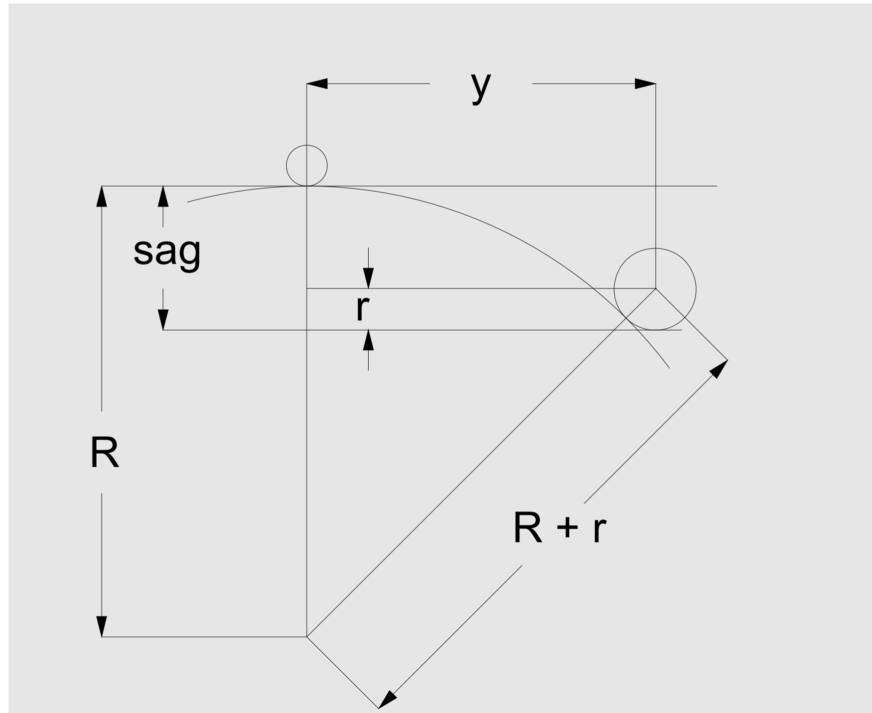
Math is correct

Drawing is wrong!

Spherometer math





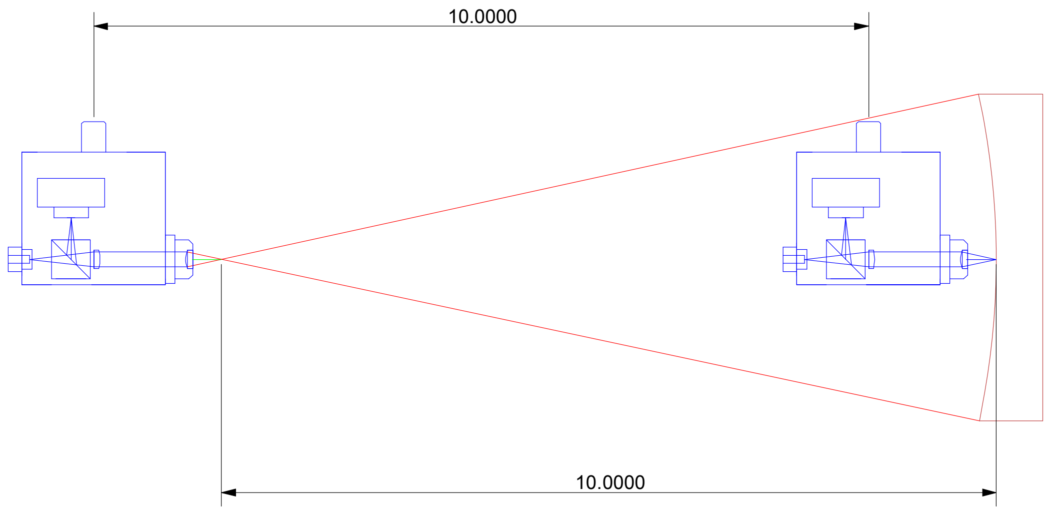


$$(R - (sag + r))^2 + y^2 = (R + r)^2$$

$$R = sag/2 + (y^2)/(2*sag) +/- r$$

Measuring radii – specular surfaces

Two rather different methods – Cat's eye and center of curvature or
Use test plate and count fringes
Test plate almost only choice if convex surface and radius exceeds
working distance of transmission sphere

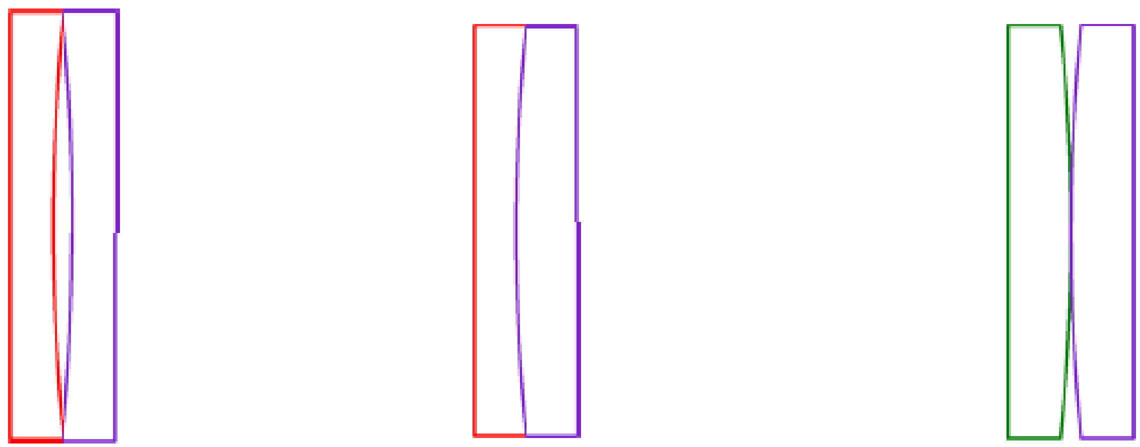


Can use interferometer or an autostigmatic microscope
Interferometer is most sensitive but seldom need to know better than few μm
Measure from center of curvature to Cat's eye, you move along the normal

Measuring with a test plate

Assumption is the radius of the concave half of the test plate is accurate
This is not necessarily so, most measured in own shop

Convex half should be within a fringe or better of concave half



Concave match   Exact match   Convex match

Power in a test plate match

- If there are too many power fringes in a match it is difficult to judge the irregularity
- The ratio between power and irregularity should be no more than 5:1
- Remember the ISO 10110 call out is in fringe spacings (fringes to us) where 1 fringe is $\lambda/2$ p-v surface error over the clear aperture
- Thus power call out may have to be tighter than necessary if using test plates

Concerns using test plates

- Measuring radii with autostigmatic microscope; depth of focus is ~$\lambda(f/\#)^2$
- Reasonable spec for interferometer unless using power term to correct for focus
- Slow surfaces will have larger depth of focus
- Sub-diameter test plates, power error goes as square of diameter
- Never use test plate of <1/2 diameter of surface being tested

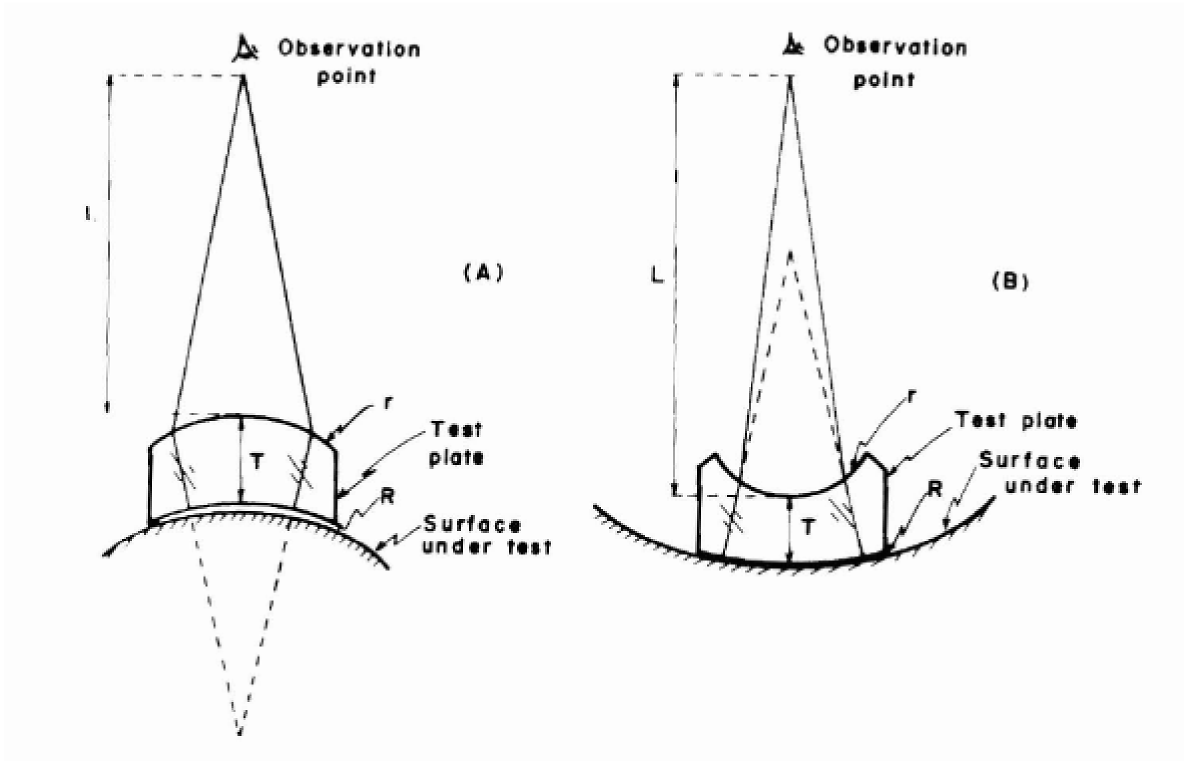
Best practices using test plates

- Use test plate lists in lens design programs
- Match as many surfaces as possible
- New test plate pairs cost ~$1000 each, more if over 100 mm ø
- Many (most) shops still use test plates to control radius and figure
- Easier to do on the shop floor
- QC with interferometer in metrology lab

Best practice specifying radius

- Indicate the design radius on drawing in the radius box with no tolerance
- Use 3/A, B, C to tolerance the radius where A is the power in fringes. You will have to calculate the sag from the ΔR tolerance. Be is the irregularity so A should not be more than 5B
- This way the radius is not over specified
- If tolerance is quite loose and interferometer will be used, just put tolerance on radius and 3/-, B

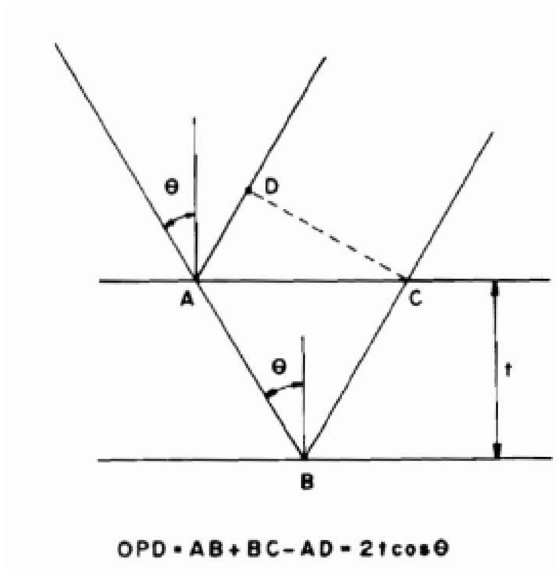
Steep radii – aplanatic backs

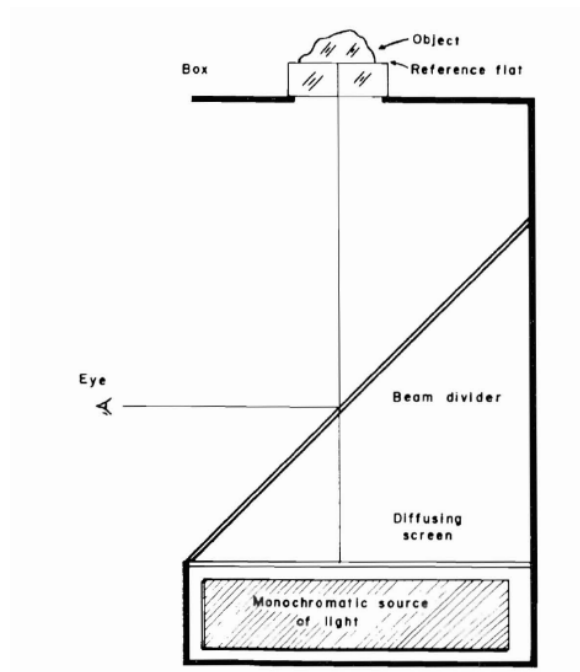


$$r = \frac{(N-1)(R+T)L}{NL+R+T} \qquad r = \frac{(N-1)(R-T)L}{NL-R+T}$$

Note of caution

- Even perfectly flat flats will not look flat if viewed close up – for same reason as aplanatic backs – rays are not normal to the surface
- Particularly bad effect for large flats – large angles

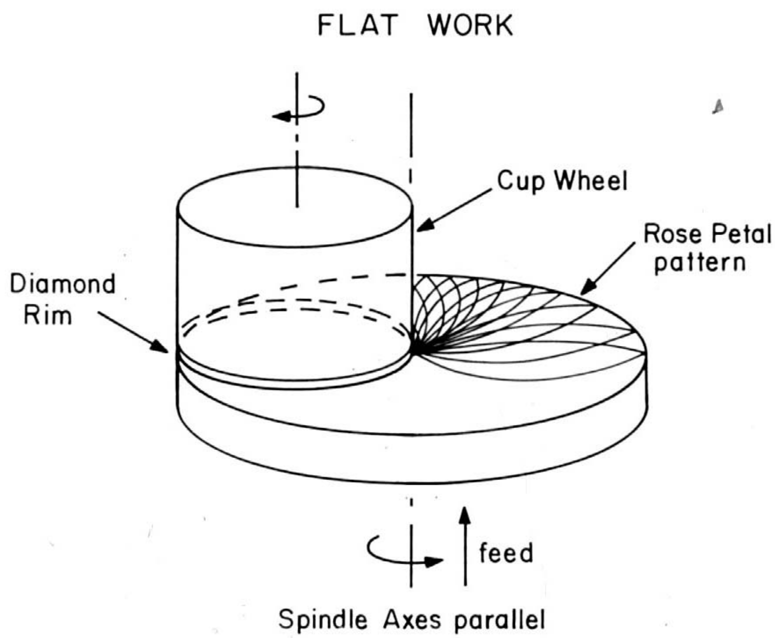


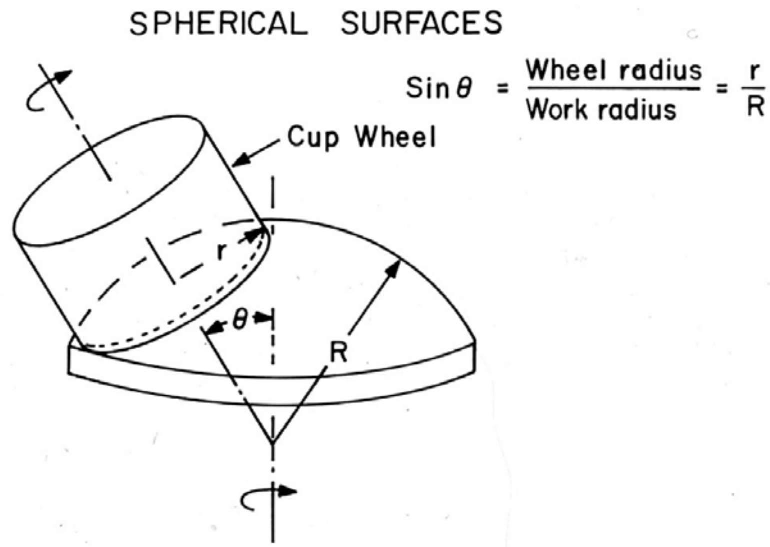


Tolerance for example mirror

- Assume we want to hold the f/# and total length constant
- With f/4 cone, a 8 μm radius error will make spot 2 μm φ
  - This is a .0016% tolerance and unrealistically tight
- If mirror is respaced by about the radius error TOTR is ok
  - There is a loss of performance by a 0.1% tolerance
  - Probably a 0.25 mm tolerance would be reasonable if respaced
- Radius tolerance gives a feel for figure (sag) tolerance
  - Look at sag error for 8 μm radius error

Sphere fabrication - generation





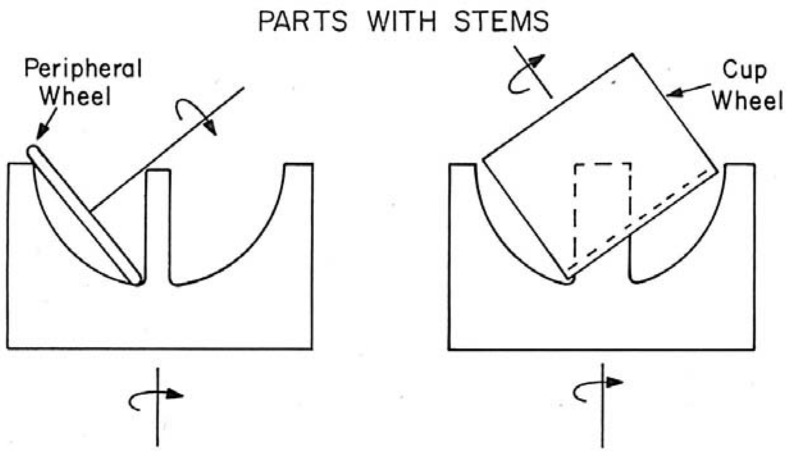
For plane surfaces axes of work and wheel parallel

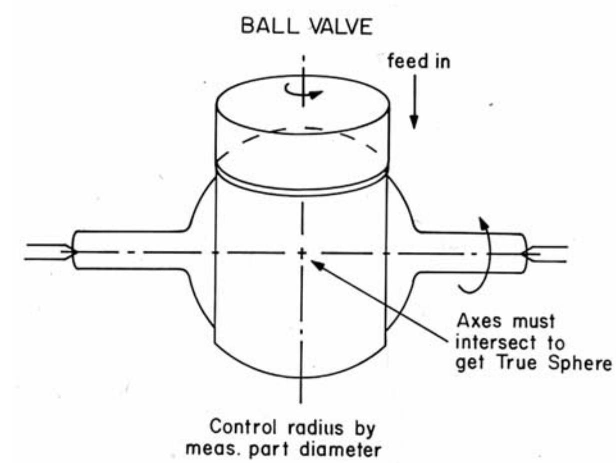
For spherical surfaces axis of wheel tipped in plane of page

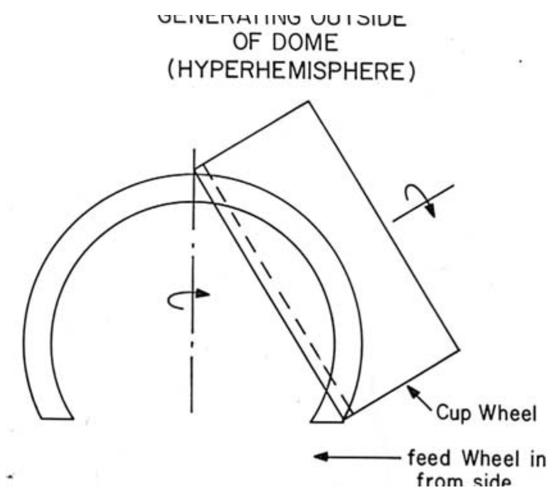
Inside edge of wheel must go over center of work, otherwise a tip is left
"r" is radius of wheel where wheel touches work, use template to find
Wheel axis intersects work axis at the center of curvature of the work

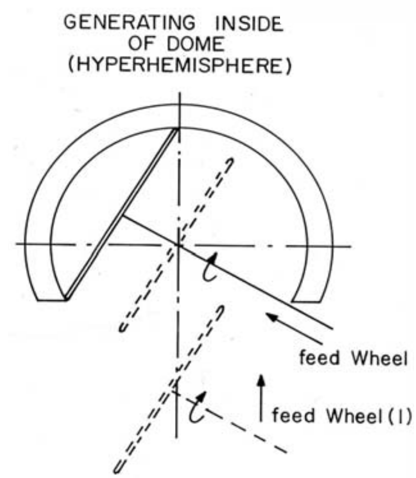
Generator set up for flat surface

Generating other spherical shapes









Generator set up as a saw

Set up to cut cylindrical piece into slices like baloney

Saw is fed in from side as cylinder rotates on lower spindle

Lapping a sphere

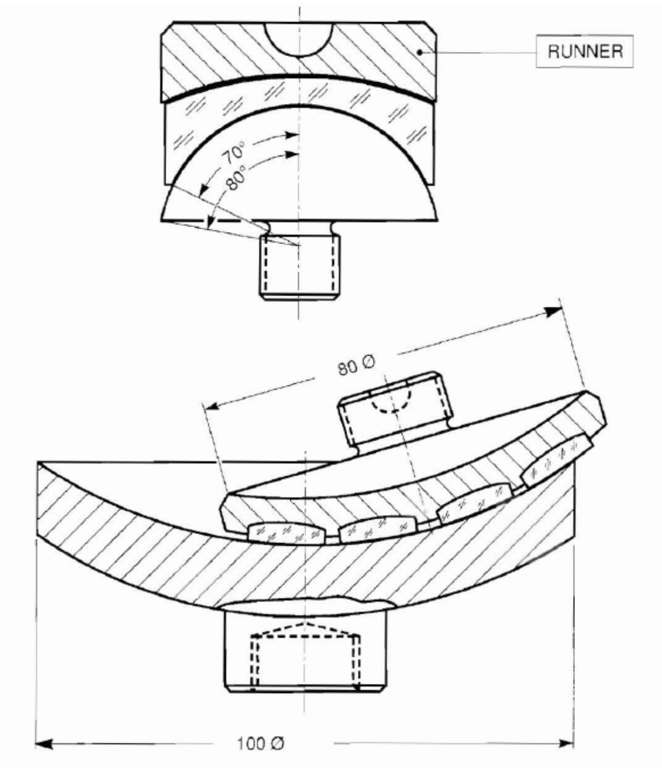
- Lapping removes generator damage to surface
  - Done traditionally with cast iron tools and loose abrasive
  - Now done with diamond pellets on generator type machine
- Trick is holding or correcting radius
  - Spherometer is used to monitor radius
  - Protective chamfer added at this stage
- Stroke on machine used to change radius
  - Both tool and work change radius together
  - Radii of tool and work differ by diameter of abrasive; 10-40 μm
- When surface lapped out with 10 μm and right radius
  - Polishing begins with pitch lap
  - Lap gets correct curve by being “pressed” on lapped work

Polishing a sphere

- Polishing starts with fast stroke and pressure
  - Idea to remove lapping damage and maintain radius
- Once polished out process slowed up, less pressure
  - Work for figure, radius and finish
  - Start by re-pressing lap
  - Best figure using hard pitch but
  - Hard pitch tends to produce scratches
  - Good figure and finish difficult to achieve simultaneously
  - Remember how figure tolerances work with element position
- Figure checked with test plate with work on machine
  - Get simultaneous check of radius

Strokes to change radius

Workpiece on Bottom, **TOOL** on **TOP**		*Workpiece on Top,* **TOOL** on **BOTTOM**	
Polish from **EDGE**	Polish from **CENTER**	Polish from **EDGE**	Polish from **CENTER**
Large swing of Eccenter	*Small swing* of Eccenter	*Small swing* of Eccenter	*Large swing* of Eccenter
Pin forward of Center	*Pin over* Center	*Pin over* Center	*Pin forward* of Center
Swing bias	*No swing* bias	*No swing* bias	*Swing* bias
Larger tool	*Smaller* tool	*Larger* tool	*Smaller* tool
Coarse polishing compound	*Fine* polishing compound	*Coarse* polishing compound	*Fine* polishing compound
Radius of polishing tool nearly the *same* as lens radius	Radius of concave polishing tool *larger* than lens radius	Radius of polishing tool nearly the *same* as lens radius	Radius of convex polishing tool *smaller* than lens radius



Conclusions

- Big difference between flats is creating the sag
  - Measuring and maintaining a specific radius
  - Big potential cost difference – new tooling new for each radius
  - Less standardized approach than for flats
- Save money by matching radii to existing test plates
  - Often can force designs to match all but one radius
- Spherical mirrors may have loose radius tolerance
  - Assuming there is a way of compensating for radius error
- Will have same relatively tight figure requirement
  - Just as a plane mirror, it is a mirror
  - Almost all spherical mirrors used as near normal incidence