Technical Report Synopsis:

Design and Specification of Diamond Turned Optics

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Optics 521: Grad Student Report
December 1, 2008

Abstract

This synopsis covers the key elements of a paper by Robert A. Clark entitled, "Design and Specification of Diamond Turned Optics." His paper presents a basic outline of the specifications needed for an optic, with an emphasis on diamond turning materials and capabilities. The major topics covered by the paper include materials that can be diamond turned, diamond machine tools, surface figure and finish, aspheres, post polishing, and coatings.

Material Choices for Diamond Turning

The first section of the paper provides an in depth analysis of materials that may be used for diamond turning including metals, polymers, and crystals. The author acknowledges that there are other materials not noted in the paper which may be used for diamond turning, but they will not produce surfaces adequate for optical applications. A chart of common materials from the paper is listed in Appendix A.

Metals
Most non-ferrous metals are able to be diamond turned (excluding titanium, molybdenum, beryllium, and nickel). All aluminum alloys may undergo this process, but heat-treatable series are recommended. The preferred choice is often 6061, which is readily available. The author also goes into detailed explanation about the different forms of alloys available (Plate, Wrought Bar, Extruded bar, and Forged) as well as their common applications and advantages/ disadvantages. A201 is specifically mentioned as a material that is readily diamond machinable and can be cast to a near finished shape due to its lack of crystallites that usually form at boundaries of alloys. The picture shown below of three different aluminum alloys with the same cutting parameters also demonstrates the superiority of A201.

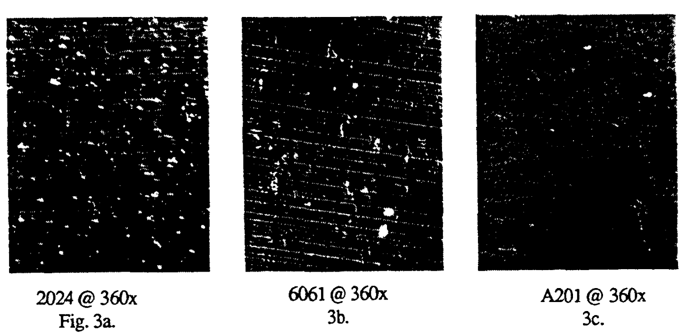

Figure 1: Aluminum Alloy Comparisons

The author continues the discussion of metal materials by noting that nickel in wrought form or electrolytic plate is not diamond machinable, however electroless nickel is, and it may be considered of interest to the designer for the following five reasons:

1) Corrosion Resistance
2) Wear Resistance
3) Renders a substrate material that was previously not diamond machinable into one that is
4) Geometry (to get a reflective surface in an otherwise difficult location).
5) To permit post polishing

Polymers and Crystals
The most popular polymers for diamond turning listed by author are acrylic, polycarbonate, and polystyrene (in optical grades). He also notes that copolymers are also available for use. Although the final production method for polymers may be injection molding, it is often more cost effective for the prototypes to be diamond turned since custom molds are often expensive.

Germanium is the most common of the IR crystals that is diamond turned, and has better surface finish than any metal or polymer. Zinc Sulfide is also diamond machinable and has the advantage of transmitting from 0.4 to 12 um. The author notes that Zinc Selenide and Silicon do not diamond machine as well as these materials and can sometimes cause abnormal tool wear due to their high hardness.

Surface Figure and Finish

The second section of the paper is a more general overview of what specifications should be included for a manufacturer, regardless of it will be diamond turned or not. The author covers radius of curvature, irregularity, aspheric figure, clear aperture, slope, and surface roughness.

For radius of curvature and irregularity specifications, the author gives only a brief outline of how the terms are defined, typical tolerances that are applied, and how they are tested. He then spends a great deal of time addressing aspheric surfaces (equation in Appendix A). One suggestion he makes is that a base radius tolerance should be called out in addition to a maxiumum departure from theoretical for an asphere. Contact profilometry is a common and accurate way to evaluate an aspheric surface and the author includes pictures of traces from a Talysurf contact profilometer. He claims it is generally understood that figure accuracy is given as a peak-to-valley (PV) measurement, but as a rule of thumb, PV values are about 5-7 times higher than the RMS value.

A brief description of clear aperture and slope are then given. The author makes note of the fact that although clear apertures are usually standard, IR, boresighting, and off-axis systems may require special specifications. He states that the more specific the drawing can define the requirements, the more likely cost will be minimized. Slope is a specification that is much more important for diamond turned surfaces since conventional loose abrasive polishing rarely produces significant slope errors. The slope is defined as the tangent angle of local incline from the global departure. Typical tolerances are 2 arc seconds and are understood to refer to low spatial frequencies (~3-30 cycles/aperture).

The last part of this section discusses surface roughness, but mostly references other resources for the reader to turn to (for both its definition and the effects of diamond turning). The basic message he reiterates is that a designer's roughness criteria should be based on how much scatter, and loss of energy, can be tolerated by the total system.

Although a bit out of order in the paper, the author then briefly talks about diamond machine tools and the figure and finish capabilities that were available at the time. He lists a few major suppliers of diamond turning machines as well as a comparison of their capabilities (Appendix A).

Post Polishing and Coating

Post polishing is working the surface of an optical component with loose abrasive to improve figure and/or finish beyond what diamond turning can accomplish. It is mostly used to minimize scatter in the shorter wavelengths, since diamond turning can quickly achieve good figures, even with aspheres. The author then outlines a sequence of operations for a specific post polishing configuration.

A general discussion on coating follows, since diamond turned optics are typically coated the same as any other optics. He calls out the MIL specifications for environmental durability and also includes a useful chart that lists the reflectance of a variety of metals over a large wavelength range.

Conclusion

This paper gives a comprehensive overview of the specifications needed to manufacture a lens, with special attention to diamond machined optics. The author advocates the need for a more global standardization of optical specifications and proposes a more general tabulation of specifications which include the parameters necessary for diamond turned optics (below). This paper serves as an excellent introduction for a designer who is unsure of how to specify the important aspects of a drawing for manufacturing purposes. Anyone who has considered using diamond turning would find this paper very helpful through both the designing and production stages of an optical element.

	Radius	Radius Tol.	Power	Irreg.	Astig.	Slope	Scratch/ Dig	C.A.
R_1	6.9302	± .004	4	1	.5f	2 sec	60/40	.280
R_2	5.392*	± .004	3	1	.5f	2 sec	80/50	.320

*R =
S =
K =
A_1 =
A_2 =
A_3 =
A_4 =

References:
Malacara, Daniel. Optical Shop Testing (Wiley Series in Pure and Applied Optics). New York: Wiley-Interscience, 1992.

R. A. Clark "Design and Specification of Diamond-Turned Optics" Critical Review Vol. CR38, *Infrared Optical Design and Fabrication*, ed. R. Hartmann, [1991]

Appendix A

Diamond Machinable Materials

Metals	Polymers	Crystals
Aluminum	Acrylic	Germanium
Alloys	PMMA	Zinc Sulfide
1100		
2011		
2107	Polycarbonate	Zinc Selenide
2024	Lexan	Calcium Fluoride
3003		Barium Fluoride
5086		
5186	Polystyrene	Silicon
6061		Cadmium Telluride
7075		
A201 Cast	Copolymers	Mercury Cadmium Telluride
Copper (OFHC, Electroplated)	NAS	Tellurium Dioxide
Beryllium Copper	SAN	Gallium Arsenide
Brass	CR-39	Amtir
Tin	TPX	Lithium Niobate
Silver		Potassium Dihydrogen Phosphate (KDP)
Gold		
Zinc		
Nickel (Electroless Plate)		

Aspheric Surface Equation (from Malacara)

$$Z = \frac{cS^2}{1 + [1 - (K+1)c^2S^2]^{1/2}} + A_1S^4 + A_2S^6 + A_3S^8 + A_4S^{10}$$

where
- $c = 1/R$ = Curvature
- R = Vertex (Base) radius
- $S = (x^2 + y^2)^{1/2}$
- K = Conic Constant
- A_1, A_2, A_3, A_4 = Higher Order Coefficients

Conic Section K values:

- Hyperboloid $K < -1$
- Paraboloid $K = -1$
- Ellipsoid rotated about its major axis $-1 < K < 0$
- Sphere $K = 0$
- Ellipsoid rotated about its minor axis $K > 0$

Diamond Machine Tool Comparisons:

Gen. I Machines	Figure P-V @ 632 nm.	Finish Å Ra.
Rank Pneumo MSG 325	0.4	150
Moore Special Tool M-18	0.4	150
Gen. II Machines		
Rank Pneumo Nanoform 600	0.16	20
Cranfield Precision Nanacentre	0.16	50

3 Inch Dia. Aluminum, Sphere 10 inch R. of C.