OPTI 521 Tutorial Report

Specifying optics to be made by single point diamond turning

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1. Introduction

Diamond turning is a process of mechanical machining of precision elements using lathes or derivative machine tools (e.g., turn-mills, rotary transfers) equipped with natural or synthetic diamond-tipped tool bits, and the term single-point diamond turning (SPDT) is sometimes applied. The process of diamond turning is widely used to manufacture high-quality aspheric optical elements from crystals, metals, acrylic, and other materials. Plastic optics are frequently molded using diamond turned mold inserts.

Optical elements produced by the means of diamond turning are used in optical assemblies in telescopes, video projectors, missile guidance systems, lasers, scientific research instruments, and numerous other systems and devices. Most SPDT today is done with computer numerical control (CNC) machine tools.

2. Working process

2.1 Basic information

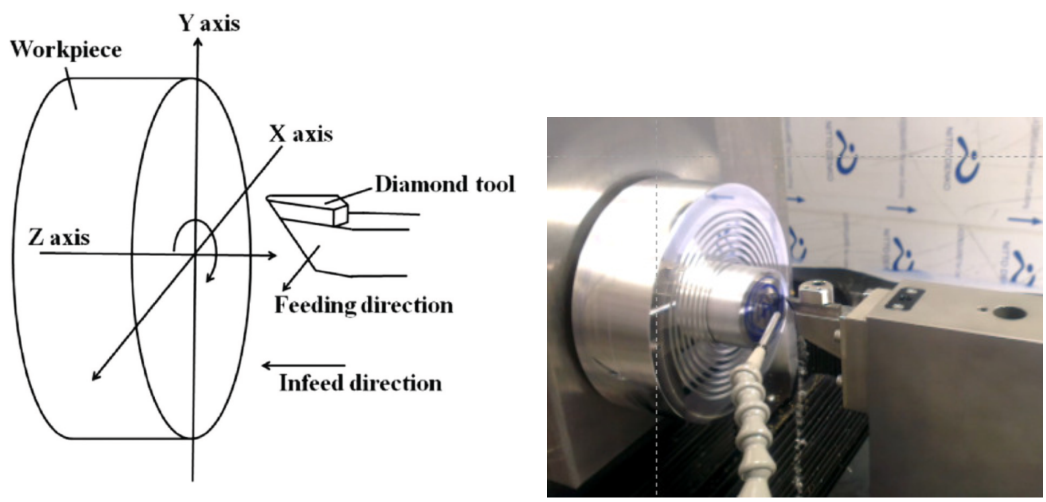


Figure 1. 4-axis diamond turning machine. [1]

Figure 1 shows the simple diagram of a 4-axis diamond turning machine, the X axis is the feeding direction, the Y axis controls the height of the workpiece, the Z

axis is the infeed direction, and the C axis (not marked in the figure) is the turning direction of the spindle.
As shown in the right side of the figure 1, a nozzle is placed besides the diamond tool. While cutting metal, cooling liquid must be used to cool the contact point. However, the liquid could damage the plastic, so only air is used when cutting plastic.

2.2 Feeding direction

During operation, the moving direction of the diamond tool depends on the turning direction of the spindle. If the spindle is turning clockwise, then the tool must move from the right edge of the workpiece to the center (or from the center to the right edge). When turning counterclockwise, the toll must move from the left edge to the center (or from the center to the left edge).

2.3 Centering

Before cutting, the workpiece must be placed at the center of the spindle such that the rotation axis is the same as the spindle. A gauge is used to detect the decenter distance of the workpiece, and then a hammer is used to move the workpiece on the vacuum chuck. Through this process, the decenter distance could be less than 0.2 μm.

2.4 Balancing

Around the turning spindle, there are 12 screws on the side. Adjusting the position of the screws can change the balancing of the spindle. This process can make sure that the spindle is turning smoothly during the cutting process.

2.5 Tool alignment

As shown in figure 2, the tool position must be aligned before the workpiece is cut. The vertical position (Y axis) must be aligned using microscope. If it is misaligned, the center of the workpiece will have some materials left behind, with a shape of rod or cone, depending which direction is misaligned. The horizontal position (X axis) must be aligned using interferometer. If it is misaligned, the shape of the workpiece will not be correct.

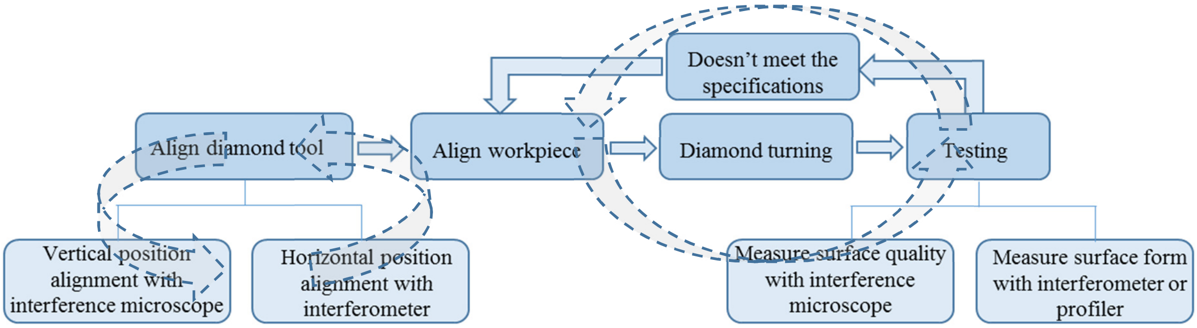


Figure 2. Current diamond turning process

2.6 Testing

Once the turning process is complete and the surface has been fabricated by the machine, the workpiece must be removed from the machine's spindle where it was mounted during the cutting process in order to be measured. The current testing method includes measuring the surface with both a standard interferometer to check the overall surface shape as well as measuring with an interferometric microscope to test the roughness of the surface caused by the tool. If the optical surface is found to be inaccurate in comparison to the desired shape or roughness, the piece must then be replaced on the machine and the alignment, cutting, and testing process must be repeated.

3. Examples

3.1 Aspherical Surface

Aspheric lenses contain at least one optical surface of non-constant radius of curvature. The variability of radius is the primary differentiator from a spherical lens. The standard ISO 10110—Part 12 describes surface functions of second order with axial symmetry as

$$z = \frac{r^2/R}{1 + \sqrt{1 - (1 + \kappa)(r^2/R^2)}} + \sum_{n=2}^{m} A_{2n} r^{2n} \, ,$$

where r is the radial coordinate, z is the sag, and R is the vertex radius of curvature. The conic constant κ is 0 for spheres, -1 for parabolas, <-1 for hyperbolas, between -1 and 0 for oblate ellipses and >0 for prolate ellipses. The $A_{2n}r^{2n}$ terms are the even higher order aspheric terms. It is better to use even polynomials, not odd polynomials. The n starts with 2 since the n=1 term is redundant with base radius.

These parameters can be set and the program in diamond turning machine will generate the coordinates according to the radius of the diamond tool, such that the aspherical surface can be cut. This is one of the surface types that is widely used on the diamond turning machine.

3.2 Lens array

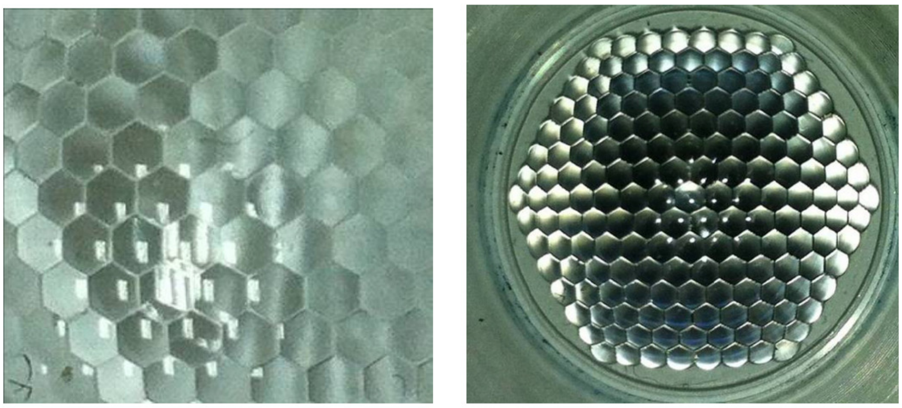
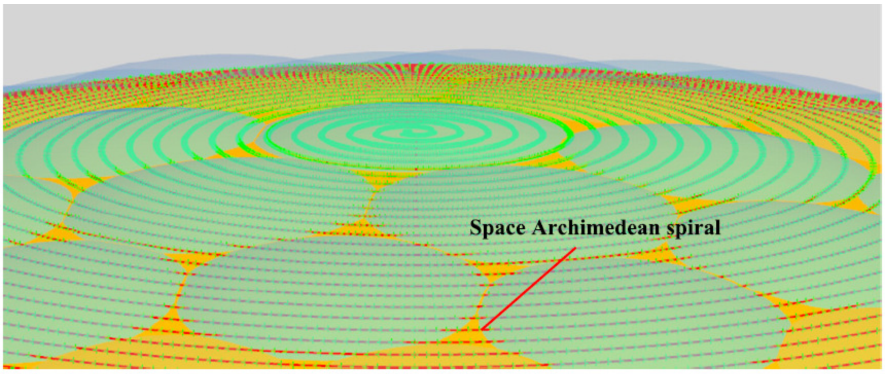
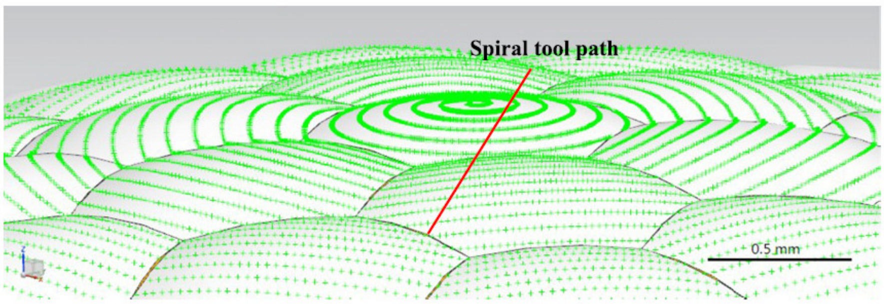


Figure 3. Machined compound-eye surface. [2]



(c) Space Archimedean spiral.



(d) Spiral tool path on the designed surface.

Figure 4. Spiral tool path generation for compound-eye surface. [2]

As shown in figure 3 and 4, lens array can be fabricated after properly designed. Note that cutting the lens array could be very difficult, depending on the sag of the lens array element. Large clearance angle of the tool is needed for large sag surfaces. If the clearance angle needed for the tool is too large (larger than 10 degrees), special tools must be used, or the cutting procedure must be redesigned and optimized. However, this problem usually exists only in convex surfaces, so if the surface is not machinable, cutting it into a concave shape and then mold it could be a solution.

3.3 Freeform: Illumination

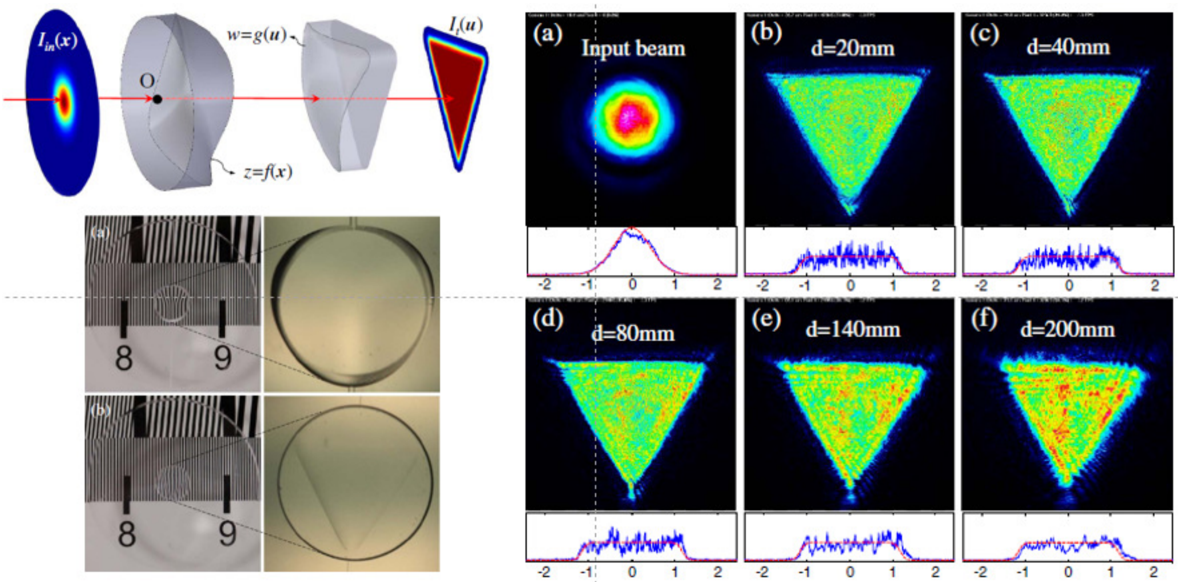


Figure 5. Double freeform optics. [3]

Figure 5 shows the creation of an unconventional flattop beam with a large depth of field by employing double freeform optical surfaces. The output beam is designed with continuous variations from the flattop to almost zero near the edges to resist the influence of diffraction on its propagation. This challenging problem is solved by naturally incorporating an optimal transport map computation scheme for unconventional boundary conditions with a simultaneous point-by-point double surface construction procedure.
The long-range propagated triangular beam is generated through a plano-freeform lens pair fabricated by a diamond-tuning machine.

3.4 Endoscope

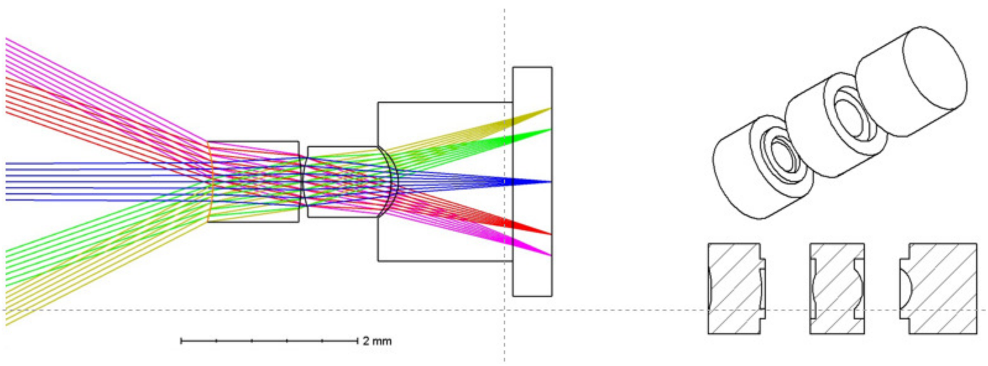


Figure 6. Design of an endoscope.

As shown in figure 6, the endoscope elements are fabricated into the same size, and the mounting structures are added at the edge, such that the elements can be combined nicely, greatly reduce the errors (tilt, decenter, distance error…etc.) induced by the mounting tube or spacer.

4. Drawbacks

There are inevitable tool marks on the finished surfaces, shown in figure 7. These small features can degrade the optical performance of the system.

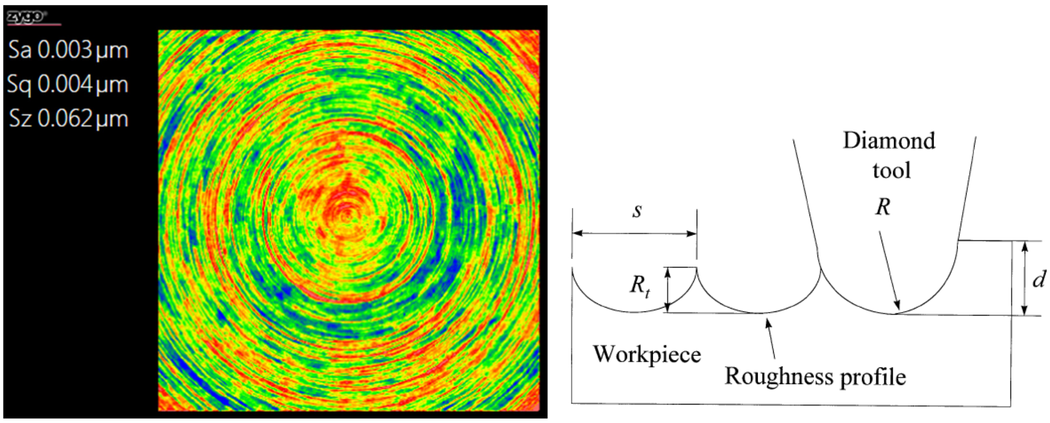


Figure 7. Inevitable tool marks [1]

Basically, diamond turned surfaces have a high specular brightness and require no additional polishing or buffing, unlike other conventionally machined surfaces. These tool marks usually doesn’t matter if the optical elements is large enough, but could be crucial if the elements are small.

5. Material limitations and possible solution

Generally, diamond turning is restricted to certain materials. Materials that are readily machinable include plastics, metals, and infrared crystals. One common material that cannot be used on diamond turning machines is glass.

One solution is to machine the mold of the desired surface using other material, then use a glass press molding machine to fabricate them, as shown in figure 8.

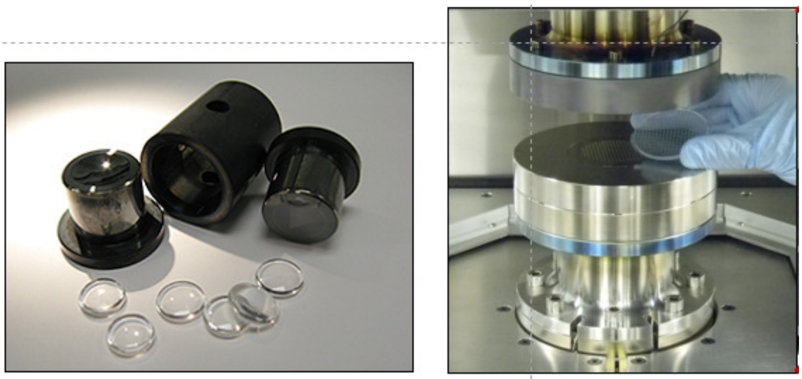


Figure 8. Machined mold and glass press molding machine.

Figure 9 shows an example. The left picture shows the lens array design, the center picture shows the Copper mold machined on the diamond turning machine, and the right picture shows the final piece fabricated in BK7.

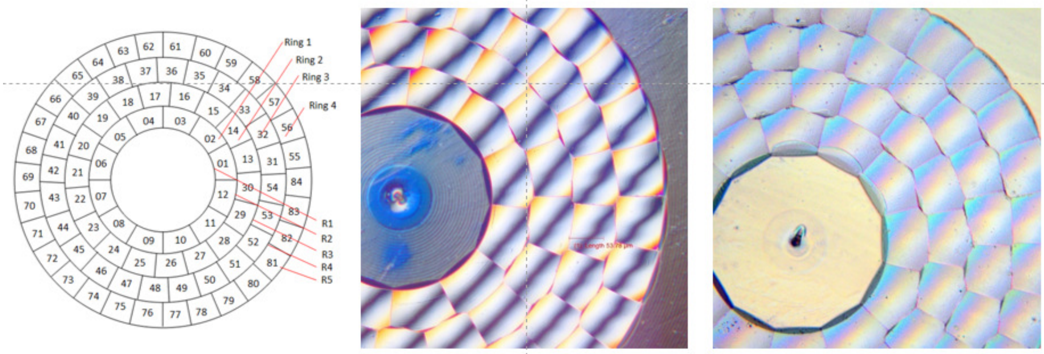


Figure 9. Lens array design, machined mold, and desired piece.

6. Conclusions

In this tutorial, the working process of a 4-axis single-point diamond turning machine, and some samples that it can fabricate are introduced.
Drawbacks and material limitations are also introduced, and possible solution is proposed.

7. References

[1] C. F. Cheung and W. B. Lee, “Modelling and simulation of surface topography in ultra-precision diamond turning,” Proceedings of the Institution of Mechanical Engineers, 214.6 (2000)

[2] Hu Gong, Yi Wang, Le Song, F.Z. Fang, “Spiral tool path generation for diamond turning optical freeform surfaces of quasi-revolution” Computer-Aided Design, Vol. 59, Pages 15–22 (2015)

[3] Z. Feng, B. D. Froese, C. Huang, D. Ma, and R. Liang, “Creating

unconventional geometric beams with large depth of field using double freeform-surface optics," Appl. Opt. 54, 6277-6281 (2015)