Specifying optics to be made by single point diamond turning

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1. Abstract

Optical lenses can be manufactured by single point diamond turning with high quality. By spinning an optical block against a single point diamond with precisely controlled movement, a rotational symmetric surface (spherical or aspheric) can be accurately fabricated. This method is often used to fabricate high quality plastic lenses. While most of the mass produced plastic lenses will be eventually fabricated with injection molding, single point diamond turning allows prototyping a product with relatively low initial cost. Apart from plastic lenses, single point diamond turning is also often used to fabricate infrared optical lenses.

This tutorial serves to give the basic guideline to understand the specification of optical surface not only made by single point diamond turning, it can also be applied to conventionally polished optics and injection molded optics. Surface tilt/decenter will not be discussed here because the specification of this quantity is the same as the conventionally polished optics.

2. Material

The first thing we should specify is the material. Not all optical materials are diamond turnable. For the materials to be diamond turnable, they have to be relatively soft. Some of the more common consumer plastic optical materials include Polymenthymethacrylate (PMMA), Polycarbonates (PC), Polystyrene (PS), Cyclo Olefin Polymer (COP), Optical Polyester (OKP4), etc. For the IR optics, some common diamond turnable materials include Calcium fluoride (and similar fluorite crystal), Chalcogenide, Germanium, Silicon, Zinc selenide, Zinc sulphide, Sodium chloride (and similar chloride crystal), Cadmium telluride, etc.

It has to be noted that the mechanical properties of the optical materials affect the level of quality of the final product. It is often to see optics manufacturer to specify the best possible surface quality for different kinds of material. For example, optics made of PC tends to leave tooling mark after it is diamond turned because PC is a soft material. On the other hand, optics made of PMMA tends to have surface with relatively better quality.

Of course, material is not the sole factor that determines the final surface quality. The surface quality depends on the size of the diamond tip, spinning speed, and other machining factors, it will not be discussed here.

3. Surface quality

The surface quality of optical lenses made by diamond turning is mainly described 3 specifications, namely: i) Surface power/Radius of curvature, ii) Figure error/Irregularity, iii) Surface roughness. These quantities are most often specified by the optics manufacturer.

For more detailed classification of surface errors, it is further categorized into low spatial frequency range (LSRF), mid spatial frequency range (MSFR) and high spatial frequency range (HSRF). As will be discussed later, the figure error/irregularity is considered in the low spatial frequency range, it usually directly affects the image quality in terms of wavefront aberration. The surface roughness is considered in the high spatial frequency range, it accounts for the scattering properties which is potentially crucial for stray light performance. Finally, the mid spatial is somewhere in between the low and high spatial frequency, but its theory is not quite well developed yet. The mid spatial frequency error is not commonly specified by the optics manufacturer, hence it will not be discussed in this tutorial.

3.1) Surface Power

Similar to optical lenses made by conventional polishing method, optical lenses made by diamond turning are specified with surface power. The surface power of a surface basically comes from its curved surface, hence it is specified as the radius of curvature, in mm.

When an optical lenses is diamond turned, its surface will be measured as a 1D line profile, or a 2D surface map depending on the measuring equipment. Based on the measurement data, the "Best-Fit Radius" will be calculated according to the surface form as described below:

$$z = f(r) = \frac{\frac{r^2}{R}}{1 + \sqrt{1 - (1+\kappa)\left(\frac{r}{R}\right)^2}} + \sum_{n=2}^{m} A_{2n} \cdot r^{2x}, \qquad \text{Eqn. (1)}$$

where z is the sag as measured from the vertex, r is the lateral coordinate (maximum corresponds to half diameter of lens). For spherical surface, conic constant κ and even aspheric coefficients A_{2n} are zeros. With the measurement data z as a function of r, the surface radius of curvature R can be determined. This R is the best-fit radius.

When we specify the tolerance of a lens surface, the first thing is to specify the tolerance of the surface power, which is specified as the error of radius of curvature, in mm. Depending on the manufacturer, the accuracy of the surface power varies. For example, optics manufacturer such as Ophir Optronics and Lambda Research Optics promise they are able to produce diamond turned surface with accuracy up to ±0.05% of its radius of curvature [1,2].

Depending on the manufacturer, the surface power can be specified differently. Some manufacturers define the specification of the error of the surface power in terms of <u>number of fringes</u> (e.g. 1 fringe @ λ=633nm) or <u>fraction of wavelength</u> (e.g. λ/2 @ λ=633nm), which is the common way for specifying conventionally polished optics. For example, optics manufacturer such CVI Laser Optics and Kaleido Technology specify their manufacturing ability of optical surfaces in terms of fraction of wavelength [3,4].

Now, we see there are multiple ways of specifying the optics surface power. Below is the equation from Ray-Optics which allows us to convert between the number of fringe and the error radius of curvature easily [5]:

$$\Delta R = 4N\lambda R^2/\phi^2 \qquad \text{Eqn. (2)}$$

$$N = \phi^2 \Delta R/4\lambda R^2 \lambda \qquad \text{Eqn. (3)}$$

where N is the number of fringes (due to error of surface power), ΔR is the difference in the radius (between the part and the test plate), ϕ is diameter of interfering area, and λ is the test wavelength. For reflective interference, because of the double pass configuration, 1 fringe corresponds to half a wavelength instead of 1 wavelength optical path difference. Therefore, the error of the surface power in terms of fraction of wavelength (Peak to Valley), is simply the number of fringe divided by 2, with unit of wavelength.

However, care has to be extra taken when we apply the rule of thumb of equating 1 fringe to half a wavelength. It really depends on the test configuration. Although majority of the interferometric testing uses reflective configuration, we need to confirm the test configuration. Here is an article from SPIE discussing about this. [6]

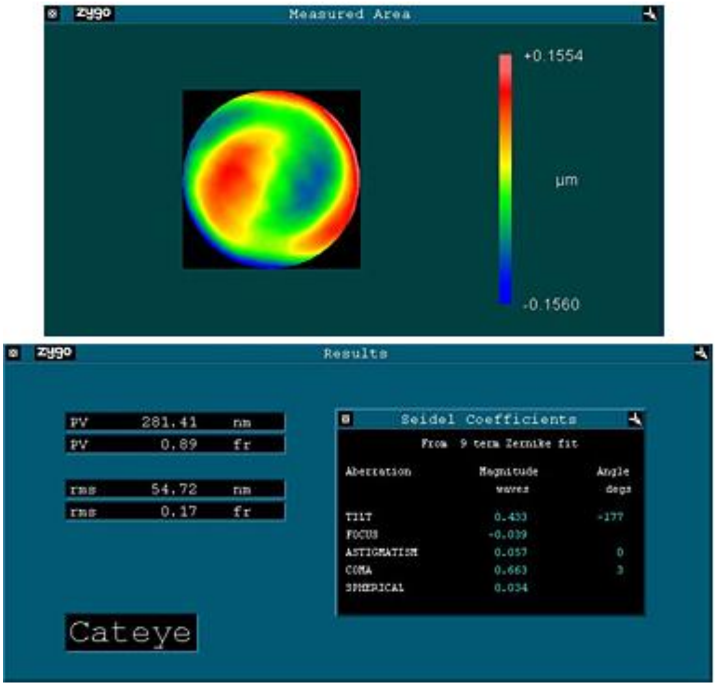
3.2) Surface Figure/Irregularity

Once the "best fit radius" or "surface power" is determined, the fitted surface profile of the lens surface will be removed from the actual data points (measurement). What is left is normally defined as the "error profile/map". Basically, this line profile or 2D map shows the difference between the actual surface (measurement) and the ideal surface in analytic form (equation 1). This is also known as the height of local departures from figure, or irregularity. For example, for a spherical surface, a low irregularity surface means the form of the surface is very close to a true sphere. On the other hand, a surface with big error of irregularity means the shape of the surface deviates significantly from a true sphere, this is undesired because it leads to aberrated wavefront and eventually leads to degraded image quality.

Similarly, the quantity for such error can be expressed in terms of μm, nm, fraction of wavelength, or number of fringes. If the surface is measured with profilometer (e.g. Taylor Hobson equipment), the quantity of irregularity will be expressed in terms of PV (Peak to Valley) or RMS (Root Mean Square), with unit of μm or nm depends on the magnitude of error.

On the other hand, if the surface is measured with interferometer (e.g. Zygo equipment), the quantity of irregularity will be expressed in terms of fraction of wavelength or fringes (with specified test wavelength).

Once again, the quantities can be converted with equation (2) and (3) with caution of the test configuration. Here is an example of surface measurement with Zygo interferometer [7]:



Here we see the PV irregularity is 281.41nm, or 0.89 fringes. Apparently this equipment use standard HeNe laser with 633nm, if we apply the rule of thumb of conversion, 0.89 fringes x 633nm ÷ 2 = 281.68nm. For this particular measured surface, the figure error or irregularity is about 1 fringe or λ/2, which is considered low quality surface, the associated wavefront aberration causes noticeable amount of image degradation. For more details about the quality of lens surface with given figure error, one can refer to Newport's specification standard [8]. This is not a universal standard, but it's quite commonly seen in optics industry.

One more common thing we could observe from optics industry standard is that, optics manufacturers tend to specify surfaces figure error in PV instead of RMS despite RMS quantity could better describe the surface figure error in general. Hence, while we specify the requirement of the surface figure, we normally specify in PV quantity, be it in nm, fraction of wavelength, or fringes.

Lastly, figure error can be expressed in even more complicated forms, such as Seidel Coefficient (as shown on the figure above), or Zernike aberration. If this surface error 2D map is to be decomposed into multiple terms of Zernike aberrations, one could get the insight of how the wavefront aberration is generated associated with a tested surface. Such practice is usually seen in high end optical system (such as interferometer where wavefront aberration is crucial), it might not be common for optics made by diamond turning.

3.3) Surface Roughness

The next thing we can specify an optical surface is the surface roughness. This quantity is not quite commonly seen for conventionally polished optics. The reason is because by lathing an optical surface with a diamond tip, it could potentially create micro structure if the diamond turning process is not well controlled.

Surface roughness describes the high frequency component of the surface profile. Likewise, it can be expressed in PV, R_a (arithmetic average), R_q (RMS). R_a, R_q are defined as:

$$R_a = \frac{1}{N}\sum_{i=1}^{N}|y_i|$$

$$R_q = \sqrt{\frac{1}{N}\sum_{i=1}^{N}y_i^2}$$

For surface roughness specification, PV metric does not really describe the overall smoothness of a surface. R_q is the most commonly used metric to describe surface roughness, some manufacturers also work with R_a specification. There are many other metrics and standards for describing surface roughness, but in most of the cases R_q is sufficient to describe the specification for surface roughness. The unit of surface roughness is usually in units of nm, or Å.

Surface roughness can be measured with point contact method (e.g. Taylor Hobson PGI Series), or white light interferometry (e.g. Zygo NewView Series), or atomic force microscopy (e.g. Nanowerk).

4. Aspheric Surface

Likewise, for the aspheric surface, the conic constant and aspheric coefficients can be determined by numerically fitted to be measurement data. Technically, we can specify the tolerance of the conic constant and the aspheric coefficients in terms of percentage error. However, it is not usually done this way. Here is an example of an aspheric lens from Thorlab [9]:

ASPHERIC COEFFICIENTS

	R	k	A_4	A_6	A_8	A_{10}	A_{12}	A_{14}	A_{16}
S1	6.215	-1	2.0059414e-04	-1.0498431e-07	-1.1263556e-08	-1.0201221e-010	8.4002262e-013	4.6362363e-015	1.2062946e-016
S2	INFINITE	-	-	-	-	-	-	-	-

ASPHERIC LENS EQUATION

$$z = \frac{Y^2}{R(1+\sqrt{1-(1+k)Y^2/R^2})} + A_4Y^4 + A_6Y^6 + A_8Y^8 + A_{10}Y^{10} + A_{12}Y^{12} + A_{14}Y^{14} + A_{16}Y^{16}$$

The above sag equation is straightforward to specify an aspheric surface, but when it comes to manufacturing and testing purpose, it becomes impractical to specify the tolerance based on the fitted aspheric coefficients. We can see for higher order aspheric coefficients, the magnitude is extremely small.

A common way to tolerance the aspheric surface is by defining the gradient error as an angular tolerance, i.e. the maximum slope departure from a specific form. For example, what is usually done is illustrated in the table below [10]:

h (mm)	z (mm)	Δz (mm)	Slope tolerance (Slope sampling length= 1 ± 0.1 mm)
0	0	0	0.3′
5	0.219	0.002	0.5′
10	0.825	0.004	0.5′
15	1.599	0.006	0.8′
19	1.934	0.008	1'

For a given cross section, at different radial height (h) of the surface, the sag error (Δz) and the slope error are specified. Take note that the slope sampling length has to be specified. As long as the sag error and the slope error over the sampling length at corresponding radial height do not exceed the specified tolerance, the aspheric surface is within the tolerance.

5. Conclusion

In summary, the specification of the diamond turned optics (usually plastic and IR material) is very similar to the conventionally polished optics (usually glass). As some of the optics manufacturers specify the surface error in terms radius error and sag error, the optics designer has to be familiar with the specification and able to do conversion from fringes/waves with conventional interferometric testing.

6. Reference

[1] **http://www.ophiropt.com/optics/downloads/ophir_optronics_optics_group_profile.pdf**

[2] **http://www.lambda.cc/new-products/diamond-turning/**

[3] **http://cvilaseroptics.com/products/Spherical-Lenses**

[4] **http://www.kaleido-technology.com/products/Diamond-turned-optics.htm.html**

[5] **http://www.ray-optics.com/Handy%20formulas%20updated%208-31-09-2.pdf**

[6] **http://spie.org/newsroom/fringe-elements**

[7] **http://zygo.de/?/en/met/applications/surfaceform/**

[8] **https://www.newport.com/n/optical-surfaces**

[9] **https://www.thorlabs.com/newgrouppage9.cfm?objectgroup_id=7176**

[10] **https://drive.google.com/file/d/0BwdaIsqVUPtGdm1RSFUtVVRQY0k/view**