Specifications and manufacturing considerations of diamond-machined optical components

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Abstract

This paper will review the specifications of diamond-machined optical components with special emphasis on manufacturing considerations. The specifications are divided into several topic areas. These are: material considerations, optical surface descriptions and evaluation techniques, single-point machined surface texture, defect and cosmetic considerations, coating, plating, surface finishing and environmental considerations.

Introduction

The optical engineering task is to produce optical systems that perform to a pre-determined specification. For precision imaging systems these system specifications are generally described by some form of optical transfer function (OTF) requirement. Starting with an optical design, the optical engineer must divide the system into component parts and their respective specifications. The component specifications are, in all but the simplest cases, very different in nature from the resultant system specification. The component features that affect system performace are described by surface geometries, material considerations, scatter characteristics, alignment considerations and other factors.

The task of constructing component specifications from system specifications is not an easy one. To perform this task with confidence that the final produced system will function properly typically requires: detailed optical tolerances, complex stray and scattered light calculations, mechanical and structural considerations, material science understanding and previous experience with similar optical systems. Even after such laborious effort it is rare not to find some overlooked consideration as a result of first prototype testing.

Before reviewing these specifications it is important to remember the following: the establishment of specifications for any optical component is the task of the optical engineer. The impact of these component specifications on final system performance is the engineer's responsibility and not that of the fabricator's. Although most fabricators are willing to assist the engineer with experienced information about how component tolerances will affect typical system performances, no two systems' requirements are exactly the same. Components that perform well in one instance may not be appropriate in another.

Since the burden of component specifications is on the optical engineer it is imperative that the engineer understand the method of manufacturing. Because many component specifications are statistical in nature (e.g. peak-to-valley surface topology and arithmetic average surface texture) a knowledge of manufacturing considerations will assist in understanding the nature of the component to be supplied.

The single-point diamond machining of optical components is a well-established fabrication technology. This process involves the machining of specific materials using a single-crystal, polished, natural, gem-quality diamond cutting tool. The machining is performed on a machine tool with resolution and accuracy capable of yielding optical surfaces.

Although the diamond machining process was experimented with forty years ago, its early development was slow. Less than ten years ago there were fewer than ten diamond machining facilities in the United States. Recent improvements in the technology of diamond machining have been dramatic. Partially because of the wide acceptance of the use of diamond machined components for military and commercial applications, there are now many firms offering production optical machining services and many with in-house diamond machining capabilities. This rapid growth in capabilities and potential has created a situation where optical engineers are willing to utilize single-point diamond machining technology but are unfamiliar with specifying its components.

This paper will review those single-point diamond machining manufacturing considerations that influence the establishment of meaningful and relevant specifications. A list of the topic considerations to be reviewed are:

1. material considerations
2. optical surface descriptions and evaluation techniques
3. single-point machined surface texture
4. defect and cosmetic considerations
5. coating, plating, surface finishing and environmental considerations

With the existence of many single-point diamond machining fabricators, there are naturally many different machining approaches in use. Each approach is intended to have certain advantages and trade-offs for specific types of components and tolerances. This paper's treatment of component specifications is intended to be general and independent of a particular technique or machine tool. Specific questions about holding tolerances or the applicability of a certain technique should be directed to the intended fabricator.

Material Considerations

The task of choosing appropriate materials for optical systems is based on a number of criteria. [1] Optical engineers typically choose materials based upon the following material properties:

1. optical
2. mechanical

3. thermal
4. environmental
5. availability and cost.

For all of these properties to be considered in a single application is rare. Typically, different component applications will require the evaluation of only one or two criteria. Transmissive components are generally chosen for their optical properties; reflective components, for their mechanical and thermal properties. Materials for use in molds to fabricate optical components must meet thermal and environmental considerations.

Not all materials routinely considered by optical engineers for component fabrication are single-point diamond machinable. [2] A list of the most requested materials that are not diamond machinable are:

1. silicon based glasses and ceramics
2. ferrous metals (including all types of steel)
3. beryllium
4. titanium
5. molybdenum
6. nickel (although electroless nickel plating is diamond machinable)

Although many diamond machining fabricators are involved in the bonded diamond grinding and conventional polishing of these materials, often using single-point diamond machining-type machine tools, these hybrid fabrication techniques are not considered diamond machining.

The list of materials that are diamond machinable continues to grow. A p ial list of those materials that have been successfully fabricated by di mond machining is: [3]

Metals:
- Aluminum alloys (1100, 2011, 2017, 2024, 3003, 5086, 5186, 6061, 7075)
- Brass
- Copper (oxygen free high conductivity - OFHC, electroplated, and beryllium alloyed)
- Gold
- Nickel (electroless plate)
- Silver
- Tin
- Zinc

Polymers:
- Acetal, Acrylic, Fluoroplastic, Nylon, Polycarbonate, Polypropylene, Polystyrene, Polysulfone, Silicon

IR Crystals:
- Cadmium Sulfide
- Cadmium Telluride
- Calcium Fluoride
- Cesium Iodide
- Galium Arsenide
- Germanium
- Lithium Niobate
- Potassium Bromide

Potassium Dihydrogen Phosphate (KDP)
Silicon
Sodium Chloride
Tellurium Dioxide
Zinc Selenide
Zinc Sulfide

Not all of these materials single-point diamond machine equally well. [4] Optimum manufacturing conditions (e.g. speeds and feeds, coolants, and tool conditions) will be different for each material. Several of these materials are preferred materials in the sense that the single-point diamond turning process can yield optically "smooth" and geometrically stable surfaces. For the metals, these are the following: 6061 aluminum, OFHC copper, electroplated copper and electroless nickel. These four materials make up the bulk of single-point diamond machined metals. For the polymers, the ability to machine a "good" surface has correlation with the polymer molecular chain length and elasticity characteristics, with the acrylics machining best.

The individual nature of the IR crystals' material considerations make their surfaces unique. Generally, the single crystal materials will machine to better surface textures than those machined from polycrystalline blanks. All of the IR crystal materials are subject to subsurface damage and therefore require special controlled grinding preparation of the substrate. By controlled material removal in smaller increments, similar to the technique used for precision glass subsurface damage limitation, satisfactory surface finishes can be obtained.

An important consideration in the diamond machining of metals is the proper preparation of the metal substrate so that dimensional stability will be present in the final mirror. The metallurgical considerations are vital for the substrate preparation whether the diamond machining is to be done on the bulk substrate or on an overplating. The general military and federal specifications for particular materials are useful in properly specifying the materials and processes.

The most common material for single-point diamond machining in a plated material is electroless nickel. A discussion of electroless nickel as it applies to the diamond machining process can be found in two articles. [5,6] Electroless nickel plate is an especially valuable material to the optical engineer for a number of reasons. It can be post-polished to excellent degrees of surface texture (making the components usable at visible and shorter wavelengths). [7] Electroless nickel plating yields an especially durable surface for optical molding applications. The direct single-point diamond machining of electroless nickel plate can yield superior surface texture for many applications than the machining in any bulk material.

Electroless nickel plate also has a number of disadvantages. The cost of electroless nickel-plated components will be higher than components made from bulk metals. Tool wear in electroless nickel is high. For many reasons (e.g. inclusions, pitting, inadequate bonding), failures of the electroless nickel to be suitable for diamond machining are common. The platings, which typically average only 0.003 inch thick, permit a limited number of machining passes to clean the material before breakthrough occurs. Of course, there are bimetallic thermal considerations with any plating.

Along with copper, the most common material for direct on-substrate diamond machining is aluminum. Aluminum is a preferred material for diamond machining because it is inexpensive, machines well, and has good reflectivity even uncoated. [8] Also, aluminum does not wear diamond tools rapidly, so production runs can be made with a minimum of tool changes. One negative consideration of using aluminum is its dimensional instability if not properly prepared. Below is a generic recommended procedure for the heat treatment and stabilization for aluminum mirror substrates [figure 1].

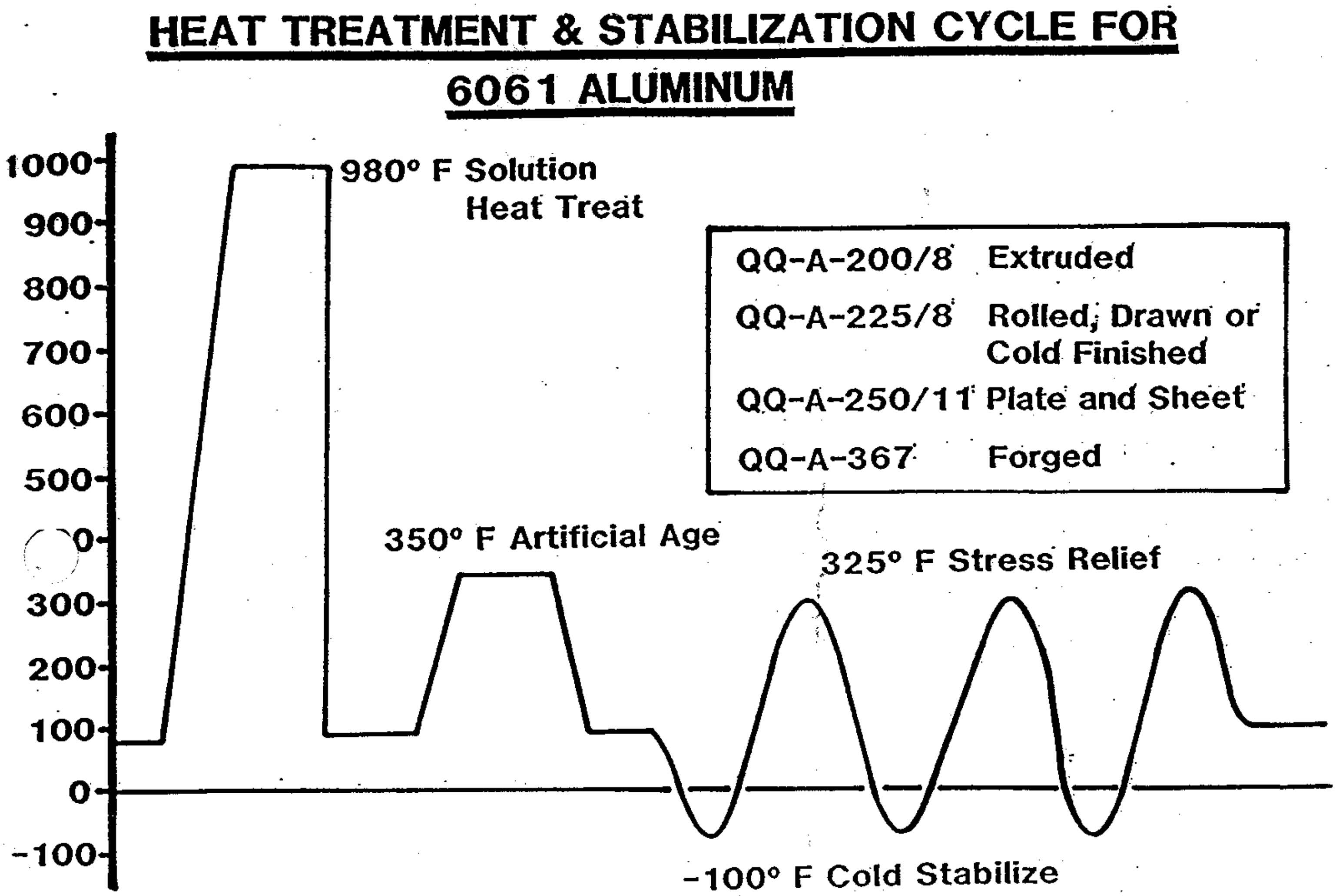


Figure 1

The following is a recommended pre-diamond machining specification for the heat treatment and stabilization of the following 6061 alloy mirror substrates:

Federal Specification QQ-A-200/8	6061 Aluminum Alloy, Extruded
Federal Specification QQ-A-225/8	6061 Aluminum Alloy, Rolled, Drawn, or Cold Finished
Federal Specification QQ-A-250/11	6061 Aluminum Alloy, Plate & Sheet
Federal Specification QQ-A-367	Aluminum Alloy, Forged

1. Rough machine the mirror blank to within 0.020" of all final critical dimensions. If the mirror has an unusually high aspect ratio (greater than 12:1) or an unusual configuration, leave more material in anticipation of warping.

2. In accordance with the Military Specification MIL-H-6088 (heat treatment of aluminum alloys) solution heat treat, quench and permit the material to come to a T4 condition as designated by the American National Standards Institute H35.1 (Alloy and Temper Designation System for Aluminum).

3. At this point an optional mechanical stress relief to place the material in a T451 condition may be used. Note that this mechanical stress relief is a stretching operation for rolled or extruded stock and a compression for forgings. Note also that large optical components should be fabricated such that the principle grain direction becomes the resultant mirrors optical axis.

4. A dimensional check of the blank should be made to insure that the heat treatment has not warped the blank sufficiently. If it has, re-rough machining should happen at this point. Tap all required holes.

5. Artificially age the mirror in accordance with the Military Specification MIL-H-6088 (heat treatment of aluminum alloys) to the T6 (or T651) condition as designated by the American National Standards Institute ANSI H35.1 (Alloy and Temper Designation System for Aluminum).

6. Stabilize the mirror blank against further dimensional changes by subjecting the blank to a three-times stabilization thermal cycle. This stabilization cycle shall be from -100 degrees F to +325 degrees F at a rate not to exceed 15 degrees F per minute.

7. Finish machine to final dimensions, and proceed with diamond machining.

Optical Surface Descriptions and Evaluation Techniques

One advantage of diamond machining is that it allows fabrication of unusual aspheric optical surfaces. Diamond machined surfaces can have greater degrees of asphericity than surfaces manufactured by conventional means. The limits imposed on permissible surface goemetries by diamond machining are few:

1. The geometrical description of the surface must be rotationally symmetric. The component may be an off-axis section provided its generating curve has rotational symmetry. An exception to this rule is the cylinder with elliptic cross-section produced by a flycutter-style machine tool.

2. The components size must be within the limits of slide travels and swing of the machine tool. In most cases it will be slide travels that restrict part size. Occasionally, small off-axis components will have geometries that place the component too far from the rotational axis and

outside the swing of the machine tool.

3. There must exist a continuous tool path that provides sufficient clearances for fabrication. Surfaces with coves or labyrinth sections (atypical of optical surfaces) are not possible.

4. Concave surfaces where the first derivative is not continuous will have, when fabricated, a finite radius in the root of the crease. This is typcial of fresnel surface connections and at the center of hollow axicons.

Even with these restrictions, diamond machining permits the fabrication of many unusual optical geometries. Some surfaces that have been machined ar(

1. generalized aspheres with spherical, conic, even and odd polynomial terms
2. non circular cross-sectional toroids
3. concave and convex cyclinders and axicons
4. Fresnel (curved or straight), echelle, and grating type surfaces
5. surfaces defined by splines and differential equations

There are many ways to specify surface geometries. In general, it is best to express the surface shape by a closed-form equation of the radial variable such as:

$$z(x)=cx^2/\left(1+\sqrt{1-(k+1)c^2x^2}\right) + a_1x^4 + a_2x^6 + a_3x^8 + a_4x^{10} \qquad \{1\}$$

The surface shape expressed in a form like this is helpful to the fabricator since first-derivatives must normally be generated. When the surface shape cannot be described by a function of the radial variable, as in the case of hyper-ellipsoids, the shape should be described by a two-branch function. In these cases a pictorial representation should be used for clarity. In all cases the surface equation should be stated on the drawing since sign conventions and symbolism vary between optical designers. A partial table of sagitta values on the drawing is useful as a reference. A table of sagitta values alone is not sufficient to define an optical surfac because different numerical curve fitting techniques will yield many curves to one table of data.

The tolerancing of a surface's geometry is a function of that component's effect on the optical system and must be defined by the optical designer. It is customary to tolerance aspherics by defining a permissable zone of error (figure error) about the nominal surface. This is done by specifying surface distortion in fractions of a system related wavelength, either in peak-to-valley or root-mean-squared (rms) deviation.

Another common tolerance applied to surface geometry is permissable gradient error. This tolerance is specified as an angular tolerance and controls the maximum slope departure from the specified form. This tolerance is often expressed in units of wavelength per inches, wavelength per mm, arc seconds or microradians. For diamond machined components this error is applied only to macroscopic surface form errors and not to the residual tools marks. Tool mark microtopology characteristics are controlled a separate surface texture (roughness) specification.

The testing method for establishing these tolerances should be examined by the optical engineer. There are many ways to test aspheric shapes for figure accuracy. [9,10,11] Aspherics intended to be used with other components can sometimes be tested as a system wavefront specification. When the surface shape is a conic section of revolution, it is tested by axial conjugate matching interferometric techniques. The most widely used method for evaluating a single generalized aspheric surface is wavefront matching interferometry. The distortion of a wavefront to test aspheric surfaces can be produced by three distinct types of optical elements: computer generated holograms, null lenses and null reflective aspheric compensators.

Though computer generated holograms and null lenses have been used extensively for aspheric testing, they have several disadvantages. Aligning the surface under test with the hologram or null lens is difficult and position errors will influence test results. Also there is no ready means to qualify wavefront performance from the null optic. Cost considerations for holograms or null lenses may be as much as for the component to be tested.

A new technique for evaluating aspheric surfaces involves the use of diamond machined null reflective aspheric compensators. These compensators are designed to be the end reflector in an interference cavity where the surface under test is evaluated in a double-pass configuration (see Figure 2 for schematic testing configurations). The compensator design is based on the attainment of an axial stigmatic image in a centered optical system by the use of a final surface asphere. [12] This form of testing has many advantages. The compensator can be diamond machined. Conjugates for the test can be designed to minimize the size of the compensator, hence its cost. Many null reflective components have been fabricated on the end of a 1/2 inch aluminum dowel. The small size permits the diamond machining to hold tight geometry tolerances on the aspheric surface. Because the optic is diamond machined, integral alignment surfaces are added to reduce set-up time and alignment errors.

In general these aspheric reflectors cannot be independently qualified. In some instances, test conjugates have been designed for the null reflector to be nearly plane. In these instances contact straightness measurements across the surface have been sufficient to qualify the geometry.

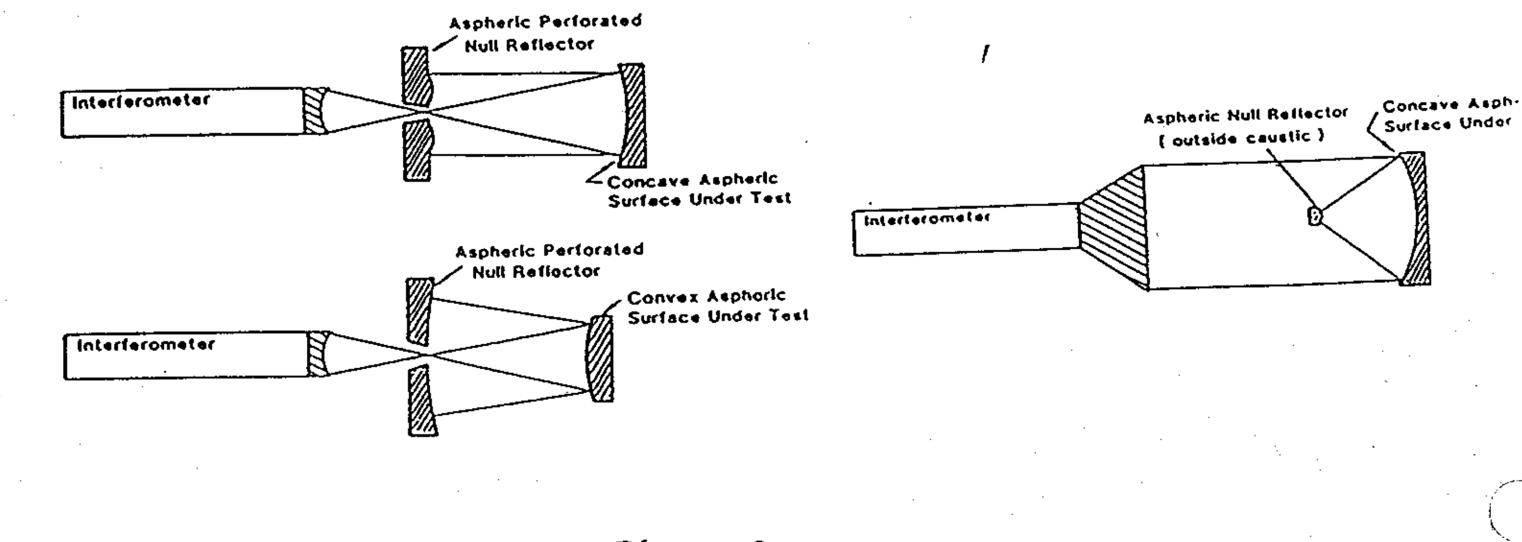


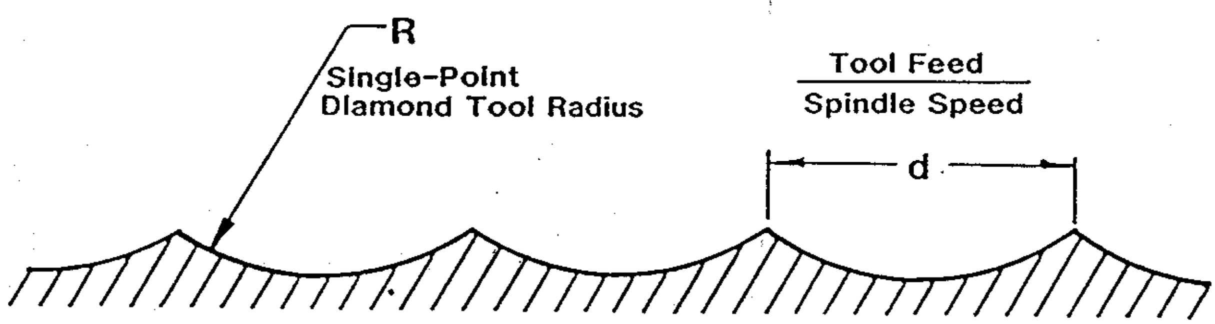
Figure 2

Single-point Machined Surface Texture

Surface induced scatter must be controlled in optical systems. [13] In addition to the associated light loss, surface scatter will reduce OTF system performance. Scattered light will be produced by both in-field-of-view sources and oblique, unbaffled stray light. It is the responsibility of the optical engineer to understand the effects of surface scatter on system performance. Diamond machined surface roughness must be specified to limit scatter to acceptable levels.

All diamond machined surfaces have residual tool marks. These surfaces have been empirically studied. [14,15,16,17] Residual tool marks yield what appear to be complex surfaces. However, the elimination of metallurgical considerations (i.e. microporosity, grain structure, and material flow) leaves a microtopology of simple tool cusps. The simple tool cusp model has been theoretically evaluated for its optical scattering characteristics. [18,19]

Tool marks appear under the microscope as parallel straight line grooves. In cross-section, these grooves are a series on concatenated circular arc cusps where the radius of the circular arc (R) is the image of the tool. The periodic spacing of the cusps (d) is the quotient of the linear feed divided by the rotational speed used to produce the surface. From this model, useful statistical information of surface texture (roughness) characteristics can be derived. If the assumption is made that the tool radius (R) is much greater than the feed-speed quotient (d) then the calculation of statistical properties becomes considerably simpler. See figure 3 below.

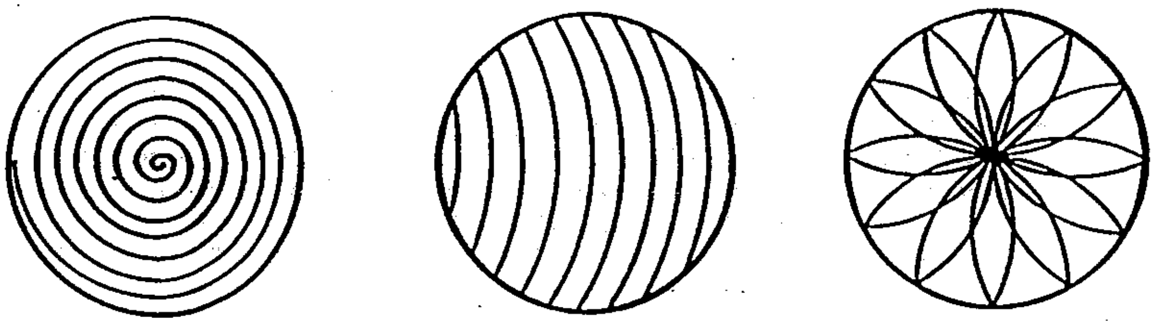


When R >> d Then

$P\text{-}V = d^2/8R$ $RMS = 0.299\ P\text{-}V$ $R_a = 0.346\ P\text{-}V$

Figure 3

One important aspect of the machined microtopology is lay orientations. [20] This is important in the calculation of diffraction effects from the entire surface. There are three types of machine lay produced on diamond machined optics. The spiral lay is typical of an X-Z, X-Z-B or R-theta contouring machine tools. The straight circular lay is typical of the patterns produced on a flycutter. The radial circular lay is produced by machining a rotating component with a flycutter head. These three forms of lay are represented in figure 4, greatly magnified.



Spiral Lay — Straight Circular Lay — Radial Circular Lay

Figure 4

To determine the feasibility of using diamond machined components for specific applications, a detailed study may not be necessary. Simplified back-of-the-envelope calculations can be performed that describe expected scatter characteristics. A calculation of surface height characteristics will determine the percentage of scattered energy, and a calculation based on surface periodicity will yield information concerning angular distribution. Using the gross assumptions that the surface height profile is Gaussian in distribution, which it is not, the total integrated scatter loss can be calculated from

$$TIS = (4\pi[rms]/\lambda)^2. \qquad (2)$$

Information about the angular nature of the scatter can be calculated from the grating equation,

$$N\lambda = d(\sin\vartheta_i \pm \sin\vartheta_s), \qquad (3)$$

where N is the diffraction order.

There are many techniques available to evaluate surface texture. Techniques for gathering surface roughness data directly include mechanical stylus probing, interference microscopy (Mireau, Fizeau, and FECO), and laser heterdyne profilometry. Those techniques that permit a direct measure of scatter characteristics are TIS (integrating spheres and Coblentz spheres) and BRDF measurements. Unfortunately, for many reasons, including the lack of commercial instruments for the purpose, the direct measure of scatter from these surfaces is seldom used.

A general recommendation for specifying the surface texture of diamond-machined components to date is to:

1. Specify an rms or Ra surface roughness.
2. Specify an appropriate machine lay that is consistent with the genera fabrication restrictions.
3. Request from the fabricator what the tool radius and residual tool mark spacing will be.

Defect and Cosmetic Considerations

The defect and cosmetic considerations of diamond machined optics are as important as the cosmetic considerations of conventionally fabricated optics and should therefore be specified where appropriate for the application. Specifying maximum surface defects on diamond machined optics is typically done to limit the scatter from such flaws or to prevent the high-power damage failure of components.

Cosmetic considerations are distinct from surface texture considerations. Although both surface texture problems and surface defects may have similar negative effects on system performance, their respective specifications are mutually exclusive. The requirements of a given scratch and dig will not pla[illegible] restrictions on surface texture. Likewise, an arithmetic average value will not determine a maximum localized defect size. On this point the ANSI standa[illegible] for surface texture is very clear:

> "Flaws are unintentional irregularities which occur at one place or at infrequent or widely varying intervals on the surface. Flaws include suc[illegible] defects as cracks, blow holes, inclusions, checks, ridges, scratches, et[illegible] Unless otherwise specified, the effect of flaws shall not be included in the roughness average measurement. Where flaws are to be restricted or controlled, a special note as to the method of inspection should be included on the drawing or in the specification." [21]

The general use of the Military Specification MIL-O-13830 (Optical Components for Fire Control Instruments; General Specification Governing the Manufacture, Assembly, and Inspection of) [22] is not recommended as a scratc[illegible] specification for diamond machined parts. This recommendation is based upon the following considerations:

1. the MIL-O-13830 scratch standard is not a performance specification. [23]
2. scratch classifications made under MIL-O-13830 criteria are visually evaluated in comparison to scratch standards made to Surface Quality standards Drawing C7641866 [24] which are fabricated on uncoated glass samples.

This last point is especially important, since many diamond turned surfaces a[illegible] highly reflective. The visual appearance of scratches is affected by many factors, notably surface reflectivity. [25,26,27] All visual tests for scratch size, such as that of ANSI - PH3, 617-1980 [28], that are made under specified lighting conditions also suffer from scratch appearance variations which are a function of surface reflectivity, general texture and material considerations. These test forms should also be rejected as appropriate specifications for diamond machined optics. It is interesting to note that MIL-M-13508 [29], a high reflectivity coating, references MIL-O-13830 for its defect comparisons.

For diamond machined components the specification of defects (cosmetics) is best done by specifying a direct dimensional measurement. This can be don[illegible] [illegible]h MIL-F-48616 [30], MIL-C-48497 [31] or some other direct dimensional specification.

Coating, Plating, Surface Finishing and Environmental Considerations

To enhance the component's optical and environmental perforance, coatings should be applied to its surfaces. These coatings can be applied by evaporated thin film deposition methods and, with metal components, chemical platings. Diamond machined infrared material components can be coated to the same military specifications as conventionally fabricated parts (e.g. MIL-C-675C [32] MIL-C-48497 [33], and MIL-F-48616 [34]). For reflective optics many metal-dielectric coatings can be used, including protected aluminum per MIL-M-13508C [35]. To characterize the optical environmental characteristics of the coating, witness samples of the component materials should be coated with the parts. If a spectrophotometer without an integrating sphere attachment is used, the witness sample should be polished.

Because most diamond machined reflective optics are metal, platings are sometimes used instead of evaporative coatings. Two of the most common finishing platings applied are gold (MIL-G-45204C [36]) and silver (QQ-S-365C [37[37]). As has been discussed, electroless nickel (MIL-C-26074B [38]) and elctrolytic copper (MIL-C-14550B [39]) can be used as a machining layer. Always include a tapped hole in the substrate for proper electrical contact.

Because stray light will reflect off the non-optical surfaces of metal mirrors, these surfaces should be finished to reduce unwanted light. This is done by roughing (rilling) and blackening these surfaces. Because the hard anodize of aluminum (MIL-A-8625C TYPE 3 [40]) is not diamond machinable it should be avoided unless proper masking is employed. Sulfuric anodizing of aluminum (MIL-A-8625C TYPE 2) is preferred because it can be diamond machined. A recommended surface treatment prior to painting an aluminum is alodyne (MIL-C-5541C [41]). Copper mirrors may be blackened by the ebonol process (MIL-F-495 [42]).

Aside from considerations of high energy density use components, which must be specified by appropriate damage threshold limits, environmental specifications are required as part of the coating requirements. Diamond machined aluminum optics should be capable of surviving temperature and humidity testing if all surfaces are properly protected. These optics should also pass adherence (tape pull) tests. Durability (cheese cloth rub) specifications should be reduced whenever possible to the lightest load and fewest strokes required. These optics will not survive the following tests: salt spray or fog, salt solubility, severe abrasion (pumice eraser), fungus growth or sand erosion (MIL-STD-810D [43]).

Conclusion

This paper has discussed considerations important to the specifications of diamond machined optical components. Additional information can be obtained from the cited references below. By better understanding the diamond machining process, improved component specification will be developed.

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39. United States Department of Defense Military Specification MIL-C-14550B, "Copper Plating (Electrodeposited)", (1975).

40. United States Department of Defense Military Specification MIL-A-8625C, "Anodic Coatings, For Aluminum and Aluminum Alloys", (1969).

41. United States Department of Defense Military Specification MIL-C-5541C, "Chemical Conversion Coatings on Aluminum and Aluminum Alloys", (1981).

42. United States Department of Defense Military Specification MIL-F-495D, "Finish, Chemical, Black, For Copper Alloys", (1975).

43. United States Department of Defense Military Specification MIL-STD-810C, "Environmental Test Methods", (1975).