# MAKING THE MOST OF PRECISION MACHINING

A guide to the design and specification of precision machined optics.

*by P. Donald Brehm*

Precision optical machining refers to the use of single-point diamond tools and specialized machine tools to produce high figure and finish accuracy on certain substrates. It has evolved over the past ten years out of special techniques for ultra-precise fabrication of machine parts. Today, standard machines, diamond tools and accessories make it possible to precision-machine optical components that interact with lightwaves in a useful and predictable manner. Like any state-of-the-art technology, precision machining places a premium on good communication between the component designer and equipment engineer, and on thorough knowledge of the special characteristics of the technology.

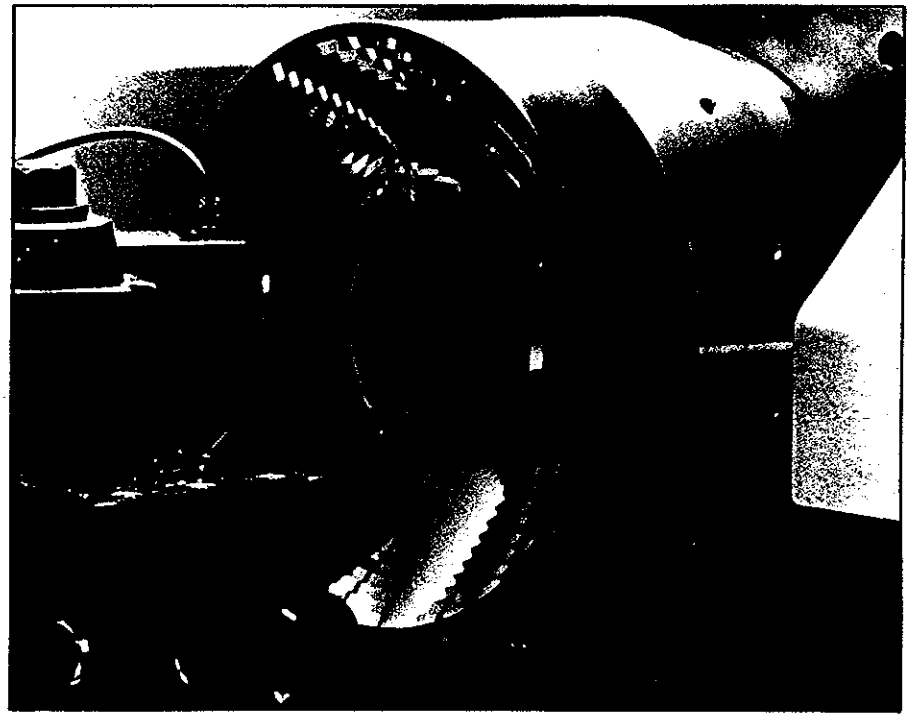

**Figure 1.**
*An internal nonlinear faceted axicon being produced by precision machining.*

### Capabilities: dos and don'ts

The development of electro-optics, particularly high-energy lasers and infrared technology, has created a need for metal and other non-glass optics. In many cases, these components must be aspheric or in other shapes difficult or impossible to produce by conventional lapping and polishing. Diamond machining provides an economical approach to the fabrication of many unconventional shapes.

Materials that have been diamond machined to optical tolerances fall into three categories: metals, infrared materials and polymers (see Table 1). These are all non-ferrous materials — diamond tools wear very quickly when cutting in the presence of iron, through graphitizing of the diamond edge. They also wear quickly when cutting molybdenum, titanium, beryllium and nickel, making optical machining of these materials impractical.

Some materials (including iron alloys) that can't be successfully cut with diamond tools can be cut with polycrystalline CBN (cubic boron nitride) or with coated tools, but the resulting surface finishes don't equal the quality of diamond-tooled finishes and normally require final polishing for optical use.

### Tooling for precision

The single crystal diamond tool has unique characteristics; the highest possible hardness, low friction, high stiffness, good thermal conductivity, and an edge that can be sharpened to atomic levels of sharpness. So it follows that the specialized machine tools used for precision machining of optics can be classed as fine instruments — they require accuracy levels normally associated with the finest metrology instruments. For instance, these machines must maintain the relationship between the cutting tool edge and work surface to within two microinches (.05$\mu$m) or better under dynamic cutting conditions. To meet these requirements, machines must be stiff, have no lost motion or backlash, have no internal vibration, be isolated from external vibration, and be thermally stable. In addition, all machine motions must be exceptionally smooth, and the control system must have microinch resolution. Because of its sharpness, the diamond cutting edge will transfer any undesired machine motions to the workpiece surface.

### Specifying surfaces

Unlike polishing, precision machining produces a predictable pattern of micro-grooves on the optical surface. The size of these grooves depends on the tool nose profile and the feed rate of the tool across the surface. These tool grooves, of course, scatter light from the surface in a preferential direction. Many times the designer can minimize the effect of this scatter on a system's optical performance by specifying the desired direction of the grooves (the "lay" of the surface). On flat surfaces, which are produced by flycutting, direction can often be varied by the way the workpiece is fixtured during mach-

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TABLE 1.
SUBSTRATE MATERIALS FOR PRECISION MACHINING.

| Metals | Infrared materials |
|---|---|
| Aluminum alloys | Germanium |
| Copper | Zinc selenide |
| Brass | Zinc sulfide |
| Tin | Lithium niobate |
| Gold | KDP |
| Silver | |
| Magnesium | **Polymers** |
| Zinc | Acrylics |
| Lead | Other plastics |
| Electroless nickel | |

ining. On axi-symmetrical shapes (such as aspherics produced by diamond turning), the grooves will be concentric about the axis with no possible directional change.

Typical peak-to-valley height of these grooves is one microinch (250A) or less for flat surfaces and three microinches (750A) or less for curved surfaces. RMS roughness values obtained from TIS (total integrated scatter measurement) normally range from 20 to 60A for the diamond-machined surfaces.

Because precision machining is not a random process like polishing, the familiar scratch-dig specifications do not apply, except, perhaps, to limit defects from handling and cleaning. Also, since diamond machining is usually done by machinists, not opticians, the optical designer must learn to specify surfaces in mechanical terms — i.e., microinches, peak-to-valley ($R_t$) or arithmetic average ($R_a$) surface roughness — as well as in terms of light scatter. A dialog between designer and precision machining methods people can usually sort out these differences.

Then, too, material conditions often contribute to light scatter from the diamond-machined surface. For example, surface impurities in aluminum alloys can have a serious effect on scatter. The sharpness of the diamond tool cleanly exposes such defects rather than smearing them over as can happen during polishing. When polycrystalline materials are precision machined, their grain boundaries usually become clearly delineated. Because the light scatter and grain boundaries of machined optics are often visible to the naked eye, the user of precision machined optics must learn to judge quality not by visible cosmetics but by system performance or functional tests. This is particularly true for cost-effective infrared optics produced by precision machining.

The figure accuracy of machined optics can be specified by three parameters: overall figure, waviness or irregularity, and slope error. Put another way, figure accuracy depends on spatial frequency and can be specified in terms of allowable surface figure deviation at a given number or range of cycles per aperture. Slope error specification must also be accompanied by frequency specification. These parameters can be measured by interferogram analysis or contact stylus instrumentation.

The figure accuracy achievable by diamond machining depends on the part configuration. Flats involve only one critical machine slide motion and so can be machined to the best overall figure — typically from one-eighth wave for parts under one inch in diameter to one-half wave for parts in the six-inch diameter range, measured at 632.8nm. Aspheric surfaces involve the computer control of several critical slide motions and can be specified to a best overall figure typically from one-half wave for small parts to one-wave for parts in the six-inch diameter range, again at 632.8nm.

**Variables in figure accuracy**

Many variables affect figure accuracy: inherent machine accuracy, thermal effects, the material being cut, tool accuracy, fixturing distortion and dynamic effects during cutting. The designer of the optical component can have a great deal of control over three of the most critical variables: the material being cut, fixturing distortion and dynamic effects. As I have said, the material specified must be compatible with diamond machining, and it must also be properly stabilized.

Fixturing distortion is probably the single biggest problem in achieving figure accuracy, since the optical component must be able to be held during the machining process without distortion. The optics designer can often ease this task by designing mounting pads or other fixturing surfaces into the optic itself. Ideally, these same surfaces should be used to mount the optic during inspection and application. The structural design of the optic determines its resistance to distortion in fixturing on the machine. In the case of parts to be diamond-turned, it also determines its resistance to dynamic distortion as the part is rotated on the spindle.

The most important message here is that the optical component designer and the precision machining engineer need to communicate as early as possible in the design stage. This mutual consideration of all aspects of the design, production, mounting and testing of the component can save countless hours, problems and cost later on.

**Aspherics simplified**

Of all areas where precision machining can be applied, the production of aspherics undoubtedly holds the greatest potential for cost savings and technical impact on the electro-optics industry. Unlike polishing, precision machining produces aspherics as easily as spherics. The optical designer can now specify aspheric elements with the assurance that they can be economically and repeatably produced, provided, of course, they fall within the capability limits of precision machining. In addition, precision reference surfaces can be machined at the same time the optical surface is produced. These reference surfaces can then be used for mounting the optic mechanically or for aligning it optically.

To specify an aspheric element, for precision machining, the designer need provide only the mathematical description of the surface contour and the required accuracies. A microcomputer programming system is used to translate these specifications onto a control tape for the computer-controlled diamond lathe. With appropriate programming software, the time span from equation to finished aspheric surface can be very short. For the first time, this allows the optical designer to evaluate the aspheric design changes within a matter of hours.

Off-axis aspherics can also be precision machined with the individual elements fixtured off-axis within the diameter limitations of the machine. The ability of diamond-machining to handle interrupted cuts and yet not cause any "roll-off" makes this operation possible. Nonspherical surfaces, such as axicons, can be easily produced by precision machining. The axicons may be linear, nonlinear or even facetted (Figures 1 and 2). Angular tolerances on conical surfaces can be held to within 5 arc seconds.

**Polygons by flycutting**

Precision machining is very cost-effective in the production of optical polygons by diamond flycutting. These polygons are usually machined in aluminum (6061-T6 preferred), and any odd or even number of facets can be produced, although numbers of facets which are whole divisors of 360 tend to be easier to produce. Angular tolerances, particularly facet to reference face (pyramidal) should not be overspecified since tight tolerances on angles can increase production costs. The designer should, however, specify overall angle tolerances and permissible facet-to-facet angle variations.

Facet flatness can be typically controlled to one-quarter wave, and surface finish to 0.2 microinch $R_a$ is standard. Full-scale production of polygons can be accomplished with automated tooling and with stacking techniques, if angular tolerances permit. Again, as with aspherics, it is particularly important for the polygon designer to work with the diamond machining production engineers. Small changes in tolerances and part configuration can often lead to large cost savings.

### Cleaning, coating, handling

Since diamond-machined optical components are normally very soft compared to the glass optics that most designers are familiar with, specification of cleaning, handling, and shipping becomes critical. If the parts are to be used without an optical coating, a strippable plastic coating will help protect the surface during shipping. Otherwise the parts must be shipped in containers that do not touch the optical surfaces. Copper mirrors often require special shipping containers purged with dry inert gas to avoid surface damage from moisture and oxidation.

Any cleaning of precision-machined optics must be specified to be done only by extremely low-force or non-contact methods. If the optics must be cleaned in the field, the designer should consider specifying electroless nickel plating or a simple SiO or $SiO_2$ coating.

Enhancement coatings of gold, silver, or dielectric thin films can be applied to properly prepared diamond-machined surfaces. Plating and coating suppliers can now advise the designer on these subjects.

### How quantity affects cost

Precision machining can be cost-effective for both small and large quantities, depending on the part configuration and other considerations. The machining of any part requires proper planning of the methods, procedures, tooling and machines to be used. For many parts, there will be more than one machining and tooling approach, the one chosen usually being based on quantity and accuracy considerations.

Flat parts in prototype quantities can often be fixtured simply on universal vacuum chucks, with double-sided tape or other temporary adhesive means, or by careful mechanical clamping. For quantity production, multiple fixturing will enable a number of parts to be machined in one pass. For example, polygons can be stacked on a mandrel and diamond-flycut in multiples. To make the best of quantity production, the designer and machinist must work together, since production considerations often require redesign of the part so that it can be fixtured in multiples.

Aspherics require not only special holding fixtures but also their own computer program. Because these items are a one-time expense, they will naturally have a greater cost impact for single-piece or small-lot production. Machine setup for aspheric parts is also more involved than for flat parts — the cutting tool must be located precisely so that the computer program and the tool point are both correctly referenced to the spindle axis. But the hardware and software still raise the cost for small quantities.

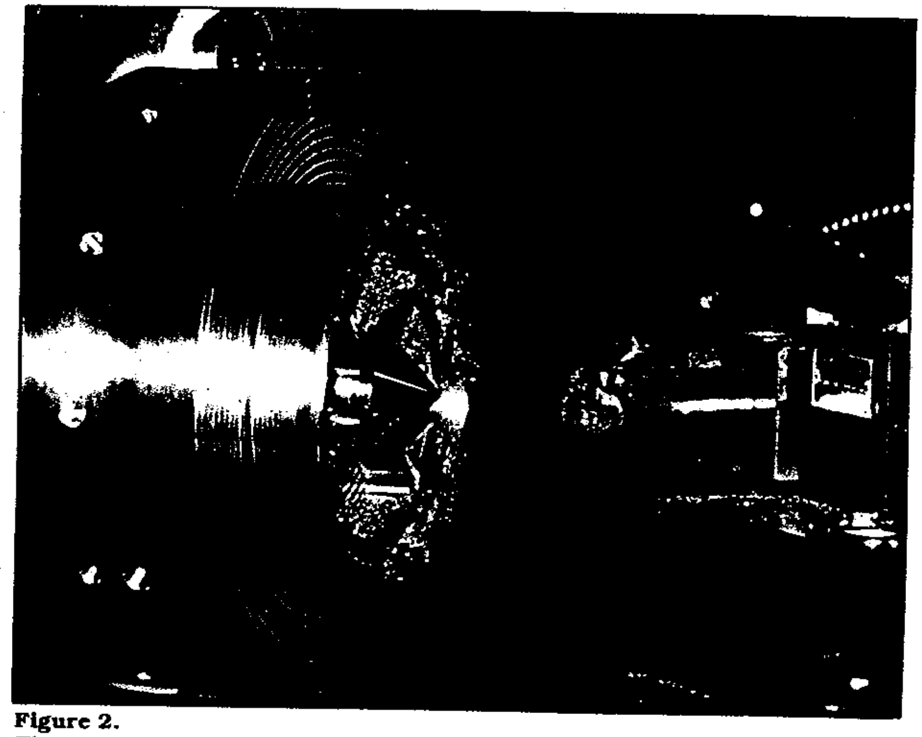

**Figure 2.**
*The internal element of a linear reflaxicon, finished completely by precision machining.*

### No cookbook yet for precision machining procedures

Precision machining of optics has not been around long enough to build up any extensive library or "cookbook" of procedures, tool angles, feeds, speeds, coolants, etc., for all the materials and geometries that can be cut. Therefore, there will be a learning curve for many parts until the optimum cutting parameters are established.

Accuracy requirements, particularly figure and geometric accuracy, have a large impact on the cost of machined optics, including the cost of parts inspection and of the fixturing and machining. To arrive at the true cost justification for machined optics, the designer must look at the entire optical system. Will metal optics permit weight reduction, higher spin speeds, integral mounts or alignment surfaces? Will they eliminate plating or coating? Will the use of machined aspherics reduce the number of elements and thus reduce centering problems? Will the higher laser damage threshold possible with diamond-machined optics be beneficial? Can the use of unconventional shapes (axicons, etc.) possible with machining improve the system? Only after the designer answers these system questions and compares cost/performance with conventional optics can the true value of machined optics for a given system be obtained. The designer must also remember that with precision machining, once the tooling and methods are established, large-quantity production of aspherics and polygons depends only on machine capacity.

Even when an analysis of costs for quantity production leads to another fabrication method, precision machining technology can play a role. Masters for replication can be diamond-machined, and the substrates for replication of aspherics are made by precision CNC (computer numerical control) machining. In the molding of plastic optics, too, precision machining is increasingly used to produce aspheric molds. Electroless nickel-plated molds can be cut with diamond tools, and stainless steel molds can be cut with CBN tools and then polished. The rapid turnaround time and low cost of a machined mold makes plastic molding a much more viable process, even for small quantities of optics.

Precision machining now stands among the proved fabrication methods available to the optics industry. The current equipment and training makes installation of an in-house precision machining capability feasible. In addition, a number of vendors are now prepared to offer contract optical machining. By understanding the strengths and limitations of the technology and learning to communicate with machining people early in the design program, the system and component designer can confidently specify the machined optics. □

**Meet the author**

P. Donald Brehm founded Pneumo [illegible]sion Inc. in 1962 and has been presi[illegible] and chief executive officer since that time. He earned his BSME degree from Rensselaer Polytechnic Institute. Mr. Brehm is a member of OSA, SPIE and SME, and is the author of many papers and lectures on precision machining and gaging.