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Design and Specification of Diamond Turned Optics

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ABSTRACT

An update on diamond machinable materials is presented with emphasis on A201 cast aluminum and electroless nickel plating. Surface figure is discussed for spherical and aspherical surfaces, including base radius tolerances, irregularity, clear aperture and slope. A review of recent work on surface finish and scatter is summarized. Current machine tool capabilities are presented with considerations for post polish, where machine produced accuracies do not suffice.

1. INTRODUCTION

At 5 year intervals and perhaps even more frequently there is a need to revisit the specifications of diamond turned optics and make some further effort to standardize the industry. The recent introduction of second generation machine tools has shown a significant narrowing of the gap between accuracies achievable with modern machine tools and the older, slower conventional methods.

Even, where the improved accuracies are not required, such as with IR applications, diamond machining offers cost and delivery advantages for spherical as well as aspheric optics.

In both cases — for increased accuracies or for cost/delivery advantages — it becomes increasingly clear that the methods of specifying optical surfaces, be they spherical or aspherical, should be absolute and not be tied to what is perceived to be their method of manufacture. It's the old adage all over again: "Don't tell them how to do it; tell them what you need!"

2. MATERIALS

Only those materials upon which we can produce an optical quality surface are considered to be diamond machinable. There may be other materials, not noted here, which produces surfaces that are only adequate for non-optical applications.

Diamond machinable materials include most non-ferrous metals, polymers, and several crystals as listed in Table 1. Notable exceptions are the ferrous alloys, titanium, molybdenum, beryllium, and nickel. Also excluded are optical glasses, quartz, and ceramics. Machining parameters such as feed rate, rpm, depth-of-cut, tool rake angles, and coolants must be optimized for each material.

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)		

Diamond Machinable Materials — Table 1.

2.1 Metals

Although all of the alloys of aluminum are diamond machinable, we recommend alloys of the heat-treatable series of 2000, 6000, and 7000. The high yield strength alloys such as 2024 and 7075 are commonly used where dynamic forces dictate their use, e.g. high spin rate polygons for use in scanners. Our preferred alloy is 6061, which is available in many stock sizes and forms.

In addition to calling out the chemical composition of an alloy by its Aluminum Association designation, such as 6061, it is also necessary to specify the temper and the form of the material which is desired. If extensive rough machining is required to yield the desired shape prior to diamond machining, it may not be necessary to specify any temper, since the material should then be solution heat treated and artificially aged to bring it to the T651 or T7 Condition. This is essential to ensure thermal and temporal stability. The heat treatments of aluminum alloys are specified in MIL-H-6088.[1] A solution heat treat consists of bringing the aluminum alloy close to its eutectic temperature, which is about 970 degrees F for 6061 and then quenching it in poly alkylene glycol within 30 seconds after removal from the furnace. The material is then artificially aged at 350°F and thermally cycled before diamond machining. Graphic presentation of the process is depicted in Fig. 1[2] Rates of heating and cooling should not exceed 15 degrees F. per minute.

Most alloys are available in 4 different forms: 1) Plate; 2) Wrought Bar; 3) Extruded Bar and; 4) Forged. We generally specify plate stock and/or wrought bar stock known respectively by their Federal designations as QQ-A-250 and QQ-A-225. The use of extruded stock, QQ-A-200 should be avoided due to its porosity. For the most critical of applications, which might involve operation at cryogenic temperatures or long term stability the use of forged stock, QQ-A-367 should be specified. It is possible with this form to specify the grain direction of the billet, so that the optical axis of a component to be made from this material may be made parallel to that grain direction and therefore tend toward an axi-symmetric material property. The system shown in Fig. 2 used a forged billet as the source for the optical bench and all mirrors. Forged stock is by far the most expensive of the aluminum alloys and requires a lead times of 8-12 weeks. Other forms of 6061 can be obtained usually within a week. Material certifications are routinely provided by most material suppliers, but only if requested. The standard certification is generic and may pertain only to a sample of the material as opposed to an analysis of the specific ingot from which your material was drawn. Chemical analysis can of course be obtained, but only with added expense. We have not seen the need to request more than the routine certification.

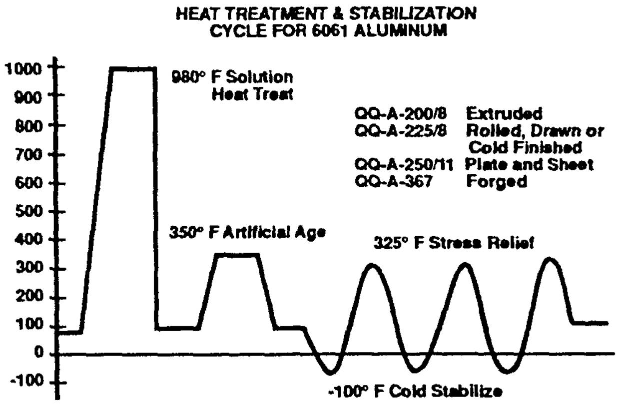


Figure 1

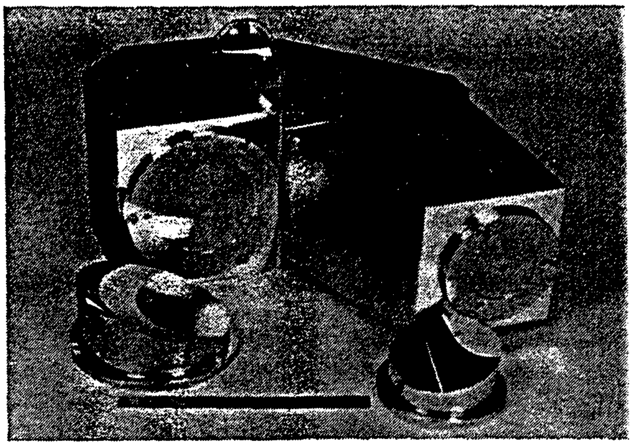
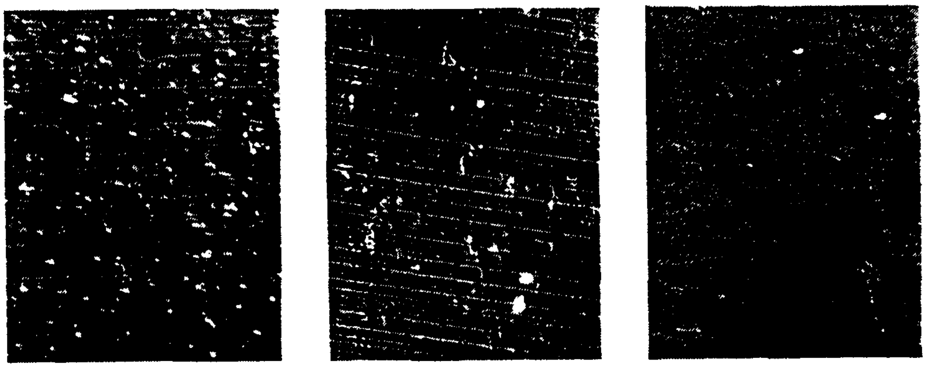


Figure 2 Seer System

The A201 Cast aluminum alloy has most recently been used as a material for optical components in that it is readily diamond machinable, is free of the crystallites that form at grain boundaries of wrought alloys, and can be cast to near net shape to reduce machining time. This latter consideration should be studied on a case-by-case basis, since modern CNC machining can remove large amounts of material rapidly and precisely. One foundry,[3] who introduced the material to the diamond machining community prepares the mirror substrate by a special process which ensures greater density of the material in the area that will become the mirror surface. Mirrors made from A201 cast alloy in this fashion have exhibited significant improvements in TIS.[4] Figure 3 a, b, c, show the dramatic differences between 2024, 6061, and A201 at 360x and machined with the same cutting parameters. Work is now proceeding to subject this material to further processing by the technique known as Hot Isostatic Pressing.



2024 @ 360x
Fig. 3a.

6061 @ 360x
3b.

A201 @ 360x
3c.

Aluminum Alloy Comparisons
Fig. 3a., b., c.

Nickel in either wrought form or electrolytic plate is not diamond machinable. Electroless nickel is rendered diamond machinable by a large percentage of phosphorus, usually in the range of 9-13%. There are five reasons why the deposition of an electroless nickel plate might be considered:

1. Corrosion Resistance. A thin nickel plate all over the optic will protect it in harsh environments.

2. Wear Resistance. The deposited nickel plate will have a Rockwell C hardness of 52-55 and can serve as a bearing surface.

3. Substrate Material Is Not Diamond Machinable. If a particular substrate material is required for other properties of that material such as strength, temperature resistance, or thermal properties then the optical surface can be rendered diamond machinable by the application of a nickel plate. Replication masters and aspheric lens molds are typical examples.

4. Geometry. In some cases where it is difficult or impossible to provide an optical reflecting surface due to the geometry of a part such as in deep ellipsoids, roof mirrors, or reflaxicons, it may be easier to nickel plate and then subsequently electrolytically gold plate to yield the final high reflecting surface. Examples of these geometries are shown in Figs. 4, 5, 6.

5. To Permit Post Polishing. If the substrate material is a soft metal such as aluminum, which is difficult to post polish, it may be advisable to preform the optic in aluminum, nickel plate and then diamond machine again prior to post polishing.

Electroless nickel plate is generally applied all over to a thickness of .004-.006 inches. Tapped holes or through holes can be easily masked, but other area masking is difficult and expensive. If it cannot be avoided, a suitable feature such as a recess, undercut, or chamfer might be added to facilitate termination of the nickel.

Diamond machining will usually remove .002-.003 of the nickel thickness. When the substrate material does not match the CTE of the plate, this differential thickness from front to back can give rise to thermal distortion due to the bi-metallic effect. Beryllium and aluminum/silicon carbide composites closely match the CTE of nickel plate and can avoid this problem. We have also applied very thin films of metals, followed directly by post polishing in an effort to avoid bi-metallic distortion.

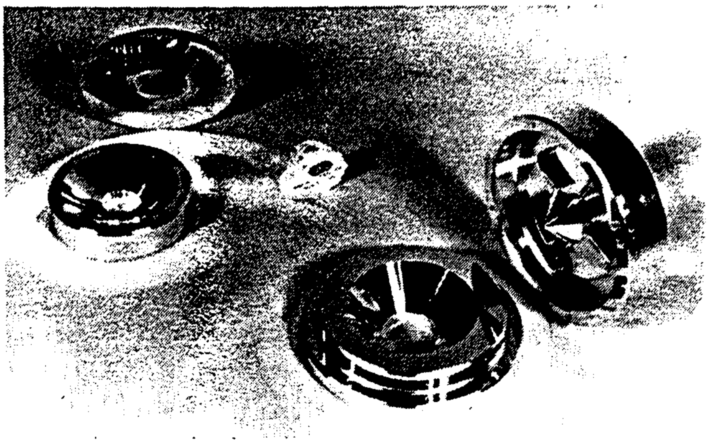


Fig. 4. Reflaxicon System Components

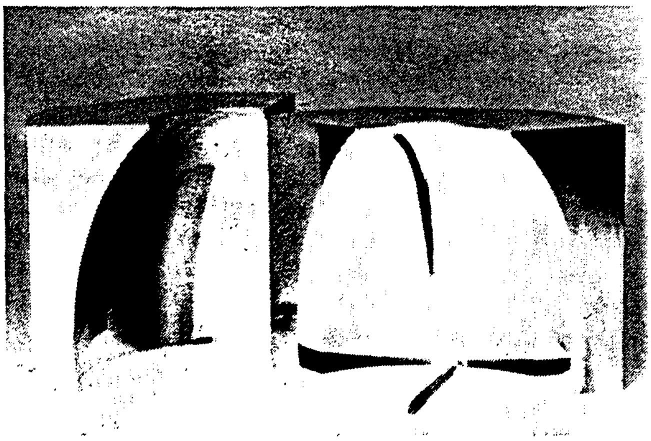


Fig. 5. Deep Ellipsoid

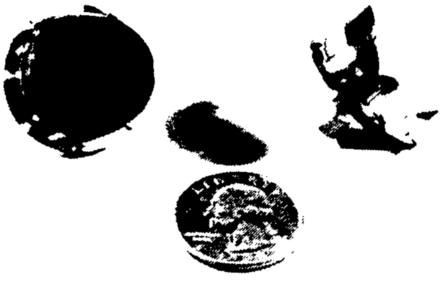


Fig. 6. Roof Mirror

2.2 Polymers

The three most popular polymers for use in diamond machining are acrylic, polycarbonate, and polystyrene. Each of these are available in optical grades. Acrylic or polymethyl methacrylate is by far the most common of all the plastics. Even though the final production method may involve the injection or compression molding of these polymers, we are very often asked to prepare prototypes by direct diamond machining prior to commiting to the much higher cost of molds. Optical parameters of these polymers and others have most recently appeared in the literature.[5] Many copolymers are also now available such as:

Methyl Methacrylate — Styrene (NAS)
Styrene — Acrylonitrile (SAN)
Allyldiglycol Carbonate (CR-39)
Poly-methyl-pentene (TPX)

2.3 Crystals

Germanium is the most common of the IR crystals, which are diamond machined. Surface finishes produced on this material are better than on any other material, including the metals and the polymers. Zinc sulfide and particularly its two water-clear versions, which are called Cleartran or Raytran by its two commercial sources,[6] has become of great interest since it transmits from 0.4 to 12.0 microns and is diamond machinable. We use this material for the construction of transmissive null optics for the testing of reflecting optical surfaces.[7] Zinc selenide does not machine as well as zinc sulfide. Although silcon is diamond machinable it is also very abrasive and results in abnormal tool wear.

Amtir 3, which is one of the chalcogenide glasses machines quite well; Amtir 1 is subject to edge chipping and is easily scratched. Cadmium telluride also falls into this latter category.

3. SURFACE FIGURE

Tabulations appear on most refractive optic drawings specifying radius of the spherical surface together with tolerances of radius, power, irregularity and surface defects in terms of scratch and dig. Many designers specify the spherical surface in grind and polish terminology, while the aspheric surface will be specified suitable for diamond machining. The implication of course is that the spherical surface will always be prepared by conventional methods. In actuality, for low lot sizes (less than 10-20) diamond machining may have a cost and delivery advantage. For very large lot sizes (5000-10000) where custom tooling is justified, diamond machining may also have a cost advantage.

3.1 Radius of Curvature

The tabulation shown in Table 2 might be representative of a typical germanium sphere/asphere. Mirrors might also be specified in this format, but the tables usefullness is greatly diminished. R_1 is the sphere in the example and its radius of curvature is given with a tolerance of± 0.05% which is typical for at least first generation diamond turning machine tools.

Any tolerance, of course, should be as broad as the design and the application can afford to minimize cost and not based simply on what the fabricator can provide.

Relatively short radii can generally be held to close limits with spherometers, par-focal microscope measurements, or interferometric means where the length of an optical bench is within practical limits, and where linear scales with vernier heads or distance measuring interferometers are accurate to micrometers. Long radii (greater than 2 meters) are not usually known to great accuracies. Errors may be in the order of 1.0-0.1%. Test plate radii in the library of many optical shops are not known to great accuracies, since traditionally they have been measured by spherometers. More accurate methods involve measurement of the radius of the concave test plate on an optical bench. Differential techniques for accurate measurement of long radii are described in the literature.[8]

	Radius	Radius Tolerance	Power Tol.	Irreg.	Scratch / Dig	C.A.
R_1	6.9302	±.004	4	1	60/40	.280
R_2	Note 6	—	—	—	60/40	.320

Tolerance Tabulation — Table 2.

Ordinarily the optician will choose or manufacture a test plate within the radius tolerance of the drawing. He will then use the test plate to guide his final polishing on the lens until the fit is within the specified power, irregularity and surface quality requirements of MIL-O-13830. The power spec. may be additive or subtractive to the radius tolerance, but since the power spec. is given in fractions of a wavelength, it becomes insignificant in relation to the radius spec. The difference in power in two orthogonal directions is astigmatism. Refer to Figure 6.

3.2 Irregularity

Irregularity refers to the height of local departures from figure. Traditionally the value for irregularity was held to 1/4 the power specification and is therefore given in waves or fringes. We have seen, however, some drawings where the tolerances for irregularity is equal to that for power. It is the intent of such a specification to control astigmatism, we are told. Use of the term "irregularity" for this purpose is not readily apparent. A more explicit specification as a drawing note should be used in this case. The German Industry Standard, DIN 3140 controls power, astigmatism, and irregularity in one coded notation.

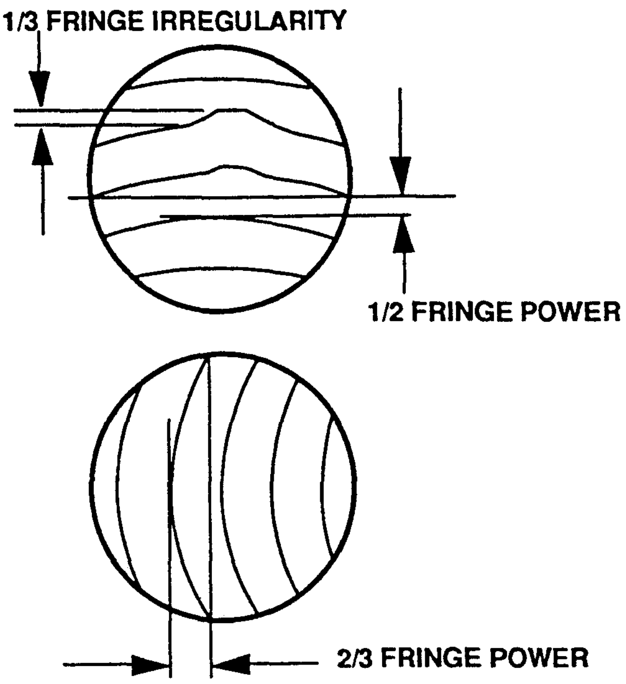


Figure 7. Power, Irregularity, Astigmatism

3.3 Aspheric Figure

The aspheric surface of R_2 in our example is defined by the closed form of the equation as presented by Malacara[9]:

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

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	$K > 0$

Incidentally, it is not uncommon to see a K value of zero with only higher order coefficients.

Sometimes the general form of the equation is presented with a tolerance, indicating maximum allowable departure from the theoretical. This method of specification also imposes a tolerance on the base radius, which might be too stringent, since power (or base radius) might be focused out in the system alignment. The departure permissible from the theoretical form should then be expressed in terms of wavelengths, but permitting the best fit of base radius.

If the optical design can accommodate a radius tolerance on the spherical radius, then the same freedom should be given to the curvature or base radius of the aspheric surface.

Figure 8 is a trace from the RTH Form Talysurf contacting profilometer. The nominal value of radius, conic constant, and higher order coefficients were inputted and printed out as the solid straight line. Peak to Valley departure from theoretical is shown as .76 micrometers. By changing the base radius only to its upper and lower limits, Peak to Valley values ranged from 2.15 micrometers "concave" to .95 micrometers "convex" as shown in Figures 8 and 9. By optimizing radius within the tolerance range, we can "bend" the aspheric form about its vertex radius to minimize P-V departure. Figure 10 is a trace of this condition and has a P-V of .43 micrometers.

It has been customary and almost understood that the figure accuracy is a Peak-to-Valley measurement, but more recently there is a trend toward specifying figure in terms of its RMS Value. As a rule of thumb, consider PV values as about 5-7 times that of RMS. For systems, error budgeting is best performed using an RSS summation of component RMS contributions. Consider also whether specifications are given in wave front error or surface figure error. The deformation of a wave front as it leaves a reflecting surface is twice that other surface figure; the wave front deformation of a transmissive optic is the RSS sum of both surface contributions times the index of the medium minus one. Its homogeniety is usually ignored. Evaluation of the surface should also consider whether a test is single pass or double pass. The budgeting of each surface contribution to total system performance should be prescribed by the optical designer.

One great advantage of contact profilometry is its ability to measure departure of the surface from theoretical in a direct absolute sense. Null transmissive or reflective test methods in conjunction with interferometers offer the best indirect method if alignments, centration, and optical quality are controlled and forced to reveal departures from absolute accuracies. The most forgiving of tests is by computer generated holograms where tip, tilt, decenter, despace, and accuracy of substrate and input data are all optimized in the test set-up without regard to absolute accuracies.

The geometrical properties of conic sections also permit determination of absolute accuracies interferometrically since measurement of vertex to focal positions can be made physically.

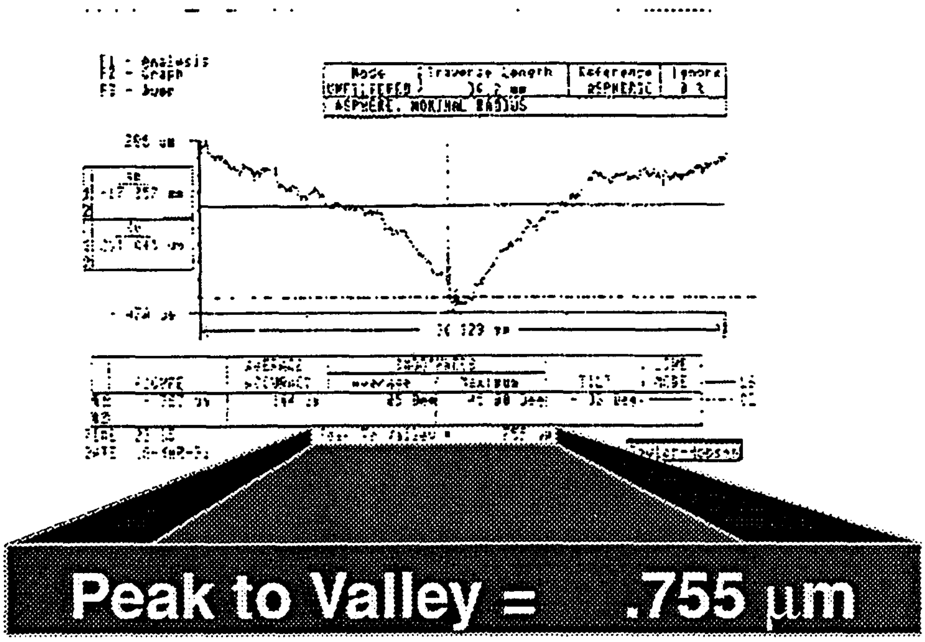


Figure 8a

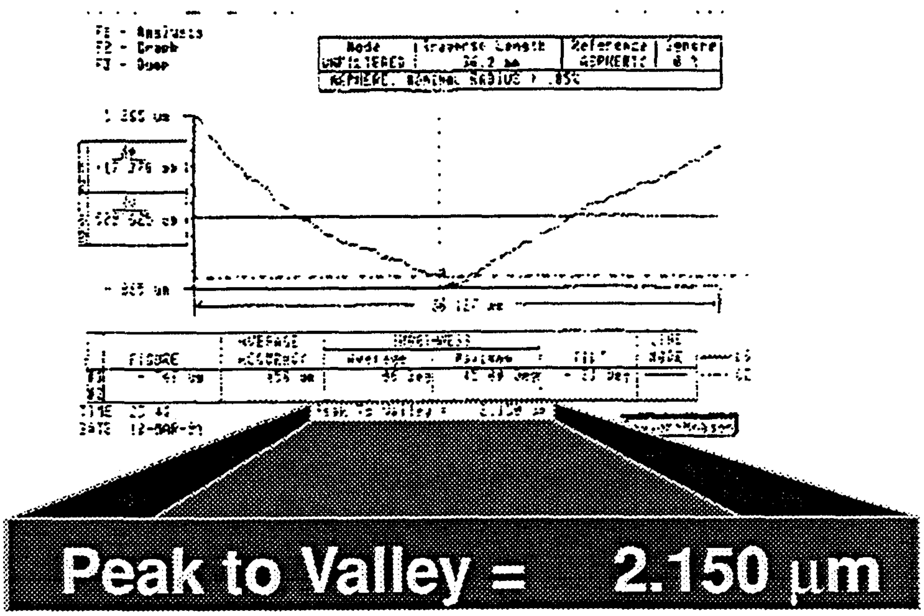


Figure 8b

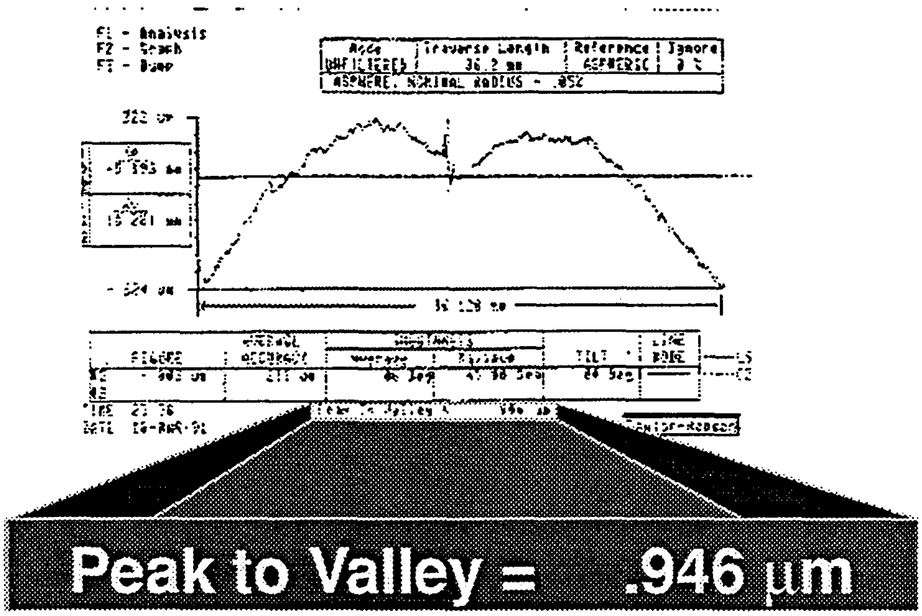


Figure 8c

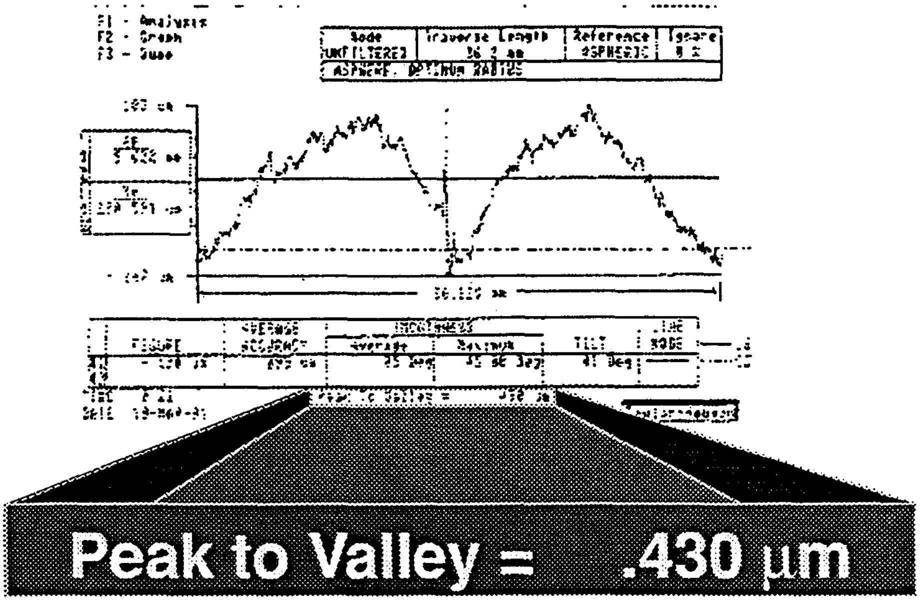


Figure 8d

3.4 Clear Aperture

The clear aperture of an optical surface refers to the total area that is used on that surface by the system. This simple definition, which may suffice for evaluation of surface quality by scratch and dig standards, may be too subtle and too restrictive for a functional evaluation. In scanning systems or multi-mirror systems, the clear aperture may be shared in time, space, or spectral bandwidth. Off-axis field points may use only a very small area of the total clear aperture. That small area then should be the basis of the required figure accuracy: "Figure accuracy over any .75 inch dia. within the clear aperture should be less than one fringe at 632 nm."

Systems, which are used for boresighting of sub-apertures, have pointing accuracies independent of surface figure quality over those sub-apertures. Visual and IR channels may have different clear apertures and different quality requirements over the same surface.

The more specific the drawing can be in defining just what is required, the more likely cost will be minimized.

3.5 Slope

Slope is the unwanted offspring of the diamond turning technology. It is defined as the angle of the tangent to the steepest inclination of a local perturbation from the global power departure. A slope specification controls the abruptness of a local departure on the surface. It is specified in angular terms: milliradians, arc seconds, or microinches per inch. Conventional, loose abrasive, methods of polishing never produce untolerable slope errors. Specifying height of the irregularity in those cases sufficed. Although slope and irregularity are controls on the same feature, it may still be valid to specify both; most drawings to my knowledge do not preclude diamond machining on the spherical side.

Typical values for diamond machining with most commercial machine tools are 2 arc seconds or 10 microinches per inch. Slope is always understood to refer to deformations of low spatial frequency in the order of 3-30 cycles per aperture. It certainly excludes the very high frequency domain attributable to diamond tool rate or the machine/optic vibrations.

4. SURFACE FINISH

It is not uncommon in our community to hear a surface finish specified as 20/10 or 60/40. These numbers, of course, refer to the scratch and dig surface imperfections which are permitted on the surface and are derived directly from MIL-O-13830. To an optician working with optical glasses or other conventionally polished materials this callout may have more meaning than those in the diamond turning sector of the business. The process of loose abrasive polishing is carried out until as the specification dictates "there is not any evidence of gray." At this point the surface finish of the optic has already achieved values much below that currently avaiable with most diamond machine tools. To specify finish or roughness that is tolerable on a diamond machined optic, it is necessary to quantify the acceptable level in terms of either RMS or arthimetic average roughness. Arithmetic Average (R_a) has been adopted as the international standard for surface roughness. Definitions of this parameter and methods of measurement are presented in the ANSI document B46.1 entitled Surface Texture[10]. Further discussion on this subject, which relates more to diamond machining, is presented in the new book entitled Surface Roughness and Scattering by Bennett and Mattson[11].

The real criteria for the value of surface roughness that can be tolerated is the amount of energy that is scattered by that surface and what this loss of efficiency means to the total system. Direct scatter measurements have not yet been widely accepted by the industry, although some commercial instrumentation has been introduced within the last several years[12].

Instead, surface roughness has been measured by either contacting or non-contacting profilometers and the scatter is calculated from the following relationship developed by the Naval Weapons Lab at China Lake[13]:

$$\mathrm{TIS} = \left(\frac{4\pi\delta}{\lambda}\right)^2$$

where δ is the RMS Surface Roughness and λ is the wavelength

The graphic presentation of this equation is a very useful tool and is shown in Figure 9[11]. A new ASTM Standard[14] for the measurement of surface roughness is based on this theory.

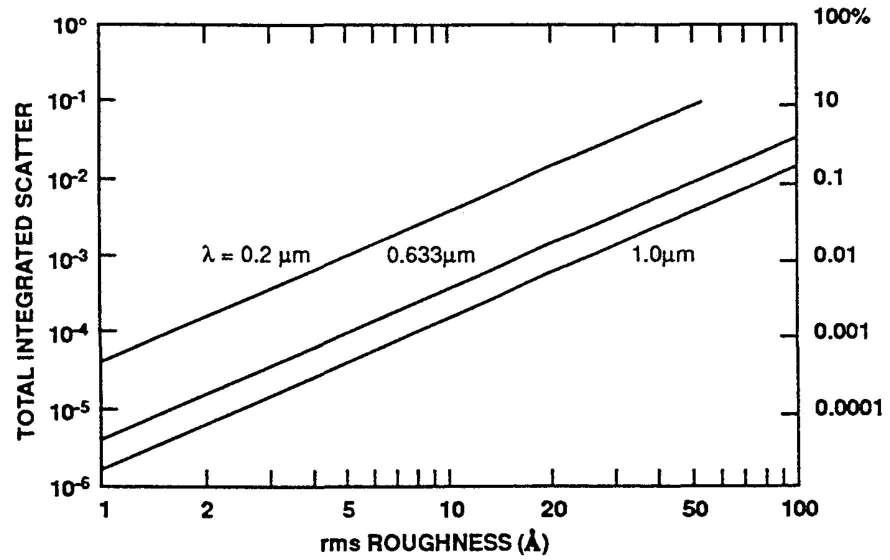


Fig. 9. Calculated TIS as a function of rms roughness for wavelengths of 0.2, 0.633, and 1.0 µm.

5. DIAMOND MACHINE TOOLS

Rank Pneumo and the Moore Special Tool Company are the two domestic producers of diamond turning equipment. Since the mid-1970's they have actively marketed their contouring machines under the model numbers of MSG-325 and M-18, respectively. Both machines are widely distributed in Europe and Asia.

Within the last 3 years, a second generation of contouring machines has been introduced to the market place by Rank Pneumo and Cranfield Precision with much increased accuracies.

A comparison of these machines and their capabilities in terms of figure and finish are given in Fig. 9. These values are approximate and should not be taken as distinct limits without more detailed discussion with the diamond machining subcontractor.

If accuracies required for a specific optical component are well beyond the capabilities of available equipment, then it may be possible and necessary to further process the optic with a post polishing process.

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.
Table 3. Machine Comparisons

6. POST POLISHING

Post polishing is that process of loose abrasive working of the surface to improve either or both figure and finish beyond that, which the diamond machine tool can produce. Most often the figure accuracy produced by the machine is adequate and only the finish must be improved to minimize scatter in the shorter wavelengths. In other cases the optician must perform the laborious task of many iterations between the polishing bench, the interferometer, and the profilometer until finish and figure goals are achieved.

The figuring of an off-axis optic from its best fit sphere to the desired asphere has traditionally been performed by mounting the optic and its surround to a strong back and then working the assembly to final finish and figure. The surround supports the lap and prevents rolled-edges on the off-axis segment. The assembly could now also be polished as a surface of revolution on a machine spindle.

With the advent of diamond machining it became possible to very quickly achieve good figure with the same approach. Now the task was reduced to one of improving finish while still preserving figure.

A somewhat harder process was also possible: avoid the complexity of making the surround and simply mount the off-axis segments on a fixture in the desired position of the parent form. Diamond machining would then be performed as with the surround, but now the post polishing task required that the optic be held stationary on the bench while the optician polishes by hand with sub-aperture laps.

In many cases, polishing within a surround cannot be performed due to the mirror configuration and complicated mounting schemes.

In other cases it may be possible to provision for post polishing and still enjoy the no-adjustment mounting advantages of diamond machining. In Fig. 10, a 2 mirror/dome system is shown with previsions for post polishing in a surround and also relating to the mounting surfaces of the optics. The sequence of operations would be as follows:

1. Conventional machine mirror and surrounds to within .001 inch of final dimensions, allowing for nickel plate thickness.
2. Nickel plate mirrors and surround components all over.
3. Diamond machine surfaces E, F, G & H on the mirrors and their surrounds.
4. Assemble each mirror to its surround as shown.
5. Perform diamond machining on each assembly establishing vertex to datum surface dimension to ensure vertex spacing of the final system.

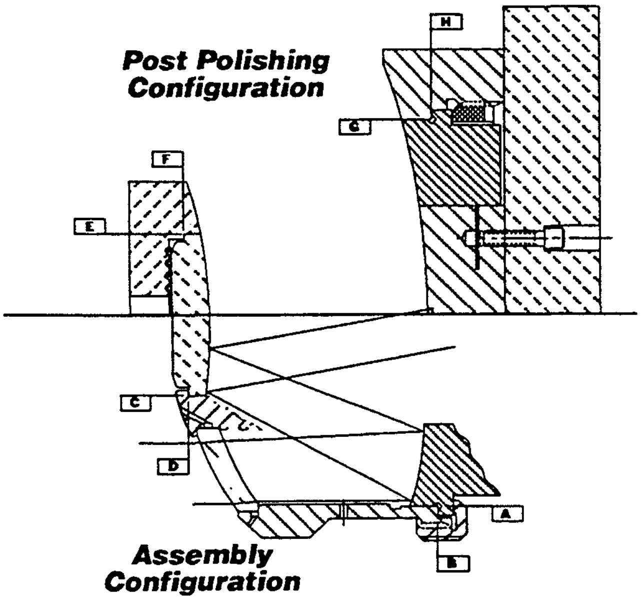


Fig. 10 Post Polishing Provisions

6. Post polish each assembly using profilometer traces or null optics to guide figure development and non-contacting profilometer such as the Wyko Topo to measure progress in surface finish improvement.
7. Independently, make up the assembly of outer housing, finished dome, and secondary mount.
8. Mount the outer surface of the dome on a vacuum chuck on the diamond turning machine. Adjust housing to center by indicating a true diameter.
9. Diamond machine surfaces A, B, C, and D in the same set-up and establishing the vertex separation of mirrors.
10. Assemble mirrors to housing.

7. FINAL OPTICAL COATING

For transmissive optics, standard or high efficiency anti-reflective evaporative coatings can be applied in the same manner as conventionally polished optics. Residual reflections can be held to 0.2 to 0.3%. Total transmission can be specified as a minimum over a spectral band or as an average over the bandwidth.

Environmental resistance and durability is specified in MIL-C-675, MIL-F-48616, and MIL-C-48497.

For reflective optics the most common coatings are protected metals. Either Aluminum, silver, or gold are chosen based on the bandwidth of interest. Table 4 is taken directly from Kingslake, which reports reflectivity of the commonly used metals. These values are reported for freshly deposited coatings at normal incidence and do not include over-coats to render the coating durable under environments. Simple over-coats usually detract from reflectivity.

For application from .6 micrometers to the far infrared an electrolytic gold plate may very well be a good choice for final coat. Electrolytic gold is hard and durable and does not require an over-coat. Gold plate does require a binding layer of nickel and where nickel plate was required for other reasons in prior operations, gold plating is a natural choice.

Table 4 Reflectance of Metals

Percent Normal-Incidence Reflectance of freshly evaporated Mirror Coatings of Aluminum, Silver, Gold, Copper, Rhodium, and Platinum, from the ultraviolet to the infrared.

λ(μ)	Al	Ag	Au	Cu	Rh	Pt
0.220	91.5	28.0	27.5	40.4	57.8	40.5
0.240	91.9	29.5	31.6	39.0	63.2	46.9
0.260	92.2	29.2	35.6	35.5	67.7	51.5
0.280	92.3	25.2	37.8	33.0	70.7	54.9
0.300	92.3	17.6	37.7	33.6	73.4	57.6
0.315	92.4	5.5	37.3	35.5	75.0	59.4
0.320	92.4	8.9	37.1	36.3	75.5	60.0
0.340	92.5	72.9	36.1	38.5	76.9	62.0
0.360	92.5	88.2	36.3	41.5	78.0	63.4
0.380	92.5	92.8	37.8	44.5	78.1	64.9
0.400	92.4	95.6	38.7	47.5	77.4	66.3
0.450	92.2	97.1	38.7	55.2	76.0	69.1
0.500	91.8	97.9	47.7	60.0	76.6	71.4
0.550	91.5	98.3	81.7	66.9	78.2	73.4
0.600	91.1	98.6	91.9	91.3	79.7	75.2
0.650	90.5	98.8	95.5	96.6	81.1	76.4
0.700	89.7	98.9	97.0	97.5	82.0	77.2
0.750	88.6	99.1	97.4	97.9	82.6	77.9
0.800	86.7	99.2	98.0	98.1	83.1	78.5
0.850	86.7	99.2	98.2	98.3	83.4	79.5
0.900	89.1	99.3	98.4	98.4	83.6	80.5
0.950	92.4	99.3	98.5	98.4	88.9	80.6
1.0	94.0	99.4	98.6	98.5	84.2	80.7
1.5	97.4	99.4	99.0	98.5	87.7	81.8
2.0	97.8	99.4	99.1	98.6	91.4	81.8
3.0	98.0	99.4	99.3	98.6	95.0	90.6
4.0	98.2	99.4	99.4	98.7	95.8	93.7
5.0	98.4	99.5	99.4	98.7	96.4	94.9
6.0	98.5	99.5	99.4	98.7	96.8	95.6
7.0	98.6	99.5	99.4	98.7	97.0	95.9
8.0	98.7	99.5	99.4	98.8	97.2	96.0
9.0	98.7	99.5	99.4	98.8	97.4	98.1
10.0	98.7	99.5	99.4	98.9	97.6	96.2
15.0	98.9	99.6	99.4	99.0	98.1	96.5
20.0	99.0	99.6	99.4			
30.0	99.2	99.6	99.4			

8. STRUCTURAL

For aluminum mirrors, thickness to long dimension aspect ratios should be in the range of 1/6 to 1/10. The ratio is dependent on the desired quality. If weight is not a concern, the least expensive mirror would be solid with 1/6 ratio.

There has been much work performed and reported in the literature on the structural design of mirrors to yield optimum temporal and thermal stability, but there is little written on the design of the mirrors to resist the dynamic forces of diamond machining. Mounts which are designed to prevent stress paths to the optical surfaces are oft times too frail for diamond machining.

9. CONCLUSION

In this writing, we have discussed some of the more salient parameters of an optical component specification. Our presentation has been simplistic, but is deemed necessary in what appears to be a scarcity of information in the literature. Drawings from many different aerospace companies differ widely in their definition of parameters and acceptance of test methods. Work must continue by the standards groups of our technical societies to arrive at more consistent methods of specifying optics.

There are two points, we have tried to emphasize here: 1. Specify both sphere and asphere to permit diamond machining of both surfaces and; 2. Include a base radius tolerance in addition to the maximum departure from theoretical for an aspheric surface.

Let's consider revision of the tolerance tabulation discussed earlier to now include a base radius tolerance, astigmatism, and slope. Standardize on 632 nm for test wavelength and the form of the equation in accordance with Malacara[9].

	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 =

Table 5. Proposed Tolerance Tabulation

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