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FABRICATION OF OPTICS BY DIAMOND TURNING*†

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10.1 GLOSSARY

- f feed rate
- h peak-to-valley height
- R tip radius of diamond tool

10.2 INTRODUCTION

The use of special machine tools with single-crystal diamond-cutting tools to produce optical surfaces on some metals and a limited range of other materials is called *diamond turning*. Over the last 50 years or so, diamond turning has matured to become the method of choice for producing some optical surfaces; in other applications, diamond turning provides a critical process step with radically different characteristics from most other optical fabrication methods.

In terms of geometry and motions required, the diamond-turning process is much like the step of "generating the optical surface" in traditional optical fabrication. However, the diamond-turning machine is a more sophisticated piece of equipment that produces the final surface, which frequently does not need the traditional polishing operation. The surface quality produced by the "best" diamond turning does not yet match the best produced by conventional polishing practice. The limits of diamond turning for both figure and surface-finish accuracy have not yet been reached—and diamond turning can be combined with postpolishing to improve surface finish and reduce scatter.[1] Also subaperture processing with small polishing tools or magnetorheological finishing (MRF) can be used to improve figure.

There are several important advantages of using diamond turning, including the ability to produce good optical surfaces to the edge of the element, to fabricate soft ductile materials that are difficult to polish, to eliminate alignment adjustments in some systems, and to fabricate shapes difficult to produce by other methods. The latest generation of diamond-turning machines incorporates up to five axes

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of computer-controlled motion, allowing for production of anamorphic optics. Use of form tools on multiaxis machines enables production of "structured" optical surfaces[2] ranging from subwavelength structures through diffractive/refractive infrared (IR) elements to optical component molds.

If the advantages of diamond turning suggest this fabrication method, then it is important to determine early in the design phase of a project whether the material specified is appropriate for diamond turning and whether slideway travels and linear and rotary axis controls are available on the diamond-turning machine to support fabrication of complex structures.

Sections in this chapter highlight the following:

- The diamond-turning process
- The advantages of diamond turning
- Diamond-turnable materials
- Comparison of diamond turning and traditional optical fabrication
- Machine tools for diamond turning
- Basic steps in diamond turning
- Surface finish of diamond-turned optics
- Metrology of diamond-turned optics
- Conclusions

10.3 THE DIAMOND-TURNING PROCESS

The diamond-turning process produces finished surfaces by very accurately cutting away a thin chip or layer of the surface. Thus, it is generally applicable to ductile materials that machine well rather than to hard brittle materials traditionally used for optical elements. However, by using a grinding head on a diamond-turning machine in place of the tool, hard brittle materials can be finished. At very small effective depths of cut, brittle materials behave in an apparently ductile manner. This attribute allows fracture-free grinding of glasses and ceramics as well as diamond turning of optical surfaces on materials such as germanium, zinc selenide, and potassium dihydrogen phosphate (KDP).

In diamond turning, both the figure and surface finish are largely determined by the machine tool and the cutting process. Note, however, that material characteristics such as grain size and inclusion size limit the ultimate surface finish achievable. The tool has to be very accurately moved with respect to the optical element to generate a good optical surface, and the edge of the diamond tool has to be extremely sharp and free of defects.

10.4 THE ADVANTAGES OF DIAMOND TURNING

Diamond turning fits within a broad spectrum of optics fabrication processes. When compared with traditional optical fabrication methods of lapping and polishing (see, for example, Chap. 9, "Optical Fabrication," by Michael P. Mandina) diamond turning has several advantages.

- It can produce good optical surfaces clear to the edge of the optical element. This is important, for example, in making scanners, polygons, special shaped flats, and when producing parts with interrupted cuts.
- It can produce optical surfaces on soft ductile materials that are extremely difficult to polish.
- It can easily produce off-axis parabolas and other difficult-to-lap aspherical shapes.
- It can produce optical elements with a significant cost advantage over conventional lapping and polishing where the relationship of the mounting surface—or other feature—to the optical surface is very critical. Expressed differently, this feature of diamond turning offers the opportunity to eliminate alignment adjustments in some systems.

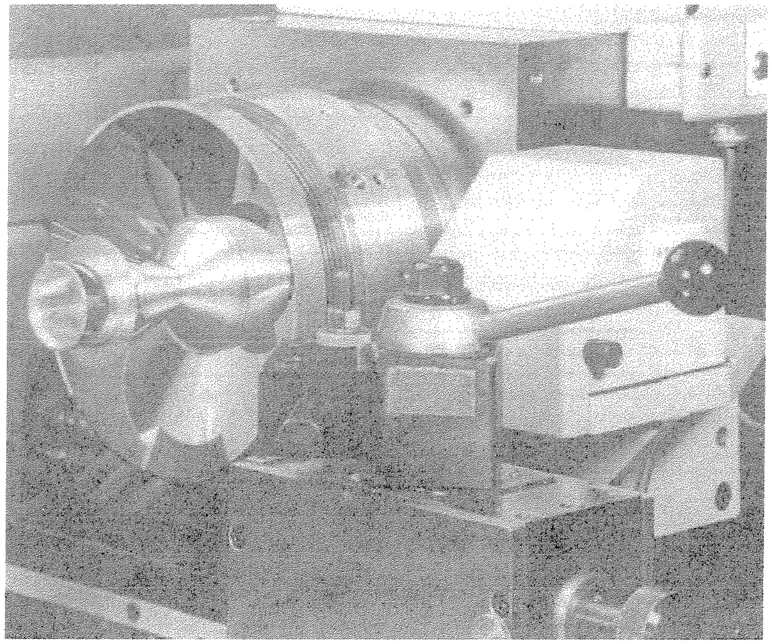


FIGURE 1 An axicon optical element being diamond turned. (*Courtesy of Rank Taylor Hobson, Keene, New Hampshire.*)

- It can fabricate optical shapes such as axicons, facetted optics, and grazing incidence X-ray optics that would be extremely difficult to fabricate by methods other than diamond turning (see Fig. 1).

Conflicts between optical requirements and diamond turnability on the one hand, and mechanical considerations on the other, often lead to the use of platings. Plating deficiencies, however, can cause as much trouble as poor bulk materials. For example, small changes in the composition of plated electroless nickel may cause dramatic changes in tool wear.[3]

Residual stress in the mirror blank, whether plated or not, can lead to changes in mirror shape with time. It is essential to pay careful attention to stress-relief prior to final diamond turning.

A decision to diamond turn an optical element, rather than fabricate it by the conventional polishing techniques, might be based on several different considerations such as type of element, size, and material. A general guide to different considerations in selecting diamond turning as a fabrication technique is presented in Table 1.

TABLE 1 General Guide to Optical Fabrication Methods

Size, m	Shape	Material	Preferred Method
Less than 0.5	Flat or sphere	Glass/ceramic	Polish
		Ductile metal	Diamond turn
	Asphere	Glass/ceramic	Grind/polish*
		Ductile metal	Diamond turn
0.5 to 2.0	Any axisymmetric	Ductile metal	Diamond turn†
Greater than 2.0	Any	Any	Large polishing machine

*Can generate shape or figure on a diamond-turning machine with a grinding head replacing the diamond tool. Subaperture polishing techniques, including techniques such as MRF, may be applied to advantage.

†Diamond-turning machines up to 2-m diameter have been built.

As indicated above, diamond turning has some unique characteristics. In some IR (and even visible) imaging systems, considerable improvements in optical performance have been obtained by combining a refractive aspheric surface and a diffractive surface in a single element. For IR applications, it is hard to produce such a component by any other fabrication process; for visible applications, such optics can be produced in volume from diamond-turned molds.

Another unique capability of diamond turning is to provide datums or alignment features machined in the same setup as the optical surface. "Snap-together" optical systems requiring no alignment adjustments after assembly are very attractive in some applications.

Over the last decade, there have been considerable advances in the ability to produce aspheric optics using computer-controlled generators and pad polishers. These technologies, combined with ion polishing, magnetorheological finishing, and computer-controlled polishing have enabled a new generation of aspheric optics. Ultimately the choice of manufacturing process requires a careful analysis of the options and the system requirements.

10.5 DIAMOND-TURNABLE MATERIALS

Selection of appropriate materials is, necessarily, a trade-off between application-specific requirements and optimization of the manufacturing process. This trade-off may drive the selection of a plated surface, for example, or the choice of fabrication steps.

Historically materials have been described as either "diamond turnable," or not, as if this were an inherent material property. This shorthand covers two different situations. One is that, in practice, some materials cause very rapid wear of the diamond; for example, it is widely known that ferrous materials cause rapid tool wear. The other is that, particularly for certain plastics, tool-workpiece interactions produce unacceptable optical surfaces.

A number of listings of diamond-turnable materials, such as the one included in Table 2, have been published. Such listings should be treated with caution. Typically, they are incomplete and do not provide sufficient information on the materials that are listed. For example, good optical surfaces are not generally produced on all aluminum alloys: Aluminum Alloy 6061 (Aluminum Association, Inc. designation) is the most commonly used alloy, although certain 5000 series and 7000 series alloys have their proponents, and 2024 aluminum has been used but, in general, does not produce the best surfaces.

TABLE 2 Diamond-Turnable Materials

Metals	Nonmetals	Plastics
Aluminum	Calcium fluoride	Polymethymethacrylate
Brass	Magnesium fluoride	Polycarbonates
Copper	Cadmium telluride	Polyimide
Beryllium copper	Zinc selenide	
Bronze	Zinc sulphide	
Gold	Gallium arsenide	
Silver	Sodium chloride	
Lead	Calcium chloride	
Platinum	Germanium	
Tin	Strontium fluoride	
Zinc	Sodium fluoride	
Electroless nickel	KDP	
	KTP	
	Silicon	

Similarly, gold is considered diamond-turnable, but problems have been reported machining large gold-plated optics. Conventional electroplated nickels (and bulk nickel) give rapid tool wear, but electroless nickel with phosphorous contents above about 10 percent, if appropriately heat treated, can be machined effectively.[4] Higher phosphorous contents (up to 15 percent) are obtainable in electroplated nickel[5,6] which also machines extremely well. Both materials are metastable and will transform—with exposure to the necessary time/temperature conditions—to a mixture of crystalline nickel with hard phosphides. This transformation is accompanied by a volume change, a degradation of optical characteristics of the surface, and a dramatic increase in tool wear.

Platings may also be optimized to give low ductility and hence minimum burr formation when machining Fresnels or the molds for micro-optics arrays such as arrays of retroreflectors. Platings over a diamond-turned sacrificial mandrel allow production of otherwise unobtainable forms. Plated surfaces, however, have characteristics which can adversely affect both fabrication and application; at some level the resulting structure is a temperature-sensitive bimetal strip. Pits and inclusions can cause significant fabrication issues.[7]

Silicon, although included in the listing given here, should be considered marginal as tool wear can be high. Reasonably large areas of amorphous silicon cladding are reported to have been successfully machined.

Over the last decade or so there have been significant advances in understanding of diamond tool wear. Mechanisms associated with abrasion and chipping typically provide one limit to diamond tool life. For example, when machining bulk aluminums the interactions between hard inclusions and the diamond tool clearly lead to wear. Such mechanisms, however, do not explain the very rapid wear observed when machining soft, high-purity iron.

Paul et al.[8] showed that machining metallic elements containing unpaired *d*-shell electrons results in catalyzed reactions between diamond and the work material. The same mechanism explains the role of phosphorous in electroless nickel and led to a recent breakthrough by Brinksmeier et al.[9] They showed that, like phosphorous, nitrogen in a nitride surface layer on steel combines with the unpaired *d*-shell electrons from the iron. The result is a dramatic reduction in tool wear, suggesting that diamond-turned steel molds (e.g., for plastic optics) may become practical in the near future. Previous approaches—such as diamond turning at cryogenic temperatures[10] or in methane or acetylene environments[11]—provided evidence of the mechanisms at work but were not widely adopted (and in the case of cryogenic machining was not intended by the original researchers to be practical).

For a number of years, Moriwaki[12] has been developing ultrasonic-assisted machining, including cutting when the tool is vibrated with an elliptical motion. Significant reductions in tool wear have been demonstrated, although the mechanism remains controversial. The amplitude and frequency of oscillation in the cutting direction are generally selected such that separation between the rake face of the tool and the chip is expected. In this case, one might postulate poisoning of the catalytic process by, for example, hydrocarbon-based cutting fluids. Elliptical motion would also move the clearance face out of contact. Other measurements show significant reductions in cutting forces,[13] suggesting a reduction of tool temperatures.

In case of some plastics, recent work by Gubbels et al.[14] shows that the chemical explanations of Paul et al.[8] do not apply, but that triboelectric effects dominate. In general, there are some suggestions that parameters, such as surface speed, are more important for successful diamond machining of plastics than for metal and crystalline substrates. Some plastics are diamond turned in volume production.

Other material characteristics, in addition to the material composition, are important. For example, large grain size results in a more pronounced "orange peel" as tools become dull and the variation in modulus of the different grain orientations leads to different deflections due to cutting forces. Residual stresses can relax over time and cause changes in figure. Because of these types of problems it is important to involve experienced personnel early in the design phase[15] to ensure that the material specified is appropriate. In some projects, the part is so valuable and/or so difficult to produce by other techniques, it is worth consuming tools more rapidly than would normally be acceptable. However, such a decision should be taken consciously, not by default late in a project.

10.6 COMPARISON OF DIAMOND TURNING AND TRADITIONAL OPTICAL FABRICATION

In diamond turning, the final shape and surface of the optic produced depend on the machine tool accuracy, whereas, in traditional optical fabrication, the final shape and surface of the optical element depend on the process variables involved with using an abrasive-loaded lap. The differences between diamond turning and traditional optical fabrication can be summarized by describing diamond turning as a displacement-controlled process versus a force-controlled process for traditional optical fabrication.[16] The goal in diamond turning is to have a machine tool that produces an extremely accurate path with the diamond tool, hence a displacement-controlled process. A traditional polishing machine used for optical fabrication depends on the force being constant over the area where the abrasive-loaded lap—or tool—touches the surface being worked. Selective removal of material can be produced by increasing the lap pressure in selected areas or by use of a zone lap. The stiffness of a diamond-turning machine is important because, to control the displacement, it is important that cutting forces and other influences do not cause unwanted displacements. Feeds, speeds, and depth of cut are typically much lower in diamond turning than conventional machining, thus giving lower forces. However, the displacements of concern are also much lower. Thus the stiffness required is as much, or more, of a concern than conventional machining even though the total force capability may be lower for diamond turning.

10.7 MACHINE TOOLS FOR DIAMOND TURNING

In general, the machine tools used for diamond turning are very expensive compared to the equipment needed for traditional optical fabrication. The positioning accuracy required for diamond turning is beyond the capability of conventional machine tools, thus some of the first widely adopted diamond-turning machines for fabricating optics were modified Moore measuring machines.[17]

Although there are some records of machine tools being used to generate optical surfaces as early as the seventeenth century, most of the effort is modern, accelerated in the 1960s and 1970s with the advent of computer-based machine tool controls and laser interferometer systems used as positional feedback devices. Evans[18] has documented much of the history of diamond turning and provides an extensive reference list. Ikawa[19] summarizes some of the research in metal cutting related to diamond turning and associated machine tools.

The early diamond-turning machines were two-axis lathes that could produce axisymmetric optical elements. With recent advances in computer-based control systems, and improved motion control and feedback sensors, multiaxis diamond-turning machines have become readily available. Two commercial diamond-turning machines are shown in Fig. 2. Both machines can be configured with five-axis motion control combining both linear and rotary axes. Measuring scales have replaced the laser interferometers in many diamond-turning machines and give a very reliable positioning feedback system at lower cost.

Programming of these multiaxis machines draws on the technology developed in precision machine shops for large five-axis machine tools used to make complicated parts. By adapting the multiaxis control to diamond-turning machines, a great variety of shapes can now be diamond turned which opens up the process to many new optical applications. Before judging an optical element shape to be unsuitable for diamond turning, a manufacturer of modern diamond-turning machines should be consulted.

Producing nonaxisymmetric parts—such as an off-axis parabola machined while centered on the rotating axis—has become possible with fast tool servos. These systems can rapidly move a cutting tool a short distance coordinated with the rotation of the spindle.[20] There are also cases where the machine's slideways or rotary motions can be used to produce nonaxisymmetric parts.

Many diamond-turning machines are used in the traditional turning lathe mode where the workpiece turns and the tool is held stationary in the tool post. Most diamond-turning machines can also be configured such that the tool rotates about the spindle axis—commonly called fly cutting—to produce components such as long flat mirror surfaces or other milled surfaces.

10.8 BASIC STEPS IN DIAMOND TURNING

Much like the traditional optical-fabrication process, the diamond-turning process can be described as a series of steps used to make an optical element. The steps used in diamond turning are

1. *Preparing the blank* with all the required features of the element with an extra thickness of material (generally 0.1-mm extra material or plating is adequate) on the surface to be diamond turned
2. *Mounting the blank* in an appropriate fixture or chuck on the diamond-turning machine
3. *Selecting the diamond tool* appropriate for the material and shape of the optical component
4. *Mounting and adjusting the diamond tool* on the machine
5. *Machining the optical surface* to final shape and surface quality
6. *Cleaning the optical surface* to remove cutting oils or solvents

Mounting the optical element blank on a diamond-turning machine is extremely important. If a blank is slightly distorted in the holding fixture, and then machined to a perfect shape on the machine, it will be a distorted mirror when released from the fixture. Therefore, fixtures and chucks to hold mirrors during diamond turning need to be carefully designed to prevent distortion. Often the best way to hold a mirror during machining is to use the same mounting method that will be used to hold the mirror in service.

It is advantageous in many applications to machine a substrate of aluminum or copper and then add a plating to be diamond turned. The design and application of platings is part science and part art. Many aspects of the platings as related to diamond turning were covered at the ASPE Spring 1991 Topical Meeting.[7]

Tool setting—the mounting and adjusting of the diamond-tipped cutting tool—is often accomplished by cutting a test surface, either on the actual mirror blank to be later machined over, or by placing a test piece on the machine just for tool setting. If the cutting tool is too high or too low, a defect at the center of a mirror is produced. It is possible, using reasonable care and patience, to set the tool height within about 0.1 μm of the exact center. Setting the tool in the feed direction after the height is correct is somewhat more difficult. For example, an error in setting will produce an ogive shape rather than a sphere which is not obvious until the figure is measured. Gerchman[21] describes these types of defects.

The selection of the tool for diamond turning is important. Large cutting tip radii (2 mm or greater) are often used when producing flats, convex, or concave mirrors with large radius of curvature. However, small-radii diamond tools are available (in the range of 0.1 mm) for making small deep mirrors or molds. Tools with special geometries, including so-called "dead sharp" tools, can be obtained for such applications as Fresnel lenses or retroreflector arrays. In general, approximately 0° rake tools, with about 5° or 6° front clearance, are used for diamond-turning ductile metals. Negative rake tools are often good for crystalline materials and positive rakes may be beneficial when machining some plastics. The cutting edge has to be chip free to produce a good diamond-turned surface. A normal specification for edge quality is "chip free when examined at 1000×." The edge sharpness is a concern for very small depths of cut—especially where the depth of cut is close to the cutting edge sharpness—because the cutting forces increase and more of a plowing than a cutting process occurs. The effect of cutting edge sharpness has been investigated by researchers, for example Lucca, et al,[22] however, there is currently no convenient way to specify and inspect tools for edge sharpness.

The orientation of the diamond itself on the shank is of concern because the single-crystal diamond is anisotropic. The orientation of diamond tools has been studied, for example, by Wilks,[23] Decker,[24] and Hurt.[25] It is necessary for the tool manufacturer to mount the diamond so that it can be shaped to the required radius and produce a good cutting edge. The usual orientation for diamond tools is with the cleavage plane parallel to the rake face.

The actual diamond turning, or machining to final size and surface finish, is often the fastest part of the process. The machine-tool controller has to be programmed to move the tool along the correct path, the chip-removal system has to be positioned, and the cutting-fluid applicator needs to be adjusted to provide consistent clean cutting.

For machining of flats and spherical surfaces, the part programs that define the machine motion are straightforward. But when cutting aspherical surfaces, caution has to be exercised so that the radius of the tool is properly handled in calculating the tool path. Modern computer-aided design (CAD) systems perform the necessary calculations, but tests should be performed prior to cutting a difficult or expensive component.

In general, the cutting speeds for diamond turning are similar to those used for conventional machining: less than 1 m/min to more than 100 m/min. However, the slower cutting speeds produced by facing to the center of a workpiece do not affect the surface finish in diamond turning as is often the case with nondiamond tools. Thus, varying the spindle speed to keep the cutting speed constant is not necessary in diamond turning. The upper speed for diamond turning is often limited by the distortion of the optical element due to inertial forces, especially for larger elements. The upper spindle speed can also be limited due to any unbalance of the workpiece and fixture. The feed rate in diamond turning is usually adjusted to give a good theoretical surface finish. (See the following section.)

Cleaning of diamond-turned optics has a lot in common with cleaning conventionally polished optics. But because many of the diamond-turned elements are of soft metals, caution has to be exercised to prevent scratching. In general, a degreaser is used (soap or solvent), followed by a rinse in pure ethyl alcohol. The drag-wiping technique traditionally used on some glass optics can be used on some diamond-turned elements. Care must be taken to ensure that the lens tissue is very clean and remains wet. Some work has been done to study the best solvents to use for cleaning diamond-turned optics from an environmental-impact standpoint.[26]

10.9 SURFACE FINISH OF DIAMOND-TURNED OPTICS

The surface structure is different for diamond-turned surfaces as compared with conventionally polished surfaces. A diamond-turned surface is produced by moving a cutting tool across the surface of the turning component, such as the facing operation illustrated in Fig. 3. Therefore, diamond-turned elements always have some periodic surface roughness, which can produce a diffraction-grating effect, whereas polished optical surfaces have a random roughness pattern. The traditional "scratch and dig" approach to describing surfaces is not meaningful for diamond-turned surfaces.

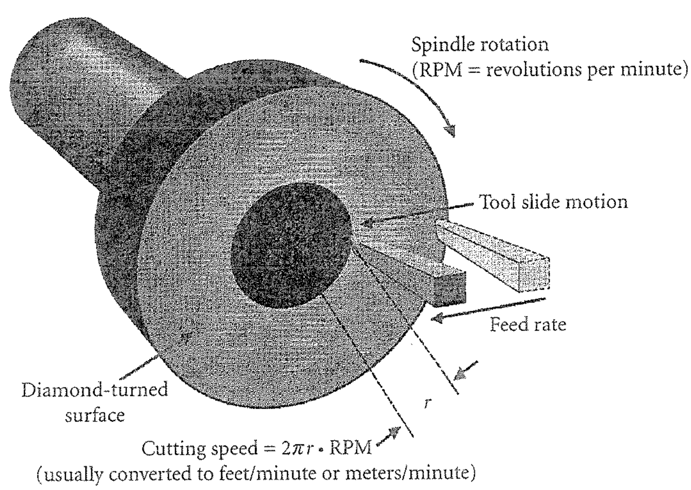


FIGURE 3 Diamond turning an optical element.

The machining process produces a periodic surface structure directly related to the tool tip radius and feed rate. The theoretical diamond-turned surface is illustrated in Fig. 4. The formula displayed in the figure for calculating the height of the cusps is

$$h = \frac{f^2}{8 \cdot R} \tag{1}$$

where h = peak-to-valley height of the periodic surface defect
f = feed per revolution
R = tool tip radius

For example, if a surface is diamond turned using a spindle speed of 31.4 rad/s (300 rpm), a feed of 7.5 mm/min, and a 5.0-mm tool tip radius:

$$h = \frac{(7.5/300)^2}{8 \times 5} = 1.56 \times 10^{-5}\,\text{mm}$$

$$h = 15.6\ \text{nm} \tag{2}$$

In addition to the "theoretical finish" based on cusp structure, the measured surface finish on diamond-turned parts is influenced by other factors.

- Waviness within the long-wavelength cut-off for surface measurement may be correlated, for example, with slide straightness errors.
- Asynchronous error motions of the spindle can cause surface defects. If, for a given angular spindle position, there is nonrepeatability in axial, radial, or tilt directions, these errors will transfer into surface structure. Details of spindle errors are important in diamond turning. Further information can be found in the "Axis of Rotation Standard."[27]
- External and self-induced vibration, not at the spindle frequency or at one of its harmonics, can have the same effect on finish—measured across the lay—as asynchronous spindle motions.
- Materials effects such as the differential elastic recovery of adjacent grains can cause steps in the machined surface that have an appearance commonly referred to as "orange peel." Impurities in the material can also degrade surface finish.
- Within each cusp, there can be a repeated surface structure related to chips in the edge of the tool.

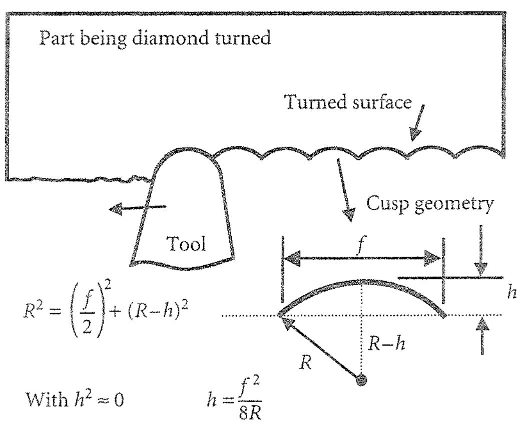
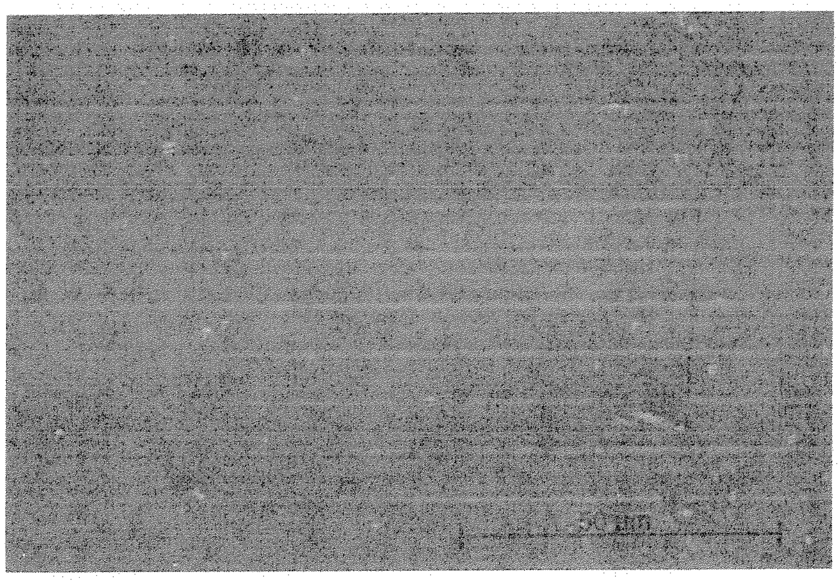
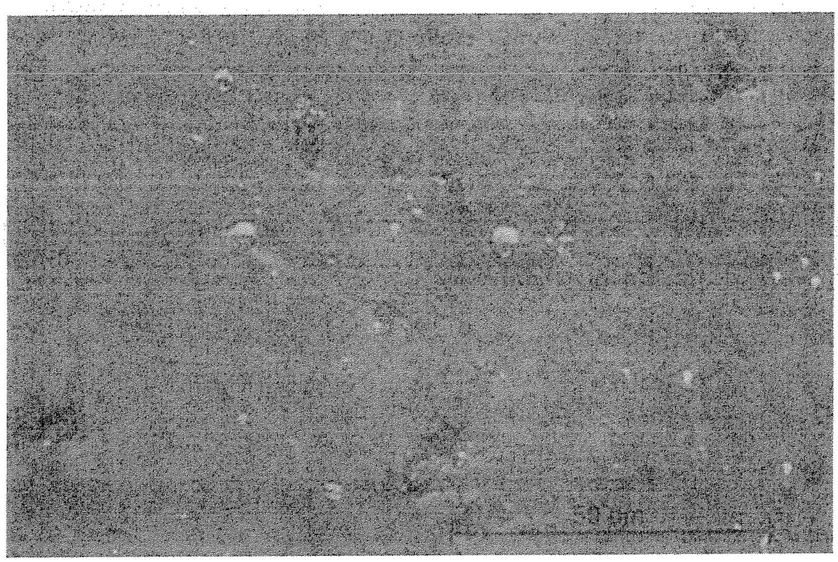


FIGURE 4 "Cusp" surface of diamond-turned optical element.

The Nomarski microscope is an excellent means of qualitatively evaluating diamond-turned surfaces. The Nomarski photo in Fig. 5*a* illustrates the periodic structure of a diamond-turned surface. The feed rate used in producing the surface causes the wavelength of the periodic structure to be about 8 μm. Figure 5*b* illustrates other defects in the diamond-turned surface when the Nomarski microscope is adjusted such that the periodic cusps are not seen.[28]



(a)



(b)

FIGURE 5 Nomarski micrograph of a diamond-turned aluminum alloy (*a*) aligned so that the grooves can be seen and (*b*) aligned so that the grooves are canceled. (*From Bennett, p. 84.*[28])

10.10 METROLOGY OF DIAMOND-TURNED OPTICS

In general, measurement of diamond-turned optics is similar to the measurement of any other optic; figure, midspatial frequency errors, transmitted wavefront, and surface roughness may all need characterization, depending on the specification. As with other optics, the choice of figure metrology is driven by the optical surface itself. Classical null tests—especially autocollimation tests for parabolae and the related tests for other conics—are widely used. Over the last decade or so, use of in-cavity holograms in Fizeau tests has increased. What remains elusive is a general test. Over a limited range of surfaces, subaperture stitching[29] may be viable or, for circularly symmetric aspheres, zonal stitching.[30] Kuechel[31] described a zonal technique that uses only the zone of null data and, hence, is free of retrace errors and applicable to a range of aspheres without the need for null optics. An instrument based on this technique is shown in Fig. 6.

One area in which diamond turning differs from conventional optics production is that the machine itself can be used as a measuring machine. The diamond tool can be replaced with an appropriate sensor (such as a capacitance sensor, air bearing linear variable differential transformer (LVDT), optical triangulation sensor, etc.) or the sensor can be built into an auxiliary mount. With sufficient care,[32] the geometric errors of the machine can be mapped so that the limits in the metrology are the uncertainties associated with probing and with the environment. This approach is particularly advantageous when making (and measuring) radical aspheres or discontinuous, structured surfaces[2] such as molds for facetted automotive lighting. On multiaxis machines, it is sometimes more useful to use a different combination of axes for metrology than for machining to better decouple machine geometry errors from measurement uncertainty. For example, on a diamond-turning machine with a B axis (rotary table), near hemispheres and some aspheres can conveniently be machined using only the x and y axes, with measurement of the departure from a best-fit sphere performed using a separate probe mounted on the rotary table.

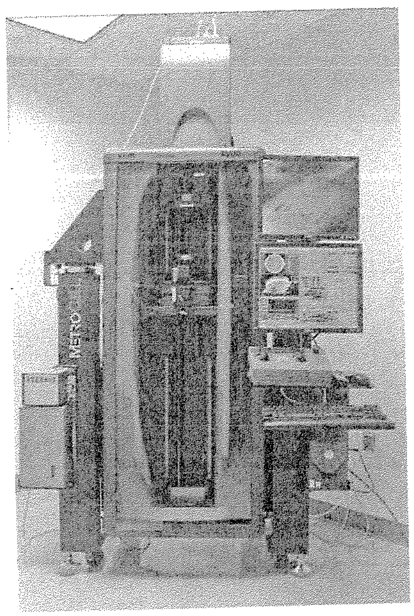


FIGURE 6 Aspheric measuring system. (*Courtesy Zygo Corporation, Middlefield, CT.*)

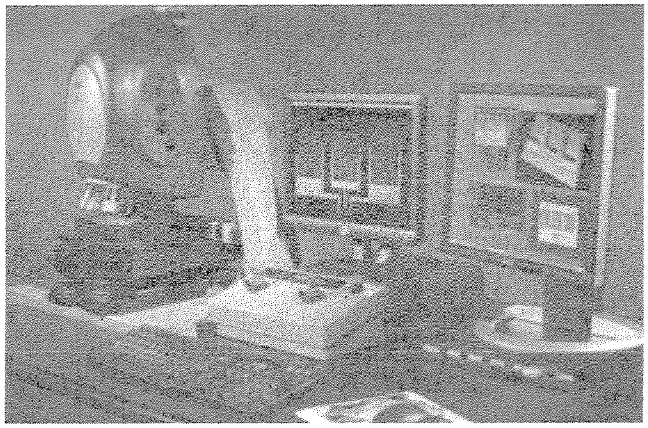


FIGURE 7 Microinterferometer. (*Courtesy of Zygo Corporation*).

There is little practical difference between measuring optical surfaces produced using traditional methods and by diamond turning. It is worth bearing in mind, however, that during diamond turning there is usually a monotonic progression in cutting from outside diameter to inside diameter or vice versa; hence, diamond tool wear or small edge nicks will cause a degradation in finish that depends on position on the part. The surface finish measurement sampling strategy should be adjusted accordingly. Surfaces produced using traditional 2-axis or 3-axis diamond-turning have significantly different characteristics along and transverse to the lay; scattering is isotropic, a characteristic that should be considered in both the specification and metrology of diamond-turned optics. Four-axis and 5-axis machining using methods akin to milling produce cusp structures usually at different spatial wavelengths in both directions.

Microinterferometers (Fig. 7) have become the tool of choice for characterizing optical surfaces at spatial wavelengths down to the limits posed by the instrument transfer function.[33] Microinterferometers—particularly those using scanning coherence techniques frequently referred to as scanning white light interferometry (SWLI)—can be useful, provided the surface slopes and lateral extent are compatible with the available numerical aperture of the objective and the field of view. Replication—for example, using dental replica materials, silicone-based caulks, two-part epoxies, and the like—allows sampling of large surfaces, although there is inevitably some increase in "noise" due to the replication process.

Higher spatial frequency structured surfaces, such as retroreflectors or other micro-optic arrays,[34] often pose metrology challenges for which there is no general solution.

10.11 CONCLUSIONS

Diamond turning has been used for many years to commercially produce infrared optics. Some visible and ultraviolet applications are now possible. Moreover, the limits of diamond turning for both figure and surface finish accuracy have not yet been reached. Taniguchi[35] and others have shown that precision in both conventional machining and ultraprecision machining, such as diamond turning, has steadily improved for many decades, with roughly a factor of three improvements possible every 10 years. If this trend continues, we could expect diamond-turning machines with accuracies below 10 nm and even approaching 1 nm by the year 2020. Yet, it is important to remember that it becomes increasingly difficult to push the capabilities in this regime—nor is it clear that it is cost effective to do so. Other manufacturing techniques may be more appropriate for production of the highest quality optics.

The technology developed for diamond-turning optics in some industries is now beginning to impact the precision machining of nonoptical components. In the future, the improvement of all machine tools will likely be driven by both optical and nonoptical applications, with diamond-turning machines possibly reaching the accuracy level that will allow visible and ultraviolet optics to be fabricated by machining or grinding without postpolishing.

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