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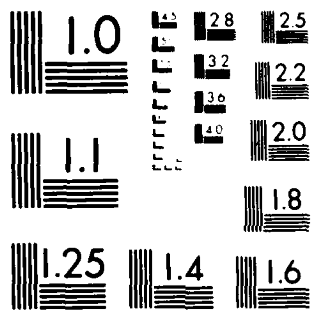

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Precision Machining application and technology: an overview and perspective *

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Abstract

After presenting a rule of thumb to evaluate the economical benefit of diamond turning compared to conventional polishing, applications of spinner mirrors, injection molding masters, and X-ray optics are discussed. Non-optical applications are included as well as precision grinding materials incompatible with diamond turning. KEY WORDS: Diamond Turning, Precision Machining, Precision Grinding, Quartz Grinding, X-ray Optics.

Introduction

Diamond turning precision machining of optics is now an accepted method of optical fabrication[1]. Department of Defense commercialization efforts have paid off with enhanced commercial capabilities and stimulated interest.

Diamond turning is actually a sub-set of precision machining. This paper will primarily describe applications of diamond turning. It begins with a rule of thumb to help evaluate when diamond turning is more economical than conventional optical processing. Next, specific applications of spinner mirrors, injection molding master, and X-ray optics are discussed. Non-optical applications of diamond turning give further ideas of the value of this precision technology. Finally, precision grinding of materials incompatible with diamond turning will be discussed including some interesting Japanese results on quartz.

Economies of diamond turning

One must exercise care in selecting diamond turning over conventional optical processes. I propose the following rule of thumb which will be helpful when trying to decide whether diamond turning is more economical than conventional optical processing.

Rule of thumb

Diamond turning is more economical than conventional optical processing for: (1) aspherics, (2) for situations with unusual geometrical constraints such as (a) center, (b) angles, (c) repeatability and (d) absolute size, (3) materials difficult to polish and simultaneously achieve finish and figure.

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A current application of diamond turning which exemplifies several aspects of my rule of thumb is the diamond turning of 27 cm x 27 cm x 1 cm KDP frequency doublers by P. Baker of Pneumo West for the Lawrence Livermore National Laboratory. The requirement for a 80 A rms surface finish simultaneously with less than a half-wave in the visible wavefront distortion presented an inordinately difficult polishing problem. In addition to being very soft, KDP is anisotropic with a biaxial thermal expansion coefficient. Therefore, a cylinder often resulted during the polishing.

The KDP also had very demanding angular, absolute geometry, and repeatability requirements. The KDP had to be phase matched, i.e., have its laser propagation axis aligned within five micro-radians of the optimum orientation to give maximum frequency conversion efficiency. The thickness had to be repeatable to within one micrometer. The initial order of 82 samples (20 of them will be used for the Phebus system) are excellent candidates for diamond turning.

Baker has reported some interesting results from his initial diamond turning of the material. Based on his experience from the DARPA-sponsored machining of glass effort[2], he has devised machining parameters to achieve the required accuacies. He feels that a cracking mechanism rather than a ductile material removal is involved. The cracking mechanism is due to the high compressive loads resulting from the machining parameters used. Although he has observed no tool edge wear, he has seen tool top erosion extending at about a 120° angle from the contact point.

Spinner mirrors

Wilson has declared that "precision diamond machining of optics has brought multifacet laser scanners into the realm of economic and technical feasibility[3]." He describes an interesting ten-faceted mirror fabricated from a single piece of 6061 T6 aluminum by Professional Instruments. The air bearing spindle rotor and mirror were diamond fly cut from the same piece. The 12 x 16 mm facets were flat to approximately 20th wave in the visible, the pyramidal static error was 3.5 arc-seconds and pyramidal dynamic error at 12,000 rpm was just under 4 arc-seconds. The resolution of the test method was less than 0.5 arc-seconds. Wilson felt precision-machined multifaceted spinners would be best used to satisfy requirements for high-angular repeatability and high speed such as for laser recorders, facsimile printers, laser scanners, high-speed cameras, commercial film scanner, spatial light modulator addressors, and automated inspection scanners.

Diamond turning molds for injection molding optics

Injection molding offers significant economical leverage because of its compatability to mass production coupled with accuracy reproducibility required for optical tolerances. Weeks and Ford have reported interesting work at Polaroid of injection molding lenses for cameras. Lytle of MU

Engineering reports they can hold figure to better than 1 fringe in the visible, radius within 0.2%, and center to 0.001" (2.5 E-2 mm) for lenses of approximately 1" (25 mm) diameter. Lytle's results are especially encouraging to the optical designer since the results are relatively insensitive to the f-number of the lens. In fact Lytle has found that faster lenses hold the tolerances easier than slower ones because the increased surface tension improves the optical quality of the injection molded lenses.

Injection molding combined with diamond turning offers a whole new freedom to optical designers. Diamond turning can make the molds to almost any figure of revolution. Lytle draws the powerful analogy that constraining an optical designer to spherical surfaces is akin to constraining the electrical engineering designer to using ONLY 1 megaohm resistors, 5 picofarad capacitors, and 10 millihenry inductors. Although the job can be done, the results are often cumbersome and surely not optimum.

Lytle showed me a striking example demonstrating the advantages of plastic optics including impressive capabilities. He had a 6-element lens assembly demonstrating less than 1/2 fringe single-pass abberation capable of resolving 300 line pairs per mm. The lenses were made using molds that had been diamond turned and no post-polishing was required. I was impressed with the quality of the image as well as the assembly's lightness. Lytle mentioned that the assembly designed to hold the original glass set didn't operate as well because of the lightness of the plastic set!

Let's consider some of the advantages of injection molded plastic ashperes. (Some of these benefits are obviously generic to aspheres vs spheres, and are not constrained to just injection molded plastics.) One can get better performance with the same number of surfaces. A corollary to this is that one can achieve the same performance with less surfaces. Because of these first two advantages, coupled with the lighter density of plastic compared to glass, lighter weight systems are possible.

Mr. Red Smathers, of the Army Night Vision Electro-Optics Lab, inspired and led a cooperative effort including the Lawrence Livermore National Laboratory (LLNL), Materials Laboratory of the Air Force Wright Aeronautical Laboratories, and MU Engineering. Smathers had an aspheric designed for use in both the objective and in the eye piece of a night vision goggle. The design was compromised so that two of these lenses could be used in both the objective and the eye piece. Better performance would have resulted from designing four different aspheres, two for the objective and two for the eye piece. The 15 mm diameter lens was very aspheric (mm's of asphericity) on one side and spherical on the other. The insert molds were diamond turned by LLNL in electroless nickel. MU Engineering did the injection molding.

Qualitative tests of the molded optics were performed by replacing nine glass elements in the objective with the two injection molded plastic aspheres. There was no difference in the performance as observed by the naked eye. Similar results were obtained when replacing 5 elements in the eye piece with two aspheres. MTF measurements at 40 line pairs/mm showed an improvement by the plastic lens set over the 0.6 value obtained for the glass elements in the objective.

Another interesting advantage of aspheric surfaces is desensitizing the assembly tolerances. I was surprised when Lytle told me that since abberations per aspheric surfaces are markedly lower per surface than for spherical surfaces, decentering errors per abberation are less for asphericss.

A final advantage that we consider here is that improved repeatability results in higher yield. There are several manifestation of this advantage. The first is obviously cost. The second is availability and the flexibility to get many systems up quickly. Time wasted waiting for parts to be delivered can be reduced. Production time is also significantly reduced because of the mass production nature of the injection molding process. However, it must be remembered that this time advantage can be lost if extended time to get the molds is required because of the lack of diamond turning or other economical and quick processes to manufacture and test them.

With all the advantages of injection molded plastic optics, why are they not used more? There are some applications where glass must be used, e.g., chemical resistance. (Properties of plastics are being improved. Laser damage resistance comparable to glass has been reported[4].) Also, there are some technical disadvantages to aspheres, such as the cascade effect of slope errors being more sensitive than in the case of spherics. When only a few components are needed injection molding is not economically competitive.

Another hindrance to the optimum use of injection molded aspheres is the heavy influence of "spherical surface" design mentality on current design software. It has been suggested that a set of software be designed to use aspheres more optimally, rather than as an afterthought to improve a spherical surface design.

Availability of diamond turned molds (sometimes called "pins" or "inserts") is also a hindrance to proliferation of aspheric injection molding technology. High cost of establishing your own machine as well as availability of someone elses machine limits availability. Some of the more recently developed diamond turning machines combining spherical and linear motion may significantly reduce the cost of diamond turning machines[5] so that they can be economically feasible for injection molding firms. I feel that the on-site location of this capability will synergistically produce a wide range of designs and applications.

However, probably the greatest hindrance to proliferation of this technology is the conservative nature of the optics designer and industry to avoid risk. The major problem may be more psychological than technical. A similar problem was faced by diamond turning optics in its early stages. One of the greatest ways of overcoming this conservatism has been the demonstration of the economical benefits and, therefore, a market edge which has driven firms into utilizing diamond turning. Perhaps such a series of events shall catapult injection molding of aspheres into a position of greater importance in optics.

X-ray optics

X-ray optics are also ammenable to diamond turning[6]. Because of the grazing incidence angles, circularity easily achieved by precision air bearing spindles makes diamond turning attractive. Wills-Moren and his co-workers at the Cranfield Unit for Precision Engineering (CUPE) have described their diamond turning machine incorporating a 1.5 m diameter air bearing rotary table, plain guideways and a rolling element guideway[7]. P.A. McKeown is associated with this work. Requirements for the telecope (0.97 entrance diameter, 1.5 m long composed of three internal paraboloid section and one external hyperpoloid) include a waviness of the axial profile less than 6 nm over a 30 mm length, conicoidal figure accuracy to 1 µm, and circularity better than 1 µm. Whereas the waviness would be satisfied by post-polishing, the diamond turning machine is expected to meet the remaining requirements.

CUPE's machine base is a 5 x 2.6 x 1.6 m lightweight steel weldment filled with synthetic granite (granitran S-100) incorporating a vertical workspindle and a boring bar system mounted on the vertical Z carriage. The capacity of the machine is: 1.4 maximum external diameter, 1.2 maximum internal diameter, 0.25 m internal diameter and maximum axial length of 0.6 meter. The displacement and measuring system incorporates a Hewlett Packard 5501 laser for servo control of the X-axis, error reduction for not-straightness of motion of the Z carriage and for the planned in-situ metrology system.

Non-optical applications of diamond turning

A significant portion of precision diamond turning lathes are being used to produce computer discs. Bryant Symons, an English firm, has reported diamond turning an aluminum computer disk at 1,500 rpm, with a feed rate of 0.076 mm (0.003") per revolution at a maximum surface speed of 1675 meters/minute[8]. The surface finish was better than 0.01 micrometers Ra, measured on a Talysurf profilometer. Diamond turning offers both accuracy and economy. Another benefit, unquantified to the best of my knowledge, is the improved nature of the surface. As observed by others, diamond turned surfaces are less susceptible to oxidation. Also, they have a higher reflectivity and damage resistance than most conventionally polished surfaces[9]. These facts indicate a diamond turned surface is less disturbed than a polished surface. One would not be surprised that compared to a conventionally polished surface that a diamond turned surface would have improved electrical as well as optical properties.

One of the key components to diamond turning is the air bearing spindle. Several air bearing spindles are shown in Figure 1. The incorporation of an air bearing into a semi-automatic test apparatus for computer memory disks is shown in Figure 2.

Figure 1. These 10 cm (4") and 25 cm (10") Professional Instrument Air Bearing Spindles are Examples of one of the Key Components of Precision Machines

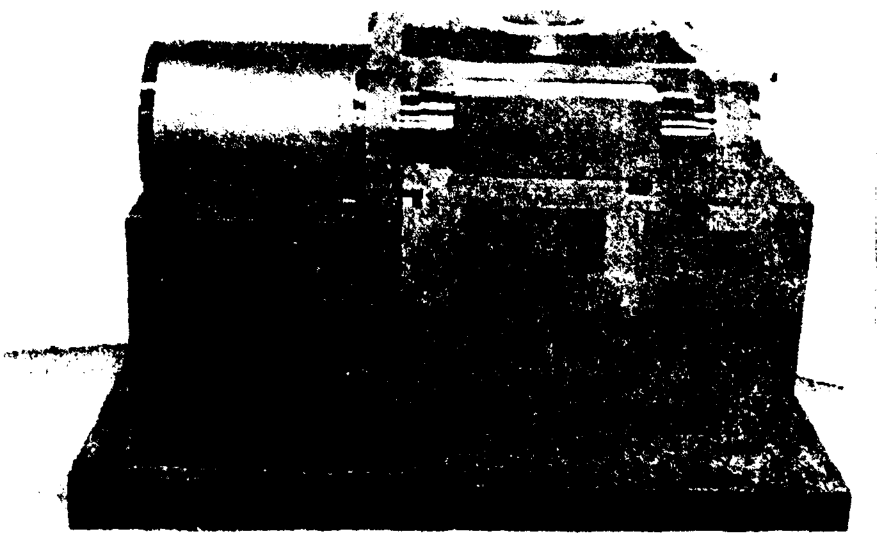

Figure 2. This Semi-Automatic Computer Disk Inspection Machine Incorporates Air Bearings and Careful Engineering to Check Microinch Tolerences

Another application is photo receptor drums and profile transport rolls used in office copying equipment. These rolls demand surface finishes better than 0.02 micrometers (1 micro inch) Ra. Aluminum, copper, and plastic materials, of plain and profiled forms can be machined in a single pass. Automation coupled with diamond turning can significantly reduce cost while improving performance when compared to conventional machining or lapping techniques. An example of such a drum is shown in Figure 3.

Figure 3. The Photocopy Drum and Computer Memory Disk Represent Non-Optical Applications which use a Significant Amount of Diamond Turning Resources. The Spinner Mirror and Turning Flats are Interesting Optical Applications

Precision grinding

Precision grinding can obtain optical tolerances on materials incompatible with diamond turning. Yoshioka and his co-workers have reported some very interesting results grinding with a wheelhead equipped composite bearing and guide/load compensation unit.[10] This unit was very rigid and coupled with a micro-positioning feed could take depths of cuts of 0.1 μm (4 micro inches). They ground the z-faces of 20x20x3 mm quartz samples with a wet-type plunge grinding technique. (The lubricant was passed through a 10 μm filter.) The surfaces were evaluated by a Rank Taylor Hobson profilometer (probably a Talysurf), electron microscopy, and depth of damage measurements by an oblique-cut method. All depths of grinding was 0.2 μm. For one case with a SD1500N100M metal bonded diamond grinding wheel at a peripheral speed of [illegible] and a table speed of [illegible] m/min, they achieved plastic flow conditions and a roughness of [illegible] μm [illegible] in the smooth areas. The surface did demonstrate some areas significantly rougher. The smallest depth of damage reported was [illegible] μm. Yoshioka's results are very encouraging to the optics industry. Furthermore, his work reported in the same paper on austenitic stainless steel gives promise for precision applications requiring steel.

Precision grinding has been one of the mainstays of Professional Instruments, Inc. They have successfully married the air bearing technology and the deterministic philosophy to achieve micro inch accuracies. Figure 4 shows a lens barrel being precision ground. Note the square surrounding flange at the bottom. This was required to successfully fixture to barrel to get the required accuracies.

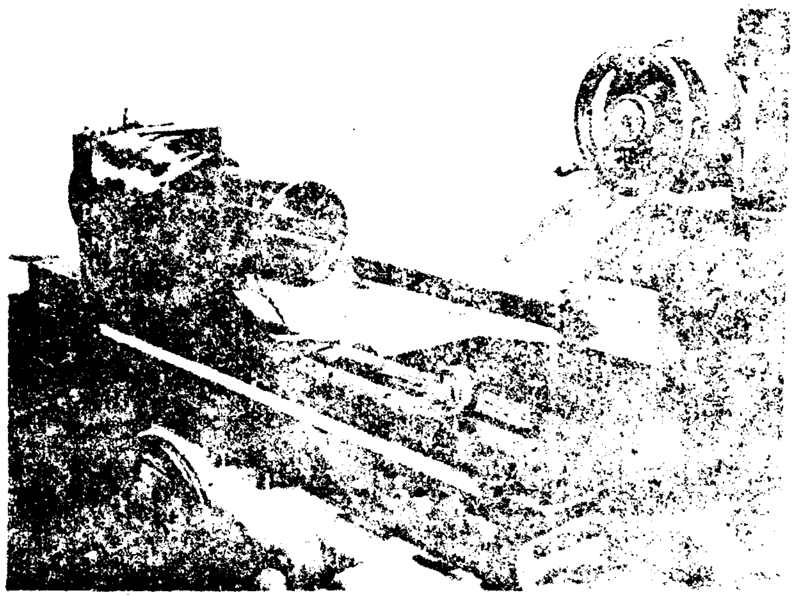

Figure 4. This Precision Lens Barrel Being Ground Presented a Dual Challenge of Machining Accuracy and Careful Fixturing.

Figure 5 shows a mild steel plate approximately 105 cm (42") square and [illegible] cm (1.75") thick. This plate has been precision ground flat and parallel to 0.5 μm (20 μ"). Grinding offers some advantages to facing/turning on center. Grinding utilizes constant wheel velocity whereas radically different tool velocity is experienced from the outside to the center of a facing cut.

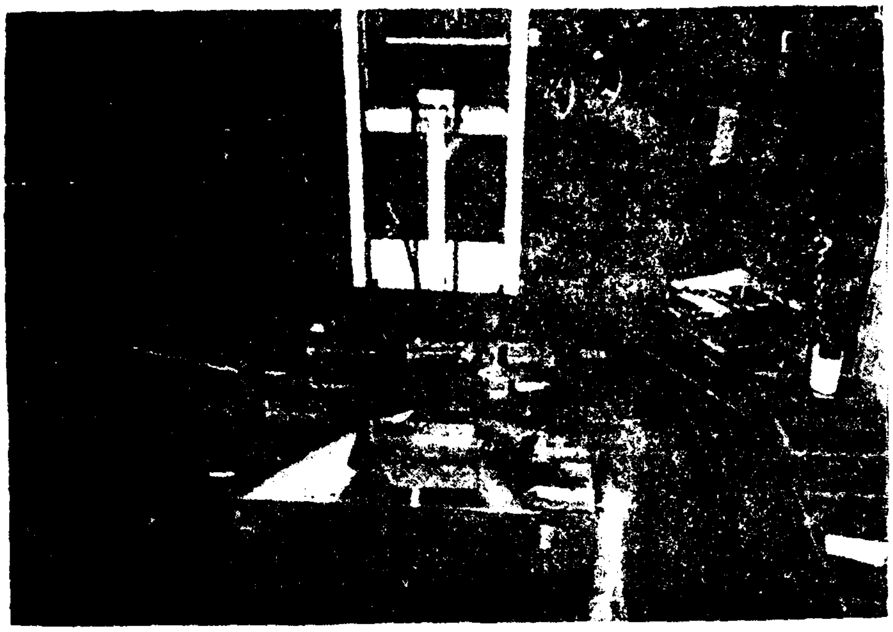

Figure 5. This Mild-Steel 105 cm (42") Square Plate was Precision Ground to 0.5 µm Accuracy.

Summary

Although diamond turning has been accepted as an optical fabrication technique, there are still many new applications that can benefit from them. By seeing the technical and cost advantages of current applications, designers and engineers should be stimulated into taking advantage of the benefits of precision machining.

Availability of machines continues to be a problem to get quick turn-around on new ideas. Machine time is available from many diamond turning organizations, but geographic separation between designer and fabricator encumbers innovation.

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