Recent design methods and software advances make it much easier to design aspheric surfaces that actually work in production and test by considering manufacturability issues at the earliest possible stage in the design process.

Designing aspheric surfaces is far easier than making or testing them, but manufacturing and testing considerations can be (and usually are, whether the designer knows it or not) made in the design stage. Early collaboration with the lens fabricator is vital to get the best performance at the lowest price with the least part-to-part variability.

Fortunately, recent design tool and optical software advances make it much easier to design economical, manufacturable, and testable aspheric surfaces. Using the manufacturing methods of Optimax and ZEMAX optical system design software, it is possible to map manufacturing needs into the design process as early as possible.

**Locking-in lens specifications**

Lens designs begin with some basic specifications—f-number (f/#), focal length, and aperture, for example—that are then used to build an initial design. After clear aperture is defined for each surface, center thicknesses are assigned for each lens element, establishing both aspect ratio (diameter/center thickness) and edge thickness for the lens.

After evaluating the system, the designer may choose certain surfaces to become aspheric, choosing both the number of surfaces and the global shape of the surface to be aspherized. For each asphere, the designer chooses a conic term and the maximum exponential order of the aspheric terms. The combination of these choices defines the aspheric departure, local curvature, and number of inflection points. These lens specifications (clear aperture, aspect ratio, edge thickness, global shape, aspheric departure, local curvature, inflection points) are established early in the design, and also happen to have the most influence on the asphere manufacturing and measurement process.

**Consequences for the lens fabricator**

The lens fabricator chooses a fabrication process by first looking at the asphere’s global shape: convex, concave, or gull-wing shaped (see Fig. 1). These global shape descriptors are listed in order of increasing complexity and cost, and each has unique challenges. Globally convex aspheres typically offer fewer limitations in manufacturing, but interferometric measurement has more limitations. The opposite is true for globally concave surfaces, with more challenges in manufacturing—specifically regarding tool radius and tool clearance—than in measurement (see Fig. 2). Gull-wing aspheres, sharing characteristics of both convex and concave aspheres, have challenges in both manufacture and measurement.
DESIGN FOR MANUFACTURING

Tool radius is defined by the local radius of curvature of the aspheric surface, and tool radius can never be larger than the shortest local radius to be created. To overcome this issue, the lens fabricator can use shorter-radius tools, but solving tool radius issues often creates tool clearance issues, especially for higher-numerical-aperture lens systems. Local radius of curvature has more influence than maximum tool radius. If the local radius changes too quickly, the fringe density in an interferometric measurement may be unmanageable.

In addition, gull-wing aspheres contain inflection points, and these are challenging to current stitching interferometry. Interferometric testing capability is less possible once an inflection point occurs inside the clear aperture, limiting the lens fabricator to profilometry—which limits how low form error can be held and hinders detection and correction of nonaxi-symmetric form errors.

Complexity is also controlled through restraint in adding aspheric coefficients. Adding aspheric coefficients adds complexity and with it, cost, creating a point of diminishing returns as coefficient terms are added. Fourth-order terms fix fourth-order errors, meaning a sixth-order term adds nothing to a fourth-order correcting asphere except cost.

Aspect ratio also comes into play when determining just how low form error can be held. Parts flex and move during polishing, and this flexing gets more pronounced as aspect ratio increases. Form error of high-aspect-ratio parts (>12:1) can change enough to move the part out of tolerance when no longer held in place for polishing.

Aspheric surfaces are polished using subaperture techniques, where the contact area of the polishing tool is significantly smaller (10–100X) than the clear aperture. The subaperture polishing tool leaves artifacts when it starts and stops polishing, requiring extra aperture to be available during processing. The lens fabricator leaves the parts oversized in diameter to provide room to enter and exit clear aperture, typically adding 4 mm to allow for tool overrun.

This oversized diameter comes into play in two ways. First, if the aspheric form is well behaved over the clear aperture but radically changes or goes inde-terminate in the tool overrun add-on aperture, manufacture or measurement may not be possible. Second, in each manufacturing step the fabricator uses the other lens surface and the diameter to position the aspheric axis. If the edge thickness is too small, the diameter may be useless as a datum or the part may be too fragile to process. For a 2.5-mm-diameter lens, edge thickness needs to be at least 1 mm after beveling, adding on another 0.25 mm per 25 mm of diameter.

Modern software allows a range of techniques that help ensure that a lens design is as manufacturable as possible.

![FIGURE 2](image)
Concave aspheric surfaces have more manufacturing issues than measurement issues: The tool radius can be larger than the local radius of the asphere, causing tool gouging (a; hatched area), and there can be tool clearance issues (b).

![FIGURE 3](image)
When designing aspheres, always add extra margin to the computed apertures (a) and thickness parameters (b) via the software to make mounting and handling easier.
A sixth-order asphere (a), when compared to a tenth-order asphere (b), shows a marked difference in terms of surface curvature. In the higher-order asphere, a cutting tool is easily trapped.

FIGURE 4. A sixth-order asphere (a), when compared to a tenth-order asphere (b), shows a marked difference in terms of surface curvature. The higher-order asphere, a cutting tool is easily trapped.

REFERENCES

Brandon Light is corporate engineer at Optimax Systems, 6367 Dean Parkway, Ontaio, NY 14519; e-mail: blight@optimaxsi.com; www.optimaxsi.com. Mark Nicholson is VP of the ZEMAX group within Radiant ZEMAX LLC, 22908 NE Alder Crest Dr., Redmond, WA 98053; e-mail: mark.nicholson@radiantzemax.com; www.radiantzemax.com.
# Asphere Decision Tree

Guidelines for crossing manufacturing characteristics with metrology options.*

*If we can measure it we can make it.*

## Types
- Convex
- Concave
- Gullwing

## Departure from best fit sphere
- Small departure: <10 µm
- Medium departure: <600 µm
- Large departure: >600 µm

## Metrology options
- Profilometry
- Interferometry
- Stitching
- CGH/Null Lens

## Cost of Measurement
- $1 µm
- $20 λ/10
- $50 λ/20
- $100 λ/40

### Achievable Measurement Limit
- **<200**: Yes
- **>200**: No

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*These are overall guidelines and not applicable in all cases. ** 50th wave possible for some forms.*