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Fabrication of Large Radii Toroidal Surfaces by Single Point Diamond Turning

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Introduction

An unconventional machining technique has been developed for producing relatively large radii quasi-toroidal surfaces which could not normally be produced by conventional diamond turning technology. The maximum radial swing capacity of a diamond turning lathe is the limiting factor for the rotational radius of any toroid. A typical diamond turned toroidal surface is produced when a part is rotated about the spindle axis while the diamond tool contours the surface with any curved path. Toric surfaces sliced horizontally, have been used in laser resonator cavities. Reference [1] describes the metrology for one such surface. This paper will address the fabrication of a special case of toroids where a rotating tool path is a circle whose center is offset from the rotational axis of the toroid by a distance greater than the minor radius of the tool path. (See Figure 1.) The quasi-toroidal surfaces produced by this technique approximate all asymmetrical combinations of concave/convex sections of a torus. Other machine configurations have been reported which offer alternative approaches to the fabrication of concave asymmetric aspheric surfaces. [2]

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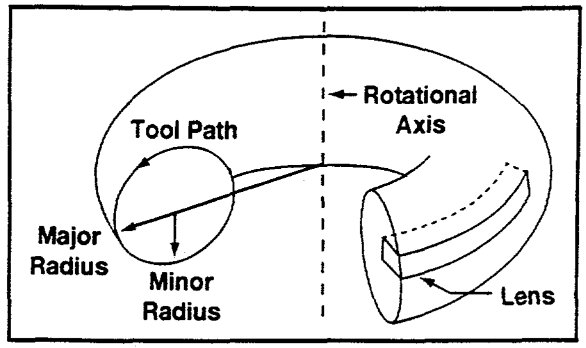

Figure 1. Torus Geometry

Prototypes of unique lenses each having two quasi-toroidal surfaces were fabricated in the Ultraprecision Manufacturing Technology Center at Oak Ridge National Laboratory. These lenses form key components of a scanned laser focusing system. (see Figure 2.) As an example of the problem faced, the specifications for one of the surfaces was equivalent to a section of a torus with a two meter diameter hole. The lenses were fabricated on a Nanoform 600 diamond turning lathe made by Rank Taylor Hobson Inc. in Keene, New Hampshire. This is a numerically controlled two axis T-base lathe with an air bearing spindle and oil hydrostatic slides. The maximum radial swing for this machine is approximately 0.3 meters.

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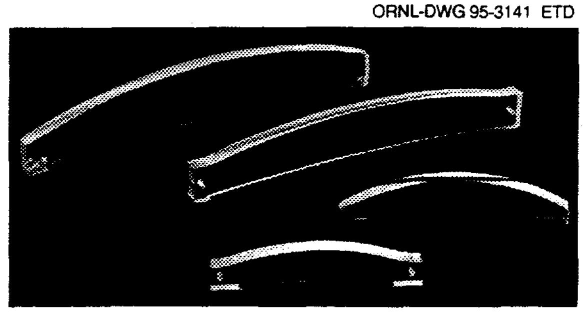

Figure 2. Laser Scanning Lenses

Description of Technique

The diamond turning lathe is used in a fly-cutting mode by rotating a hollow tool-holding fixture about the spindle axis. (See Figure 3.) The work piece is held stationary with respect to the Z slide. The X and Z slides are programmed to contour the major radius of the toroid while the diamond tool rotates with the spindle and cuts at a predetermined fixed minor radius. This arrangement produces a quasi-toroidal surface which deviates slightly from the desired toroidal surface. An elliptical error results when the cutting plane of the tool is not perpendicular to a tangent of the major circumference at every point along the curve. The magnitude of the error is a function of the angle between the cutting plane of the tool and a line normal to the surface of the major radius. For a given quasi-toroidal surface, the figure error of the surface decreases as the height off axis decreases and the angle approaches 0 degrees. (See Figures 4. and 5.)

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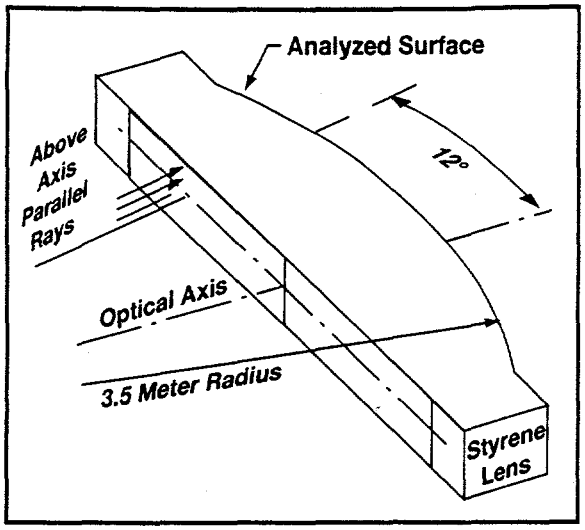

Figure 4. Error Analysis Geometry

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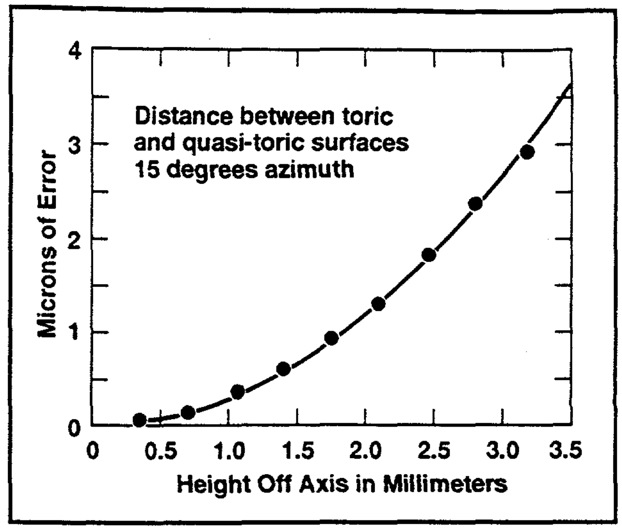


Figure 5. Error as a Function of Height

Fixtures

Figure 3. illustrates the two basic fixtures used with the lathe to machine the quasi-toroidal optical surfaces. One fixture provides stationary support of the lens blank relative to the Z axis while the other holds the diamond tool and rotates with the air bearing spindle. The spindle and the rotating pipe shaped fixture are carried on the X axis of the diamond turning lathe. The lens holding fixture consists of a large solid block with a cantilevered support bar to which the lens is clamped. The cross-section and stiffness of this steel bar was maximized based on the clearance required for the tool path of the minor radius of the toroid. The cantilevered support is required to provide clearance inside the tool path because the lens actually transverses inside the rotating fixture during the cut. This setup allows for a convex surface to be produced for the minor radius while the X and Z slides are programmed to simulate the concave or convex major radius of the toroidal surface. The design of the rotating fixture allows for the tool holder to be mounted on the inside or outside diameter of the pipe. This provides a means of cutting large diameter concave surfaces. A second rotating tool holder consisting of a round solid bar with the diamond tool mounted on its outside diameter is used to cut concave surfaces that have small minor radii. (See Figures 6. and 7.)

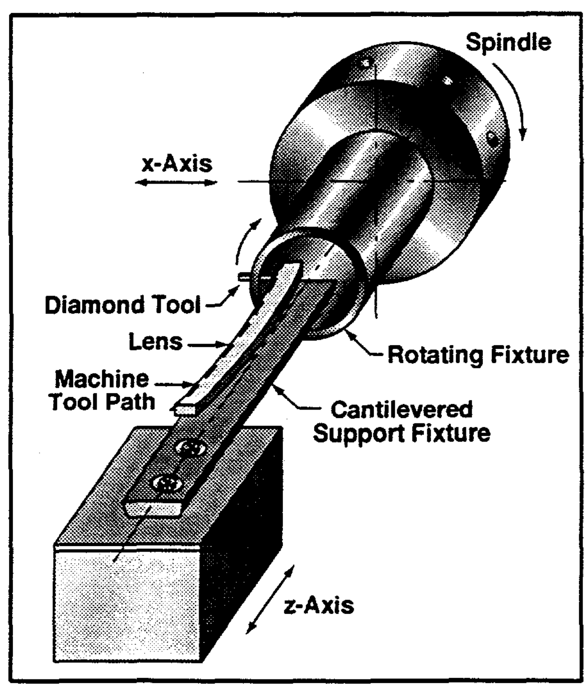
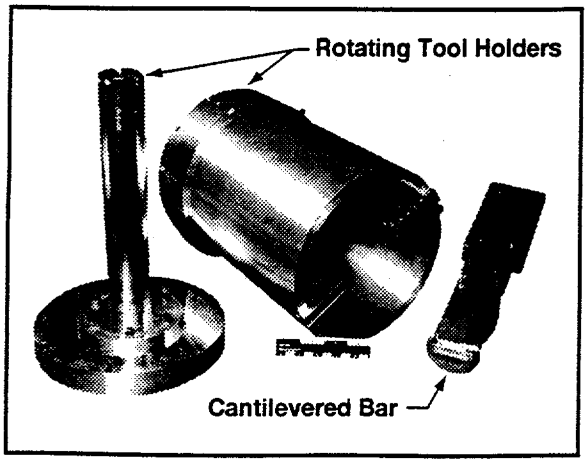


Figure 3. Toroid Fabrication Setup



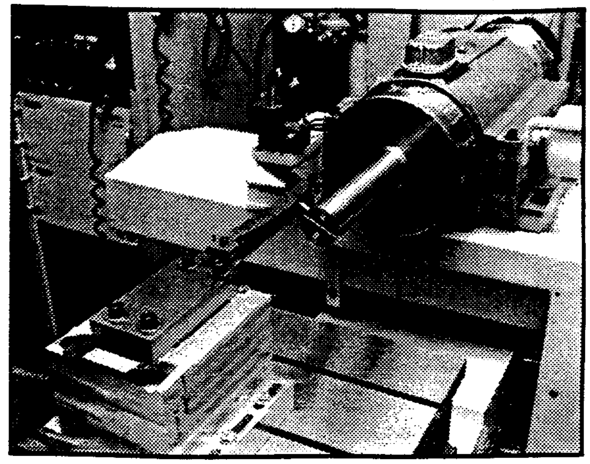


Figure 6. Fixtures

Figure 7. Setup for Concave Minor Radius and Convex Major Radius

Lens Blank Preparation

The lens blanks were fabricated on a CNC mill from optical quality cast REXOLITE ® 1422 polystyrene blocks. [3] Dowel pin holes were precisely located at each end of the blanks. The toroidal surfaces were rough machined as cylindrical surfaces on the sides of the blanks perpendicular to their optical axis. After rough machining, the blanks were tested with a polarizer and those having minimum stress and birefringence were selected. Next, the blanks were mounted on a flat disk fixture using dowel pins and thin double sided tape. The dowel pins prevented the blanks from creeping on the double sided tape by providing extra stability in the radial direction against centrifugal force. Each blank was diamond turned smooth and flat on both sides to a precise thickness. Rubber tipped set screws located in the fixture under each lens were used to push the lens free of the double sided tape without producing excessive stress.

Tool Path Radius

The technique for accurately setting the radius of the tool path without damaging the cutting edge of the diamond is illustrated in Figure 8. First, a separate test part (A) whose width is smaller than the tool path diameter is mounted on the lens support fixture. A cylindrical surface (B) is cut by Tool path 1, and the X axis coordinate (X1) is recorded. The X axis is jogged to the right and the opposite surface (C) is cut by Tool path 2, and its corresponding coordinate (X2) is recorded. The width of the part (D1) is measured with calipers. The distance (D2) between coordinates (X1) and (X2) plus the width of the part (D1) is equal to the present diameter of the tool path. The amount of correction in tool path radius is calculated and the tool is removed from its holder. The X axis is programmed to increment over the calculated correction distance and the tool is reinstalled as close as possible to surface (C) by viewing through a microscope.

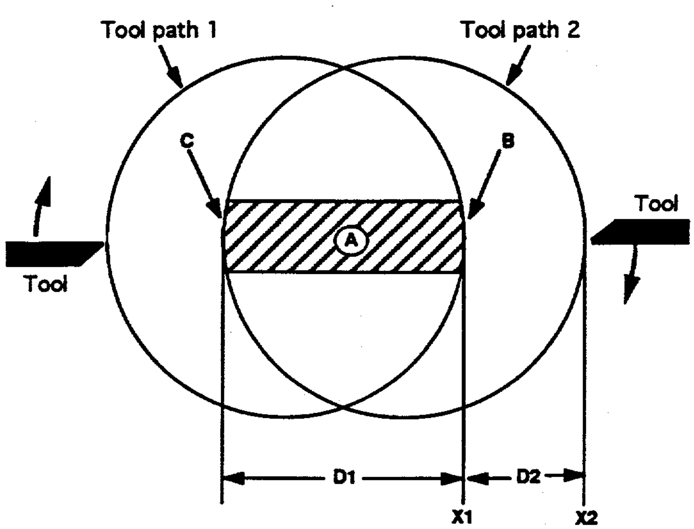


Figure 8. Technique for setting tool radius

Precision alignments

Fixture alignment and tool coordinate locations were important issues in the fabrication process. To insure accuracy, the Nanoform 600 was used in conjunction with an electronic pivot lever gauge as a coordinate measuring machine. The support fixture was aligned and shimmed for pitch, yaw, and roll with respect to the Z axis. This was accomplished by mounting the gauge on the X axis and scanning the mounting surfaces of the cantilevered support bar. At the same time, the bar height was adjusted to match the height of the optical axis of the lens to the spindle rotational axis. To maintain the same height of the optical axis of one lens surface with respect to its opposite surface, the same surface of each lens was always mounted on the support fixture between set-ups. To provide stability and minimize stress during interrupted cuts, the lens was clamped from the top with an elastic material between the clamp and the lens. This distributed the clamping force over the total area of the lens.

One important aspect of the fabrication process was the alignment of the optical axis in the Z direction for both toroidal surfaces on the same substrate. The Z coordinate of a previously diamond turned lens surface is lost any time the lens or diamond tool is relocated with respect to its support. Tool radius and lens position changes were required between setups of the different toroidal surfaces. A variation of a tool centering technique was used to relocate the Z tool coordinate with respect to the optical axis of the first surface. A small toroidal reference surface was cut after completing the first surface and before changing the setup. This reference was used to relocate the Z coordinate of the first surface before proceeding to cut the 2nd surface. A complete explanation of the "Chamfered Post Tool Centering Technique" is given in reference [4].

Conclusion

A method for producing large radius toroidal surfaces on a standard diamond turning machine has been successfully demonstrated. Convex, concave, and combination toroidal surfaces can be fabricated with small geometrical figure errors. For many applications, the resulting error is well within an acceptable range. Prototype lenses were diamond turned and used to verify critical optical designs before committing to polished molds for mass production. This technique is needed when the required radius of curvature is larger than the radial swing of the lathe. These surfaces would otherwise be impossible to produce without an extremely large radial capacity lathe. A special machine configuration with the spindle or the lens pivoting about an axis could conceivably continuously correct the cutting plane of the tool relative to the surface and eliminate all geometric errors. However, initial optical testing of these prototype lenses indicated that the quasi-toroidal surfaces produced exceptionally well focused beams.

References

[1] Saito,T.T.. Arnold, J.B., "Metrology of a Diamond Turned Toric Resonator Component", SPIE, Vol 93, 1976, pp 154-156.

[2] Morlyama, S. et. al., " Development of a Precision Diamond Turning Machine for Fabrication of Asymmetric Aspherical Mirrors", Optical Engineering, Vol 27, No. 11, Nov., 1988 pp 1008-1012.

[3] *Rexolite 1422 is a registered trademark for C-Lec Plastics, Inc.

[4] Miller, A.C., and Cunningham, J. P., "Nanometer Tool Centering for Diamond Turning Applications", Proceedings from ASPE 1992 Annual Meeting, pp 216-219.

Acknowledgements:

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