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A PERSPECTIVE ON PRECISION MACHINING,
POLISHING, AND OPTICAL REQUIREMENTS

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A perspective on precision machining, polishing, and optical requirements

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Summary

While precision machining has been applied to the manufacture of optical components for a considerable period, the process has, in general, had its thinking restricted to producing only the accurate shapes required. The purpose of this paper is to show how optical components must be considered from an optical (functional) point of view and that the manufacturing process must be selected on that basis. To fill out this perspective, simplistic examples of how optical components are specified with respect to form and finish are given, a comparison between optical polishing and precision machining is made, and some thoughts on which technique should be selected for a specific application are presented. A short discussion of future trends related to accuracy, materials, and tools is included.

Introduction

It is now well known that single point diamond turning (SPDT) or precision machining, as it is called, has become very attractive and in some cases the preferred method for producing certain classes of optical surfaces. For those not acquainted with this technology, precision machining is here defined as the combination of the very hard and sharp edges obtained from certain crystals (usually diamond) with extremely precise machine (either liquid or gas bearing) tools operating under closely controlled environmental conditions to produce finished or nearly finished optical surfaces. This technology removes some of the difficulties in forming optical surfaces encountered in conventional grinding and polishing specifically for that family of materials, both physically and chemically compatible with a diamond cutting tool. Because the tools are so hard and sharp, no cutting edge contact area is presented to the material. This promotes the cutting process by restricting it to a thin shear plane with a minimum of contact stress or friction¹. This results in a process that minimizes material deformation and hence results in both the specular finish required for optical surfaces and a contour that is an exact copy of the tool path.

The origins of precision machining date back to World War II where such organizations as Phillips Research Labs (The Netherlands), Bryant-Simmons (Great Britain), Union Carbide Corporation, Lawrence Livermore National Laboratory, Battelle Northwest, and Perkin-Elmer Corporation (USA) began to focus attention and effort on this technology. Studies specifically directed at applying this technology to the production of optical surfaces dates back to the late sixties and is largely due to the development of a viable precision air bearing spindle. Optical surfaces that could be considered more or less acceptable for infrared or long wavelength applications appeared in the early seventies. Since that time, technological advancements and experience in precision and control through such advances as the Laser Distance Measuring Interferometer and thermal control techniques have contributed to the current situation. Today, precision machining enjoys the status of a generally accepted process capable of producing a class of optical components on a routine and often high production basis.

In this paper, an attempt is made to present some perspective on how this technology impacts the optical manufacturing industry. The goal is to provide the reader with an understanding of the important characteristics of optical surfaces and how precision machining fits into and compares with the family of current optical production techniques used for producing these characteristics. It will attempt to show how and why optical surfaces are specified as they are and how well surfaces manufactured by precision machining satisfy these requirements. It will compare and contrast conventional optical manufacturing processes to precision machining in the hopes of clarifying where each process excels and fails. This will be followed by a discussion of the relationship of precision machined surface characteristics to optical functionality. Finally, some thoughts will be given as to where this technology is likely to progress and what might be expected in the future from precision machined optics.

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A snapshot of the current precision industry

Before delving into the roles and relationship between precision machining and optics it is useful to provide some insight into the precision machining industry as it currently exists in this country. As indicated there are a somewhat limited class of materials (see Table I) that lend themselves to processing by single point diamond tooling, but the variety of diamond turned products produced from these materials is quite large and rapidly expanding. Perhaps the most successful products to result from this technology have been related to computer and optical applications. Table II presents some of the more prominent and successful applications of precision machining.

Table I. List of materials currently known to be compatible with diamond tools, and hence considered machinable*

Aluminum	Electroless Nickel
Brass	Alkali Halide (salt) Crystals
Copper	Zinc Sulfide
Beryllium Copper	Zinc Selenide
Gold	Germanium
Silver	Many Plastics
Lead	Machinable Ceramics
Platinum	Potassium Dihydrogen Phosphate (KDP)
Cadmium Telluride	

Table II. Various components and products that can and have been efficiently fabricated using diamonds and precision machines

Computer memory disc's and drums	Gyro components
Recording heads	Precision pump parts
Missile components	Bearing bores and races
Various precision rolls	Dies for molded lens fab.
Photocopier components	Traveling wave tubes
Aspheric reflectors	Infrared optical components
Precision measuring instruments	Optics of unconventional geometry
X-ray telescope objectives	

As of this writing, both the advantages and true extent of the applications are just now being discovered. The number of uses, both optical and non-optical are expanding at a very rapid rate. Unfortunately, the long lead times, and in many cases, prohibitive start-up costs have developed, at least, a serious temporary shortage of accessible precision machine capacity, particularly in the optical community. The commercial potential is clear, so it is likely that the current people and machine short fall will disappear in coming years. Table III presents my understanding of the currently operating precision machine facilities in this country. This is the result of my poor preceptions and is presented only to serve as a general overview of the current level of capability. My apologies to those I've misrepresented. A considerable number of these organizations are either government complexes or heavily committed to ongoing programs, either governmental or internal, so the actual purchasable capacity is considerably less than what's indicated.

Optical specifications and precision machine manufacturing

In developing a perspective for precision machining in optical manufacture, it is important to become familiar with the purpose or functionality of the product, in this case, surface being made. By far, the most important aspect in manufacturing an optical surface is how the result interacts with the incident light, primarily with respect to those characteristics of the surface that result from the manufacturing process. Many properties of the surface and material effect this light interaction. A list of these is given in Table IV and must all be considered for good basic optical design. Once past this stage and into manufacturing, however, all these properties may be neglected except where they impact the fabrication process employed or where the fabrication in turn impacts them. When all these factors are properly accounted for, the problem of optical manufacture reduces itself to the control of the two principal shape factors effecting the optical surface quality. These factors are contour (form) and microtopography (finish).

*All of these materials can be plated or coated onto a vast number of substrates to combine the properties of those substrates with the turnable properties of the above list.

Table III. Summary of precision machining facilities
(Turning Machines)

Facility	Affiliations	Number of Operating Machines	NC	Comments
Lawrence Livermore National Laboratory	DOE	2	Yes	Laser and Weapon work
Union Carbide Corporation, Y-12 Plant	DOE	4	Yes	Laser and Weapon work
Rocky Flats (Division of Rockwell International)	DOE	1	Yes	Operational 1976 (Development funds red.)
Bendix	Private Industry	1 operational (1978-79)	Yes	
Frank Cooke Optical	Private Industry	1	Yes	
Battelle Pacific Northwest	Private Industry	1	Yes	
Bell & Howell	Private Industry	1 ?		
Perkin-Elmer	Private Industry	1	No	Template
Polaroid	Private Industry	1	Yes	
Pneumo Precision	Private Industry	1	Yes	
Applied Optics Center	Private Industry	2	No	Flats only?
Honeywell	Private Industry	5 ?	Yes	
3M & IBM	Private Industry	?	?	
Intop	Private Industry	1 ?	Yes	

From the precision machining point of view, surface contour and finish are aspects of the same problem, namely shape, and differ only in terms of the wavelength band (spatial frequency) that they occupy with respect to machining characteristics. The development of appropriate specifications for optics produced by precision machining must unite these two principal shape factors and the unique characteristics of precision machining. This is due to the fundamentally different results obtained from any production process based on considerably different mechanisms. The most obvious difference between the resultant optically polished and diamond machined surfaces is the highly correlated groove structure of the latter. As such, specifications for optical surfaces produced by precision machining will necessarily have to account for this grooving (among other things) and therefore, be process specific.

Table IV. Factors that must be considered and, if necessary, specified in the design and manufacture of optical components and surfaces.

Reflectance	}	angle of incidence
Transmittance		
Absorptance		
Spectral response (dispersion)		
Index of refraction (homogeneity)		
Weight and strength		
Resistance to environmental factors		
(Temperature, pressure, radiation, humidity, contaminants and corrosives)		
Manufacturability		
Stress and polarization effects		
Scatter and microtopography		
Contour		
Power level		
Geometry		
Coatings		

Factors in the precision machining of optics differ significantly from polishing with respect to form and finish specifications. Contour accuracy in precision machining results from a combination of machine way straightness, the feedback-control system, the leadscrew, bearing runout, and thermal effects. Microtopography values relate to a combination of theoretical finish which results from depth of cut, spindle or tool speed, tool profile, and feed rate factors, acoustic coupling, mechanical chatter and vibration. Optical surface specifications will dictate values tolerable for all these, but the key to successful manufacturing is knowing the origin and therefore believing the optical specifications in the first place.

For these reasons, the remainder of this section will concentrate on how and what is specified with respect to form and finish on an optical surface. Optical surface specifications are highly application dependent however, so it is impossible to adequately cover all the various aspects, quality criteria and methods. For more complete coverage, the reader is referred to other, more complete works on the topic²⁻⁴.

Contour

Optical surface contour, from reflecting optics for example, are usually specified and qualified with respect to how well the image reproduces the spatial content of the object field (related to resolution). Consider a reflecting optic as a black box linear system (Figure 1) which converts an incident planar or diverging spherical wavefront from any object point into a spherical wavefront converging to its geometrical image point. If we assume that the incident wavefront is perfectly flat or spherical (not always the case when atmospheric effects or other imperfect components are taken into account), then our black box (if perfect) will faithfully reproduce the object differing only in diffraction effects. If our mirror (black box) is not perfectly shaped (at least to within the limits of diffraction), the reflected wavefront will not be perfect and will form an image that differs both geometrically and in spatial content.

As in any field, there are many quality criteria that may be applied, for extraction of tolerances and hence, specifications. Perhaps the most common one in optics is simply the resolution of two object points separated by the diffraction spot size (Rayleigh Criterion)⁵. For the sake of this discussion and brevity, however, consider instead the ability of a mirror/lens to reproduce the spatial content of the object. The most common method is through the Modulation Transfer Function (MTF) whose value at any point measures that surface's ability to image a specific spatial frequency. It relates the image contrast (C) or

$$C = \frac{I_{\max} - I_{\min}}{I_{\max} + I_{\min}} \quad I = \text{light intensity}$$

to each spatial frequency the optimal system encounters. All values of the MTF will be between 0 and 1. A contrast of 1 means perfect duplication and a contrast of zero indicates that it will not be seen in the image. All values in between can be thought of as gray levels in the spatial frequency (i.e. difference between the light and dark in a black white bar pattern of that spatial frequency). This measure is defined as the modulus of the Optical Transfer function defined by

$$MTF = |OTF| = [(OTF)(OTF)^*]^{1/2}$$

where

$$OTF(x,y) = \int_{-\infty}^{\infty} da \int_{-\infty}^{\infty} db \quad P(x,y) \cdot P^*(x+a, y+b)$$

a & b = dummy variables p = pupil function

It is straight forward to see the relationship between the image of a point, the OTF, the MTF and exiting wavefront as shown in Figure 2 where for example

$$FT \quad P(x,y) = A(\zeta, n) = \frac{1}{2\pi} \int_{-\infty}^{\infty} P(x,y) e^{-i2\pi(\zeta x + ny)} dx dy$$

The MTF and diffraction image of a point object for a perfect-circular mirror is shown in Figure 3. If the mirror contains contour errors due to manufacturing, the exiting wavefront will lead or lag the proper wavefront causing phase errors to appear in the pupil P(x,y). These errors will degrade the image and be noted by drops in the MTF function. As a result, the computed volume under the MTF drops and thus can be a generalized measure of the systems performance. The amount of wavefront lead or lag, expressed in wavelengths of light can be tolerated by the corresponding drop in MTF volume. This lead/lag, if expressed in wavelengths can be directly converted to other

physical units of departure from the wavefront (microinches, micrometers, Angstroms) and related to the manufactured mirror surface through a simple factor of two. From this, the contour tolerance and specification is straight forward, at least for imaging systems

One specific precision machine error contributing to optical surface form error not found in conventional polishing operations and first discussed by Freniere and Zimmerman⁶ is decentration error. Here, the origin of the diamond tools coordinate system does not lie exactly on the spindle axis of the machine, but at some position ϵ_x and ϵ_y away from that point as shown in Figure 4. This results in a conical surface departure or error shown in Figure 5 which can be expressed by

$$E = \frac{\epsilon_x^2 + \epsilon_y^2}{2R} - \frac{o \epsilon_x}{R}$$

where ϵ_x = error parallel to the tool motion plane
 ϵ_y = error perpendicular to the tool motion plane
 E = surface departure
 R = base radius of the sphere
 o = radial position of the tool from the spindle axis

The designer will use this or other known error tolerance methods to determine either a Root Mean Square (RMS) or Peak to Valley (PV) contour error tolerance. This tolerance is almost always expressed in wavelengths of allowable departure from the ideal contour. Close interaction between the manufacturer and designer will assure that the intended tolerance is understood and achievable.

Finish

Optical surface finish, roughness, microtopography or microroughness as it is commonly termed is of interest in specification of precision machining operations primarily because of its effect on the reflectance, transmittance and stray light properties of the optic. In many applications, the machine groove structure and even microscopic ripples within the grooves (both parallel and perpendicular to the grooves) cause unacceptable changes to the above listed optical properties. Therefore, it is important to relate the characteristics of machined surfaces to the optical properties and understand when these are or are not important. A complete description of this relationship may be obtained from the work of Church⁷ and will be summarized in what follows.

The principal effect of a "rough" surface is scattered light. A schematic of what scattering is and the normally applied geometry is presented in Figure 6. One can think of an optical surface, for the sake of modeling, as a surface consisting of a very large number of sinusoidal diffraction gratings (each a Fourier component of the surface defined by $A \sin(2\pi x/d)$) of different amplitude, direction and frequency. Each of these Fourier components with their various spatial wavelengths will scatter light of wavelength λ at a specific angle (θ_s) given by

$$\sin \theta_s = \sin \theta_i \pm \lambda/d$$

These relationships indicate that the intensity of the scattered light is determined by the vertical amplitude (A) of the roughness and that the angular direction of the scattered radiation is determined by the reciprocal of the spatial wavelength (d) of the roughness. It can be shown from scalar scattering theory⁸ that the relation between the RMS roughness (σ) and the normal incidence reflectance is

$$\frac{R}{R_o} = \exp \left[\frac{-4\pi\sigma^2}{\lambda} \right] + \frac{2^5 \pi^4}{m^2} \left(\frac{\sigma}{\lambda} \right)^2 \Delta \theta^2$$

where

R = Sum of the scattered light
 R_o = Specular reflectance

This becomes extremely important in specifying precision optical surfaces when one realizes that over 1% error in measured reflectance will be obtained from surfaces whose roughness σ is only $\lambda/100$. In machine terms, this indicates that the peak to valley error (theoretical finish plus all other errors) can not exceed 1.25 microinches for red visible light ($\lambda = 6382\text{\AA}$). The errors in reflectance as a function of wavelength and rms roughness are shown in Figure 7.

For a diamond machined surface whose microtopography resembles a rotationally symmetric diffraction grating, the scattered radiation from reflection will show distinct diffraction orders related to the groove structure, while a polished surface will show a less featured, more uniform pattern. When one plots the amount of scatter normalized to the specular reflectance (R/R_0) as a function of the scattering angle, profiles typified by those shown in Figure 8 are obtained. From this, it can be inferred that, if very low scatter surfaces are required, it will in general be necessary to smooth diamond turned surfaces by polishing, ion milling or some other area averaging process to reduce the amplitude of the groove roughness.

It is well known that the smoothness of a precision machined surface is dependent on the feed and speed of the machine set up in a particular application. Donaldson, et al⁹ has shown that the theoretical finish (the best a machine can do) for a precision machined surface may be computed. Assuming the use of a round nosed tool, this is done by determining

$$p \text{ to } v \text{ height} = h = 2r_o \left(1 - \sqrt{1 - \frac{a^2}{4r_o^2}} \right)$$

which reduces to

$$h = \frac{a^2}{8r_o}$$

where r_o = tool radius

h = p to v height

a = feed

for $a \ll r_o$ (i.e. tool radius is large compared to the feed in distance per revolution.)

Other common causes of roughness are vibration between the tool and material due to mechanical or acoustical coupling, tool chatter, chip scoring caused by material lodging between the diamond cutting edge and the material, and mechanical defects or inhomogeneities in the material itself.

The bottom line to all of this is that the surface isn't good enough just because it has a "mirror finish" and one can see his face in it. It is best specified by (primarily for simplicity) by the sum of the scattered light normalized to the specular light. This is commonly titled Total Integrated Scatter (TIS) and will hopefully be standardized soon through a, to be published, ASTM standard. In some optical applications, scattering at particular angles will be allowable or even desirable while in others, it must be minimized all together. Depending on the situation, surface finish will probably be specified by either wavelengths of rms roughness (σ) or an allowable TIS within a given surface spatial frequency bandwidth. Through the scattering and theoretical finish relations given above it is possible to convert the optical requirements into feeds and speeds for the machine.

To machine optics of a specified roughness then, it is necessary to convert the required scatter, to the roughness, and finally to the machine parameters (feed, speed, tool radius, etc.) necessary to achieve the theoretical finish related to that roughness. Adjustment (usually reduction) of other known mechanical and thermal effects will also be required. For other than long wavelength (infrared) optical applications, it may not be possible to achieve the desired finish by precision machining. Here pitch or other polishing techniques where finishes of 15A rms are achieved without great difficulty can take over (assuming simple geometries).

The above is probably the most simplistic view of optical finish and contour specification you will encounter. A variety of other optical aspects must normally be taken into account if correct specification and choice of manufacturing technique are to be accomplished. Such things as coating adhesion, residual strain, angular dependence of scatter, and damage threshold can all have a profound influence on the tolerances applied for a particular surface. Adjustments to and even selection of a process may be significantly altered by these. In some cases, the effects of a manufacturing process are not even understood to know with any certainty if the product will be satisfactory. While this is beyond the scope and intent here, the reader should at least be aware of them and the overall complexity of an optical tolerance and specification problem. It is important to keep in mind that all values of contour and finish are specified in wavelengths of the light to be used and as such the absolute values change as the wavelength changes. This implies that a visible light optic operating at 0.5 μm wavelength is twice as hard to make $\lambda/4$ as an infrared optic working at 1.0 μm .

A perspective on optical polishing and precision machining

Perhaps more fundamental than how to specify optical surfaces for precision machining is the question of which process to use for producing the surface or component of interest. Before addressing this directly, the ultimate purpose of this paper, it's important to have a good feeling for how precision machining and conventional optical polishing compare. It is of particular interest with respect to processable materials, cost, speed and the ultimate surfaces achievable. The following is a brief attempt to show the differences and compare them for use in manufacturing optical surfaces.

Polishing

The removal of any material by polishing, be it glass or metal, is through a process of wear. Here, a lap, base coated with a deformable material (these vary greatly in compliance, viscosity and other material properties depending on application) and continuously fed with a polishing compound (usually a metal oxide), is placed against the surface to be worked. The lap and workpiece are moved with respect to one another in a series of rotating and oscillating motions in a known way. The resultant energy imparted to the surface by the lap, through a not well understood combination of mechanical abrasion, chemical attack, and thermal flow disrupt and remove the material. This process results in surfaces whose finish are small compared to the functional wavelength and whose shape can be controlled to some extent. This is a removal process that averages itself over the area of the lap and has been described by Preston¹⁰ as being proportional to the relative lap velocity, the pressure, and dwell time or

$$\frac{dH}{dt} = K \cdot P \cdot V \text{ or } K \cdot P \cdot \frac{ds}{dt}$$

where V = the velocity of the lap over the work surface
 P = the local pressure
 K = the wear constant (Actually, not a constant at all. Rather, a complex combination of physical and chemical properties that will not be completely understood or described for many years)
 t = the dwell time (time in which the lap actually spends over some point (x,y) on the surface)

The advantages of this process with respect to precision machining, in general, relate to the wide variety of materials than lend themselves to polishing and high quality finishes normally achieved. It is a process that is insensitive to mechanical vibration, acoustic coupling and in most cases some small variations in temperature. It is evident from the large astronomical telescope objectives in existence that there is no maximum process size (minimum is related to the smallest lap that can be practically made and manipulated). On the other hand, the area averaging nature and incomplete understanding of the mechanisms result in a process that has little geometric control. It is both time consuming and, beyond a certain level, not repeatable. The polishing compounds and carrier fluids interact with the optical material and result in polished surfaces containing considerable residual containment materials and mechanical damage. In addition, the process must be carried out in a particle free environment to achieve the quality finishes. A number of edge effects (roll-off) limit the useful area to something less than the total surface. Finally, and most importantly, polishing is generally limited to simple geometries. More will be said on this later.

Precision machining

Precision machining, combining the diamond tool and high precision machines is based on one generally accepted but, as yet, unproven tenant. That is, any surface produced by precision machining will be an exact replica of the surface of revolution traced out by the combination of tool shape and tool path. There will be no material deformation or mechanical damage during this process. The contour and surface finish will bare a one to one relationship with the tool path (including machine and control system errors) and tool shape.

The principal advantage over polishing is that the family of shapes that can be manufactured are limited only by the size of the machine workspace, the machine symmetries (generally rotational) and tool accessibility. It is possible to include the machining of integral precision mounts and references during a set up to assure extremely accurate references and eliminate the need of several stages in the alignment processes. In addition, the problem of edge effects is markedly reduced or eliminated. Finally, this process is both predictable and repeatable to within the machine accuracy which allows for reliable numerical or computer control. These advantages are obtained at the principal expense of the ultimately achievable contour and finishes obtainable (at least today) as is clear from Table V.

Table V. Best and average finish and contour obtainable from polishing and precision machining

	<u>Finish</u>		<u>Contour</u>
Optical Polishing	Best	$\sim 3A$ rms	$\sim 50A$ p to v
	Average	20 to 50A rms	$\sim 250A$ p to v
Precision Machining	Best	$\sim 10A$ rms	$\sim 1000A$ p to v
	Average	100 - 250A rms	$\sim 3000A$ p to v

This table and the previous section on scattering imply a generally inferior optical performance from precision machined surfaces with respect to scatter/finish. This problem extends even into the longer infrared wavelengths where this process is commonly used. Here, many systems operate in a regime where the background radiation exceeds the source, in some cases by orders of magnitude. Here, the scattering can cloud or even destroy detection of the signal.

The final comparative comment on precision machining with respect to optical polishing is the well known limitation of diamond turning to materials that are both physically and chemically compatible with diamonds.

The perspective. Generally, based entirely on technical merits, the selection of a manufacturing process or technique to be used on a specific optical component is a complex one. Factors generally include the optical properties described earlier, surface shape and finish quality, the number required, the delivery, and other economic factors. If we take a more simplistic view, however, the choice of manufacturing process, i.e., optical polishing or precision machining, can be related to a relatively simple rule of thumb. This rule of thumb relates to the rate of change of curvature or third derivative of the optical surface to be manufactured. Essentially it goes like this: the higher the rate of change of curvature, the better the applicability of precision machine technology. For flats and spheres whose third derivatives are zero conventional optical processing would normally be most efficient and economical. For aspheric surfaces, toroids, cones or surfaces described by polynomials, where the departure from a sphere or a flat is significant, the rate of change of curvature will also be significant. In these cases precision machine technology is most efficient for generating the basic surface. Once the computer program or control tape has been generated the machine will repeat exactly the same tool path and hence machine the same surface within the accuracies of its motions each time. The machine cares little as to whether the surface is flat, spherical, aspheric, or toroidal, it merely moves as directed each time to within whatever accuracies the machine is capable. Thus, a third derivative of the surface is a good way of determining whether the application of precision machine technology will be efficient with respect to conventional optical techniques.

Another way to view this is from the perspective of optical polishing. Normally polishing is accomplished by a wood rosin or a cold tar pitch product which is made to adhere to a rigid substrate material. Being a viscous material the pitch is allowed to flow over a period in time until its surface shape complies quite accurately to the shape of the component being manufactured. This process is termed pressing, and takes several minutes to several hours depending on the type of pitch, temperature, size of components and departure of the pitch lap from the surface that is to be fitted. As long as the curvature is zero or constant, after pressing, the lap may be rotated and oscillated about the surface without concern for the fit between the pitch lap and the part. If, however, if the part is aspheric such that the rate of change of curvature is none zero then the pitch lap will no longer conform as its moved across the surface to be polished. The larger the rate of change of curvature, the more severe this problem becomes. Optical fabricators relieve this problem, to an extent, by using soft compliant laps, but experience has shown that this is only partially satisfactory.

What we have, as a result, are two separate manufacturing processes, precision machining and conventional optical polishing, that can and are used for the manufacture of precision optical components. On the one hand we have precision machining which offers precise surface shape, versatility, extreme positional accuracy and repeatability, but which is severely limited by the surface finish typically achieved and the limited family of materials that can be successfully processed. As opposed to this, we have conventional optical grinding and polishing. Here, surfaces are obtained with extremely high surface finish on almost any relatively hard material be it metal, glass, ceramic or semi-conductor, but at the expense of positional accuracy,

repeatability, and unknown chemical and mechanical alteration to the surface. Ignoring for the moment, the more subtle difficulties of damage to the near surface region, it appears that some of the problems of both are successfully overcome by combining the two processes. By taking advantage of the precision machine's ability to produce accurate surface shapes quickly, easily and repeatedly, the form of the desired surface can be obtained. Then, by a subsequent lapping process, designed to smooth the surface without significantly altering its shape, the inherent surface finish problem can be eliminated. This combination will overcome the inherent problems of both processes and allow optical components for most any application to be produced relatively quickly and accurately.

While the above approach is somewhat simple minded, neglecting the application of the optical surface or component and the wavelength of light that the surface will see, it does indicate the relative merits of a marriage of these two processes for producing optical components.

Some thoughts on the future

As everyone knows, it is impossible to predict where a technology, in fact, anything in this day and age is likely to lead in the future. Precision machining of optics is no different. It is a fast growing and dynamic technology, however, that will likely look considerably different in future years. While it is not possible for anyone to predict that future, some current research and development programs point to areas that will likely impact that future.

We are all familiar with the fact that materials which are successfully diamond turnable are restricted to that family of materials which are both chemically and physically compatible with diamond crystals. In actuality this turnable family is quite limited (turnable materials listed in Table I), but some progress is being made to expand it through a close examination and application of the proper conditions for machinability. Materials showing some promise for the future are single crystal silicon, other nickel compounds than electroless nickel and perhaps even borosilicate glass¹¹.

The key to this material problem is the rather severe limitation of diamond compatibility. Materials containing carbon are not considered machinable due to the carbonization of the diamond crystal at the high temperatures of machining. There are, however, a number of very hard, >9 on the Moh scale, crystalline materials that show some promise as substitute or alternate tool candidates. These all have molecular crystal structures similar to that of diamond and include cubic boron nitride (CBN), cubic zirconia (CZr), yttrium aluminum garnet (YAG), and another similar material, hafnium nitride. Some very preliminary evidence indicates that single crystal silicon may be turnable with diamonds and that a 2169 stainless steel is possibly machinable with cubic boron nitride¹². In addition, work with hafnium nitride at the American Softening Point of some borosilicates and soda-lime glasses indicates, at least, the possibility of machining glass¹³. As research into new materials, both metallic (ferrous and non-ferrous) and non-metallic continues using new tool materials like these above, the family of machinable materials should expand significantly. The implications of machinability of materials such as these should speak for themselves. Interest in converting the machining art into a science through establishment of an institute or institutes and well coordinated university grants is gaining considerable momentum. Discoveries and developments in a program directed at a rational approach to understanding the physics and underlying mechanisms of machining would go a long way in upgrading the practice.

Another thought regarding the future of machining relates to the accuracy and repeatability of the machines themselves. As previously indicated, precision machining is currently capable of $\lambda/4$ (visible light) optics. This is due primarily to a combination of poorly understood or controlled process parameters and lack of adequately sensitive feedback systems. Machines with 1 meter diameter capacity require displacement measurements to $1:10^8$ for $\lambda/4$ optics. If $\lambda/10$ to $\lambda/100$ optics are to be possible, displacement measurements to $1:10^{10}$ to $1:10^{12}$ will be required.

Some work has been considered with respect to the polarization mixing problem in laser distance measuring interferometers that, if corrected, indicate the potential of achieving the $1:10^{10}$ required. In addition continued progress and improvement in bearings, spindles, servos, electronics and tools will point the way to smoother, more accurate machines, better equipped for the desired contour accuracies.

In my opinion, however, the key issue of future machining will eventually reduce itself to one of finish rather than contour. If precision machining is assumed capable of the theoretical finish then the surfaces produced will have optical scatter and reflectance performance that will be a function of only tool nose radius and feed rate. It could be that the limit to finish will eventually become more a trade-off (having selected the largest tool radius possible) between feed rate and the total time to produce the surface desired. If the feed rate is reduced to an arbitrarily slow value to produce the theoretical finish that satisfies the optical requirement the processing time and stability requirements may become unacceptable. As the accuracy and finish capability is improved, optical surfaces for shorter and shorter wavelength application will become feasible by precision machining techniques. If such is not the case, the offered marriage of polishing and machining may become the standard practice.

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Figure 1. Possible configurations of a black box, linear imaging system. Imaging relations are identical in both cases with the exception of signs on propagation direction.

Figure 2. The mathematical relationship between the optical system exit wavefront (described by $F\#$, amplitude distribution, and phase distribution), the image of a point and the MTF.

Figure 3. The diffraction image of a point object (point spread function (PSF)) and MTF for a circular mirror containing no contour errors i.e., "perfect"

Figure 4. Schematic of the problem causing decentration error in precision machining. (Ref. SPIE Proceedings Vol. 181, Page 79)

Figure 5. Effect of decentration error in the tool on the geometrical imaging properties of a spherical mirror on axis. (Ref. SPIE Proceedings Vol. 181 Page 79)

Figure 6. Schematic of the reflecting surface scattering problem. (Ref. Optical Engineering, Vol. 18, No. 2, 1979)

Error caused by surface roughness in reflectance measurements as a function of wavelength. Dotted lines indicate roughnesses of typical optically polished glass surfaces.

Error made in reflectance measurements when surface roughness is neglected. Circles represent experimental evidence.

Figure 7. The relationship between surface roughness and error in reflectance measurements. (From Bennett and Porteus, JOSA, Vol. 51, Pg 123, 1962)

R/R_0

Scattering Angle

 R/R_0

Scattering Angle

Figure 8. Plots of relative intensity of scattered radiation from flat surfaces. The upper surface is copper with a groove period of $95\mu\text{m}$ while the lower is a diamond turned gold sample with a period of $5.3\mu\text{m}$. (Ref. Church, E. L., Optical Engineering, Vol. 16, No. 4, pp 360, 1977)

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