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METROLOGY OF REFLECTION OPTICS FOR SYNCHROTRON RADIATION

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ABSTRACT

Recent years have seen an almost explosive growth in the number of beam lines on new and existing synchrotron radiation facilities throughout the world. The need for optical components to utilize the unique characteristics of synchrotron radiation has increased accordingly. Unfortunately, the technology to manufacture and measure the large, smooth, exotic optical surfaces required to focus and steer the synchrotron radiation beam has not progressed as rapidly as the operational demands on these components. Most companies do not wish to become involved with a project that requires producing a single, very expensive, aspheric optic with surface roughness and figure tolerances that are beyond their capabilities to measure. This paper will review some of the experiences of the National Synchrotron Light Source in procuring grazing incidence optical components over the past several years. We will review the specification process--how it is related to the function of the optic, and how it relates to the metrology available during the manufacturing process and after delivery to the user's laboratory. We will also discuss practical aspects of our experience with new technologies, such as single point diamond turning of metal mirrors and the use of SiC as a mirror material. Recent advances in metrology instrumentation have the potential to move the measurement of surface figure and finish from the research laboratory into the optical shop, which should stimulate growth and interest in the manufacturing of optics to meet the needs of the synchrotron radiation user community.

Introduction

The great diversity of reflection optics under design or in use at synchrotron radiation (SR) facilities around the world presents a great challenge to opticians to fabricate exotic surfaces to extremely exacting tolerances. It is also a challenge to end users to characterize the performance of each optical element prior to installation in a beam line to assure that it meets all of the requirements in the performance specification. Most end users do not have the facilities to perform extensive acceptance testing on aspherics optics. We have acknowledged this problem at Brookhaven and have taken steps to implement a metrology capability to benefit all users at the National Synchrotron Light Source (NSLS). In a larger sense, we also hope to benefit the community of manufacturers with development of practical methods to assess the quality of optical components to further the state-of-the-art in manufacturing these types of optics.

The first part of this paper will deal with the design process--how we specify a particular optical component. It will treat mainly reflection optics for x-ray and VUV applications and will not cover crystal optics at all, the reason being that crystal optics require a set of metrology tools and processes quite separate from reflection optics. The design process will lead us into the range of measurements that we need to make on various types of elements. The most important measurements from a performance standpoint are surface figure and surface finish. It will be shown that these two concepts can be thought of as two aspects of the same phenomenon--surface spatial frequency. Current state-of-the-art in manufacturing tolerances will be compared to the current needs of source-size-limited (SSL) SR optics and to future requirements for handling coherence requirements of next generation sources.

The second part of this paper will deal with metrology methods in use at Brookhaven National Laboratory (BNL). The practice of making figure and finish measurements will be discussed in the context of the methods available for their achievement. These methods include Point Spread Function (PSF) analysis using visible light for figure measurement, statistical optics techniques for figure and finish measurements using an optical profilometer, and x-ray scatter measurements to confirm the predictions made by profile measurements at visible wavelengths for scatter at x-ray wavelengths.

The Specification Process

Table I enumerates a list of mirror materials and surface figures either in use or being contemplated for use at SR facilities. Manufacturers have a large advantage over end users, in that if a manufacturer chooses to make the component, he usually has the specific metrology capability to perform the job. The end user, however, must be prepared to handle any eventuality, since once he specifies an optic, he must be prepared to measure it himself. Other alternatives are to have the quality assurance measurement made by an independent laboratory, or to accept the results of the manufacturer's test as sufficient for quality assurance purposes. Often the manufacturer will provide test data that is difficult to interpret, which makes the last alternative risky. Relying on an outside independent laboratory can be very expensive, since what is really desired by an end user is a series of measurements on the surface during some processing steps subsequent to delivery from the manufacturer. For instance, the user may want to know what happens to the surface figure upon thermal cycling or upon installation in a bending apparatus. An in-house metrology capability is essential to answer such questions in a cost-effective manner.

Figure 1 is a schematic of the logic involved in the design specification process. A conceptual design for a beam line or an instrument usually results in performance requirements for a set of optical components. In general, there is usually more than one way to select a material and a surface figure to meet the performance requirements. Usually ray tracing or aberration function analysis techniques will produce more than one acceptable design for choice of optical element, each with some different degree of complexity. An ellipsoid, for instance, may be more complex than a toroid, and hence incur higher cost or risk in its manufacture. The preferred choice may be very difficult to characterize with available metrology techniques, hence an additional cost will be incurred to provide the special metrology capability. Usually one makes several passes around the design specification loop before arriving at a satisfactory solution. New technology is also a consideration in terms of complexity, because it can either add risk with a new, unproven material or technique, or it can reduce manufacturing complexity, for example, by using diamond turning techniques to fabricate unconventional shapes.

The final outcome of this process is the design specification. This is the working document that the manufacturer must use in order to bid on the job and make the part. It should be as specific as possible and cover all aspects of the procurement. Specific topics that must be addressed in the specification are: intended use, blank size, finished size, clear aperture, tolerances, maximum departure from best-fit surface, materials, suggested or required manufacturing methods, metrology methods, cleaning and vacuum requirements, and shipping requirements i.e., type of shipping container.

Metrology Requirements

A good specification is usually written with full knowledge of the metrology capabilities of prospective suppliers. If the metrology requirements exceed the capabilities of the supplier, he is not likely to attempt the job. The designer must be aware of the types of measurements that are required to fully qualify the delivered optic and whether or not the capability exists to make those measurements. One must also consider that measurements will be required on full size components, which presents a problem for quantities such as reflectivity at x-ray wavelengths in UHV, since most experimental systems are designed only to handle small samples. In some cases witness samples may be acceptable for acceptance testing, and should be explicitly stated in the specification.

Parameters that we recognize as important to measure for our optics are outlined in Table II. Some of these measurements are not yet implemented. Some are performed in qualitative ways. Most of these measurements are not implemented in any routine way, but are done only upon special request of the end user. The tests that are performed routinely in one form or another on all delivered optics are figure and finish. It is absolutely imperative for the end user to know what the focal conjugates are for the optic and to know that the surface finish is smooth enough for his purposes. Consequently, we have spent considerable effort on developing general test methods to perform figure and finish measurements on the variety of surface figures outlined in Table I. The other measurements in Table II have been relegated to a secondary status, in large part a result of financial constraints and manpower limitation.

Figure and Finish

Surface figure and surface finish can be thought of as different aspects of the same phenomenon--namely "surface spatial frequency". This concept has been developed at length by Church and co-workers [1-5] as applied to grazing incidence x-ray optics. The general process of specular reflection and scattering from a mirror surface is illustrated schematically in Fig. 2. An incident plane wave of transverse dimension W illuminates an area of the surface of length L , where $W = L \sin \theta_i$. The width W can be thought of as the length of the surface projected into the exit pupil of the system by the sine of the grazing incidence angle, θ_i . The surface consists of an overall curvature to focus the reflected beam and a random microroughness which acts to scatter intensity outside of the central image. For purposes of illustration, we will consider a one-dimensional surface with the associated one-dimensional imaging and scattering problem. The surface can be considered to convert an ideal incident plane wavefront into a combination of an ideal spherical wavefront converging to a focus centered at point $x_0 = 0$ in the image plane, and also scattered wavefronts converging to other focal points in the image plane. The random microroughness can be considered to consist of a superposition of diffraction gratings on the surface, with spatial periods given by inverse integral multiples of the fundamental period i.e., $d_n = \frac{L}{n}$, with random phases and small amplitudes. The net effect of this grating structure is to scatter part of the reflected beam away from the specular direction, the angle of scatter given directly by the grating equation at grazing incidence:

$$\theta_s = \frac{\lambda}{d_n \sin \theta_i} \quad (1)$$

The intensity of light scattered in this direction depends on the amplitude of the surface grating component with period d_n . Thus, there is a one-to-one correspondence between angle of scatter (or position in image plane) and the frequency content of the surface microroughness.

If we examine Eq. (1) more closely, we see that we can consider the scattering process to result from diffraction by an "effective" period, $d' = d_n \sin \theta_i$, in the exit aperture of the system. The scattering process can then be illustrated as in Fig. 3 as a basic diffraction phenomenon. The physical surface can be thought of as acting as a phase screen in the exit pupil, producing a phase variation in the transmitted wavefront. The amount of phase variation in the aperture is related directly to the height profile on the surface:

$$\Phi(x_A) = \frac{4\pi}{\lambda} Z(x) \sin \theta_i \quad (2)$$

The various frequency components of the phase screen produce diffracted wavefronts at angles away from specular given by Eq. (1). The effective spatial period, $d_n \sin \theta_i$, adds a transverse component to the propagation vector:

$$k_s = k_o \sin \left(\frac{\lambda}{d_n \sin \theta_i} \right) \quad (3)$$

and brings that component to a focus at a distance

$$x_o = F \theta_s = \frac{F \lambda}{d_n \sin \theta_i} \quad (4)$$

away from the specular focus.

The entire imaging process can be written as a Fresnel-Kirchhoff diffraction integral: [6-9].

$$I(x_o) = I_o \left| \int_{-\frac{w}{2}}^{\frac{w}{2}} e^{-i 2\pi \left(\frac{x_o}{\lambda F}\right) x_A} e^{i\phi(x_A)} dx_A \right|^2 \quad (5)$$

which describes the propagation of a wavefront with phase aberration $\phi(x_A)$ converging to a focus at a distance F from the aperture.

Let us examine Eq. (5) in more detail. If we consider the ideal case of a perfect converging wavefront with no aberration, the result is the familiar sinc^2 function for imaging a point source through an aperture of width $W = L \sin \theta_1$:

$$I_o(x_o) = I_o \frac{\sin^2\left(\pi \frac{x_o}{\lambda F} L \sin \theta_1\right)}{\left(\pi \frac{x_o}{\lambda F} L \sin \theta_1\right)^2} \quad (6)$$

The intensity distribution in the image plane for the ideal point spread function (PSF) given by Eq. (6) is illustrated in Fig. 4. The first zeroes in this PSF occurs at distances $x_o = \pm \frac{\lambda F}{L \sin \theta_1}$ away from the center. This distance is a convenient measure of the size of the PSF, which we call the core of the PSF. It depends only upon the size of the aperture, $L \sin \theta_1$ and the scaling factor defined by the product of the wavelength and focal length of the system, λF . Figure 4 also illustrates the relationship among the several ways to characterize image plane phenomena. Some authors prefer to think in terms of angle or frequency space; all are interchangeable with distance provided one uses the appropriate scaling factor.

Also indicated in Fig. 4 are the minimum and maximum spatial frequency ranges sampled by a typical surface profilometer instrument. The profiler samples the surface at normal incidence with a minimum pixel size, d , usually on the order of $1 \mu\text{m}$, which corresponds to a maximum frequency in the image

plane of $f_{\max} = (d \sin \theta_i)^{-1}$. The low frequency end of the profiler range depends on the total trace length; in this case $f_{\min} = (1024 d \sin \theta_i)^{-1}$, where the total trace length on the surface is about 1 mm. The low frequency end of the profiler range approaches the core of the PSF, but because the total trace length is much less than the overall mirror size, the profiler is not sensitive to those low frequencies that affect the figure of the surface and distort the perfect image. The range of spatial frequencies covered by the profiler falls into the region characterized as "scattered light".

The other feature of interest in the image plane is the source size limit (SSL), σ , which is the geometric image of the real source as seen in the image plane. The SSL depends only on the overall system magnification and not on the angle of incidence or frequency content of the surface.

Typical X-ray Mirror Example

To illustrate the image plane relationships for a real mirror, we choose as a typical mirror one with the following properties: a working wavelength of 1 Å; a total length of $L = 50$ cm; a source distance of 10 m and an image focal distance of $F = 1$ m with a resultant magnification of 0.1; grazing angle of incidence of 3 mrad; and a source size of 200 μm , which becomes an image size of 20 μm when imaged through the $m = 0.1$ system. The actual figure of the mirror is irrelevant as long as it produces an ideal converging wavefront out of the exit pupil to a line or point focus. Figure 5 illustrates the location of various features in the image plane for two angles of incidence: normal incidence ($\theta = 90^\circ$) and the design angle ($\theta = 3$ mrad). The normal incidence case is not intended to suggest a real physical application of this mirror, but rather illustrates how the image plane parameters change as the function of the mirror changes, i.e. from being used at grazing incidence to being used at more normal incidence. However, with the advent

of multilayer x-ray reflective coatings, the use of an x-ray mirror at normal incidence will not be prohibited.

Features to note in Fig. 5 are the extremely small size of the core of the PSF for both cases and its location relative to the profiler range and SSL. At normal incidence the core is less than 1 nm wide, while at grazing incidence the core is about 100 nm wide. Both are well within the extent of the SSL, which dominates the image process at this wavelength. The profiler frequency range, however, almost entirely lies within the SSL for the normal incidence case, while at grazing incidence it is entirely outside of the SSL. In the normal incidence case the profiler is sensitive to surface spatial frequencies that affect the SSL image quality, which is in the regime of figure measurement, while in the grazing incidence case it is sensitive to spatial frequencies entirely outside of the SSL image, which, by definition, puts it into the region of scattered light. This example illustrates that a measurement of surface profile may give information on figure or finish, dependent upon the function of the mirror.

The Real World

Now we must interject some elements of the real world into the discussion of imaging at 1 Å wavelengths. One never sees the ideal PSF at this wavelength for large x-ray optics. The reasons for this are two-fold: First, coherent illumination over the whole aperture is required at a 1 Å wavelength, but is not achieved with current SR sources. The criterion for coherence in the image plane is that the product of the image size and the beam divergence be less than one-half wavelength:

$$M\sigma \cdot \frac{W}{F} < \frac{\lambda}{2} \quad (7)$$

This product must be less than about 0.5 Å, but for our typical mirror case

it is on the order of 300 Å. Only a small fraction of the aperture can be considered coherently illuminated from the finite source at this wavelength. The other reason is that "slope" errors on the order of 1 arc second spread the image incoherently in the image plane. A 1 arc second slope error will deflect the core of the PSF by about 10 μrad, which is about 10 μm for our test case. This is nearly equivalent to the SSL width of 20 μm, which means that a surface with a 1 arc second slope error tolerance would be well-matched to that SSL. If, however, the source size were made smaller, either by means of an artificial pinhole aperture or by improving the SR beam emittance, then the slope error tolerance would need to be tightened to match the source size.

The slope error tolerance of 1 arc second is a typical value achieved by manufacturers of high quality grazing incidence optics. There is, however, no universal agreement as to how to specify this tolerance or how to measure it. We may gain some insight into the meaning of this tolerance by considering what 1 arc second means for various scale lengths. Figure 6 illustrates the departure of a real surface from the best-fit asphere by a single period sinusoid of period D and amplitude A. The contribution to the mean-square surface roughness from this component is

$$\sigma_{\text{RMS}} = \frac{A}{\sqrt{2}} \quad (8)$$

and the contribution to the mean-square slope error is

$$m_{\text{RMS}} = \sqrt{2} \pi \frac{A}{D} \quad (9)$$

If we fix the value of the slope error at 1 arc second, values for the amplitude and surface roughness for various scale lengths are compiled in Table III. One sees that for a full length period (50 cm) the amplitude of the

sinusoid is on the order of one wavelength of visible light (562 nm), while for short periods, the amplitude is less than 1/100 of a wavelength of visible light. In order to fully qualify an optical component over these spatial frequency ranges, one needs to be able to measure amplitudes over a dynamic range of 10^4 with reasonable accuracy. No single instrument exists that is suitable for making these measurements on sensitive x-ray reflecting surfaces. Some methods suitable for making measurements of surface profiles on x-ray optics are discussed below.

Surface Profilers

Many devices exist for the purpose of making surface profile measurements on various types of engineering and optical surfaces. Those suitable for making measurements on full-size SR optics are indicated in Fig. 7 as a function of the range of surface spatial periods over which the instrument is capable of being used. There are two basic classes of surface profilers: those based on mechanical contact methods and those based on optical non-contact methods. Most mechanical contact methods rely on the use of a diamond-tipped LVDT stylus or ball stylus as the contact mechanism [10], although some of the measuring machines have the capability to use capacitance gauges [11]. The Talystep [12] is generally used to measure surface finish characteristics over short (1 or 2 mm) segments of the surface and is best suited to make measurements on small samples. With difficulty it can be used to make measurements on certain portions of full-size optics. The Talysurf [12] has a longer trace length but with a corresponding decrease in the vertical height sensitivity relative to the Talystep. Stylus measuring machines utilizing LVDT devices suffer from long-term drift problems which introduce artifacts into the surface profile over long traces. The Stedman-Stanley [10] machine and the Zeiss [13] machine compare

the test surface to a reference surface, the former using a laser interferometer reference arm, the latter using a double-ended LVDT stylus probe. Another class of mechanical measuring machine is based upon the traditional Moore-type measuring machine and next-generation ultra-high precision SPDT machines, such as LODTM and DTM-3 at LLNL [11]. The Moore-type machines are limited in precision by mechanical bearings and ways, while the newer SPDT machines have sophisticated interferometric control systems and ultra precision air bearing slides. With the appropriate stylus, such machines are capable of approaching the precision of the Talystep at short spatial periods, while being able to maintain accuracy over meter-long traverses. Such machines are major facilities and represent an investment beyond the resources available to the average x-ray mirror user.

The other class of profiler indicated in Fig. 7 is based on optical non-contact methods. The electron microscope and scanning tunneling microscopy [14] offer the ultimate in spatial resolution with the ability to see features down to atomic dimensions, but they are not suited to direct measurement of full-size SR mirrors. The SEM requires specially prepared replicas and offers at best a qualitative assessment of surface finish. The other optical profilers can be classified as either slope-measuring instruments or height-measuring instruments. The ZYGO interferometer, a height-measuring instrument, is widely used in the optics industry for measuring wavefront quality of conventional optics, such as lenses and spherical mirrors. Special test set-ups are needed to handle on- and off-axis conic sections, and the extreme foreshortening of grazing incidence optics makes interpretation of the interferogram very difficult. The optical lever profiler, an example of which is the Random Devices Slope Scanner [15], is, as the name suggests, a slope-measuring device. It measures the angular

deviation in a laser beam reflected from a surface that is translated across the beam. Special focusing optics allow one to adjust the beam size so that spatial periods smaller than 100 μm can be sampled. The long period cutoff is limited by the length of the sample translation stage and could, in principle, be longer. Sensitivities on the order of a few tenths of an arc second are claimed, along with a height resolution of 10 to 20 $\text{\AA}$. The pencil beam interferometer developed by von Bieren [16] is a slope-measuring device which operates by translating the measurement head over the test surface. This instrument uses the direction of the laser beam as its reference surface and is insensitive to imperfections in the translation stage. The OPTEL instrument, under development by Eastman and Zavislan [17], is based on a differential interference contrast (Nomarski) technique and is a slope measuring instrument. As with the pencil beam interferometer, the measurement head is translated over the optic, using the laser beam as the absolute slope reference. The instrument has a 50 cm scan length capability, limited only by the size of the translation mechanism, and has a minimum resolution of about 1.2 μm , limited by the separation distance between the probe beams. The WYKO Digital Optical Profiler [18-19] is a height-measuring interferometer based upon Mirau and Twyman-Green microinterferometer objectives. It is available in three magnifications with the minimum pixel size 0.65 μm and the maximum trace length of about 5.3 mm. The surface height profile is constructed by measuring the optical phase at each element in a 1024-pixel linear diode array. Neither the test surface nor the measurement head undergoes transverse linear translation during the measurement. This instrument is in use at BNL and serves as our primary means of surface finish measurement. A schematic of the WYKO instrument is shown in Fig. 8.

In addition to surface profilometry, other techniques can be used to qualify SR optical surfaces. Nomarski microscopy offers a rapid and convenient means to assess the overall surface quality. It is difficult to quantify the images obtained by this form of microscopy [20] but the trained eye can estimate surface quality to a reasonable degree of accuracy. X-ray topography has been used to evaluate the slope errors in grazing incidence flat mirrors [21] and analysis of Fresnel diffraction images at x-ray wavelengths has been used to characterize figure and finish errors on x-ray astronomy optics [22]. Angle-resolved scatter measurements at x-ray wavelengths have also been used to measure surface finish by a number of groups [23-25]. A technique for grazing incidence reflection interferometry at x-ray wavelengths has also been reported [26]. We have developed a technique to estimate surface figure errors on grazing incidence optics by analyzing the PSF generated by a visible light point source [27]. We have also developed a statistical analysis technique based on measurements made with the WYKO profiler to enable us to estimate the overall surface curvature of cylindrical optics. These techniques will be elaborated in the following sections.

Point Spread Function Analysis

A limitation of the analysis of surface profile data taken with the WYKO profiler is its inability to estimate the amplitude of long-period slope errors for surface periods outside the range of the instrument. This includes the region of full aperture figure errors, down to slope errors with periods on the order of millimeters. Since we have no long-trace profiler available to us, we have developed alternate techniques for overall figure quality measurement, one of which is the analysis of the point spread function produced by a visible light point source and a grazing incidence

optic. Although the image of a visible point source is extremely diffraction-broadened at grazing angles, the relative heights of the higher order maxima and minima in the PSF reveal a great deal of information about the quality of the optical surface in the long spatial period domain.

The technique involved in this measurement is illustrated in Fig. 9. A pinhole source is placed at the front focus of a grazing incidence optic or system. The system converts the ideal diverging spherical wave into an aberrated converging spherical wave which comes to a focus in the focal plane. A narrow slit is placed in front of a detector, which scans across the image plane. The resultant PSF is analyzed by modeling the system with a one-dimensional diffraction integral calculation based upon a direct calculation of Eq. (5). The phase aberration is modeled by the lowest order aberration possible: a single period sinusoid of amplitude A over the entire length of the mirror,

$$\Phi(x) = A \sin \left(\frac{\pi x}{L} + \Phi_0 \right)$$

The rationale for this model stems from insight into the nature of possible figuring errors that may be introduced into the surface during the polishing process. A likely error is one in which part of the surface was polished too much, leaving a low spot over a significant region. This low-frequency model works extremely well to quantify the performance of several optics and systems that we have measured to date. It allows us to predict the performance of SSL optics that are used at x-ray wavelengths by modeling the slope errors seen in the visible PSF.

Examples of the results of this analysis technique are shown in Fig. 10. The measured PSF for the NSLS PGM P5 paraboloidal (collimator) mirror [28] is compared in the upper plot with the results of the diffraction

integral model with an aberration function consisting of a symmetric cosine function with an amplitude of 0.1λ or 63.2 nm, indicative of a low spot in the center of the mirror. This type of symmetric aberration raises the intensity of the first order maxima and fills in the first nulls of the PSF. The RMS residual surface slope error computed from this aberration function is 2.7 arc seconds. The lower plot in Fig. 10 illustrates the performance of the PGM system as a whole, as measured on the P3 range. The system consists of the P5 collimating paraboloid, a plane diffraction grating used at zero order, and the P3 focusing paraboloid. One can see that the measured system diffraction pattern differs significantly between the P5 case and the ideal case. We can model this to reasonable accuracy with a sine function with an amplitude of 0.1λ or 44.2 nm. This is an asymmetric aberration function which has a net tilt across the surface. It serves to direct the aberrated intensity into the first order maximum on one side at the expense of the other side. The estimated RMS slope error for the system model is 3.8 arc seconds. Measurements made with this monochromator in zero order at short wavelengths ($\lambda < 100 \text{ \AA}$) confirm that the image is spread over a region in the focal plane corresponding to slope errors of this magnitude [29].

Another example of the use of the PSF analysis technique is shown in Fig. 11. A 42 cm long plane mirror is bent into the shape of a plane cylinder by a bending mechanism. The image plane is located 10.0 meters away from the mirror, and three scans across the image are shown as a function of the number of steps on the bending mechanism stepping motor. The best fit model curve occurs for a value of the focal length parameter, F in Eq. (5), of 10.0 meters. The model includes the effect of gravity-induced sag on the mirror, which must be considered because of its large length-to-thickness ratio [30] and also a small residual sinusoidal aberration of the type discussed above

corresponding to an RMS slope error of 1.7 arc sec, since the gravity sag term was not able to account for all of the observed aberration in the PSF. By overbending the mirror a known number of steps, a family of focal curves was measured, as shown in Fig. 11. Each measured curve was modeled by changing only the focus parameter, F . The model fits to the measured curves are in excellent agreement for the indicated focus values. The asymmetry induced by the gravity sag and aberration terms is quite evident in the measurements and both are absolutely essential for correctly modeling the observations. Correlation of the model focus value with the bending mechanism step parameter serves as a means to functionally calibrate the bending mechanism and enables one to compare the predicted performance with the actual mechanism performance.

Statistical Optics

In addition to figure measurement, surface finish is of fundamental concern to users of SR optics. Our capabilities to measure surface finish are based upon the use of the WYKO Digital Optical Profiler. We have chosen this non-contact method over mechanical stylus methods for several reasons. Foremost is the need to measure finish on full size optical components with sub-Angstrom accuracy and repeatability. Standard stylus machines cannot handle large mirrors and one is always afraid of damaging the surface with a contact stylus. Mechanical stylus machines are prone to thermal and electronic drift problems, which makes the process of detrending the data to remove surface tilt and curvature extremely difficult. The WYKO instrument, with minor modifications, eliminates these problems and offers a convenient and rapid means of measuring the profile of delicate optical surfaces. Because it is not sensitive to the drift problems associated with mechanical stylus instruments, we have also been able to employ it to make curvature

measurements on aspheric surfaces and use statistical estimation procedures to estimate the radius of curvature and, hence, assess the figure quality of SR optics. On smooth surfaces (less than 5 Å RMS residual roughness) we are able to estimate radii up to about 100 meters with a statistical accuracy of better than 10% for a reasonable number of samples [8, 31-33].

Examples of the figure and finish measurement capabilities of the WYKO profiler are shown in Figs. 12 through 15. Two toroidal surfaces are shown in Figs. 12 and 13. The former is the surface profile of a fused silica toroid both before and after removal of surface curvature by the detrending process. The estimated radius of curvature of this sample of the surface is 19.05 m with an uncertainty of ± 6.38 m. Although the uncertainty is a large fraction of an individual radius estimate, a large number of samples at random points on the surface allow one to estimate the curvature to within a reasonable tolerance. The curvature measurement is, however, very sensitive to low frequency components in the spectrum of the surface profile. The fact that the RMS surface roughness integrated over the entire bandwidth is only about 4 Å minimizes the influence of the surface roughness on this measurement. Figure 13 illustrates the surface of an electroless nickel-plated aluminum toroid with a larger radius of curvature. The larger value of the surface roughness for this surface, 6.68 Å, relative to the fused silica surface, 4.01 Å, is readily evident from the texture of the curves.

A variety of analyses can be performed on the surface profile data. We are able to extract a great deal of information about the surface from a computation of the power spectral density (PSD) in the measured profile. Two profiles with corresponding PSD curves are presented in Figs. 14 and 15 for two very different surfaces: one is a float glass sample with a thin evaporated gold coating; the other is a polished REFEL [34] silicon carbide

surface with a thin rhodium coating. The float glass surface has an RMS roughness of 3.50 Å, while the SiC surface has a roughness of 64.33 Å. Note that the sample length differs between the two measurements: the float glass measurement was done with a X10 objective, while the SiC measurement was done with a X2.5 objective. The SiC toroid had such a short radius of curvature in the sagittal direction, 10.7 mm, that the X10 objective could not be used. The diameter of the objective and its short working distance (~2 mm) prevented it from focusing on the bottom of the toroidal channel. The 13.7 mm working distance of the X2.5 objective was sufficient to clear the upper edge of the toroid and focus on the surface. Although the spatial frequency bandwidth differs slightly between the X2.5 and X10 objectives, the RMS roughness values will not change significantly and can be compared directly. One notices immediately that the magnitude of the PSD of the SiC is much greater than that of the float glass. Both, however, have the same general f^{-1} fall-off at higher frequencies.

The PSD curve can be used to predict the absolute intensity and shape of the angle-resolved scattering curve at x-ray wavelengths. Using results from scalar scattering theory for x-rays at grazing incidence [7], we can relate the amount of light scattered into a given solid angle to the value of the surface PSD over the appropriate bandwidth:

$$\frac{1}{I_o} \frac{dI_s}{d\theta_s} = \frac{2}{\pi} k^3 \sin^3 \theta_i S(f) \quad (10)$$

where

$$S(f) = \left| \frac{1}{\sqrt{L}} \int_{-\frac{L}{2}}^{\frac{L}{2}} e^{-i2\pi fx} Z(x) dx \right|^2 \quad (11)$$

is the spectrum of the surface roughness measured in the bandwidth of the WYKO profiler. Angle-resolved scatter measurements at $\lambda = 1.0 \text{ \AA}$ at a grazing angle of incidence of 3 mrad were made on a Au-coated float glass sample and on a full-size REFEL SiC mirror, both of which had roughness values similar to the surfaces in Figs. 14 and 15, respectively. Results are presented in Figs. 16 and 17. The dotted line in each figure represents the scattered light measurement. The width of the specular beam in each case is about 30 μm . Any signal outside that region is considered to be scattered. If one estimates the fraction of incident light lost to the scattered beam by integrating the area under the wings of the curve and normalizing to the area under the entire curve, one may apply the familiar total integrated scatter (TIS) formula to estimate the surface roughness:

$$\frac{I_s}{I_o} = 1 - e^{-\left(\frac{4\pi}{\lambda} \sigma \sin \theta_i\right)^2} \quad (12)$$

In order for the roughness to satisfy the limits of applicability of scalar scattering theory, the argument of the exponential factor must satisfy

$$\left(\frac{4\pi}{\lambda} \sigma \sin \theta_i\right)^2 \ll 1 \quad (13)$$

For the case of the float glass in Fig. 16, the surface roughness estimated from the TIS measurement is $\sigma = 4.3 \text{ \AA}$. This compares well with the roughness value of 4.0 $\text{\AA}$ computed from the power spectrum sample from that surface, which is shown superimposed upon the angle-resolved scatter curve with the appropriate vertical scaling factors calculated from equation (10). For the case of the SiC surface, the value of TIS computed from the scattering curve according to equation (12) is $\sigma = 17.3 \text{ \AA}$. This does not compare well with the value of about 60 $\text{\AA}$ computed from the power spectrum, which, when

superimposed on the scattering curve, lies well above the measured scatter. The reason for this discrepancy is that the SiC surface is so rough that it violates the limits of applicability of the scalar theory as imposed by Eq. (13). In this case we have $(\frac{4\pi}{\lambda} \sigma \sin \theta_1)^2 = 5.1$, which is significantly greater than 1. The surface power spectrum computed from a measurement of the surface profile is a valid indicator of the performance of an x-ray optic, but the actual performance of a rough surface cannot be calculated by the simple scalar theory. The REFEL SiC surface as measured above is unacceptable for use in the intended beam line at the NSLS, and we are in the process of having it coated with a CVD SiC film which will be capable of being polished much better than the present surface.

Conclusion

The quality of optical components depends in part on the ability to specify the appropriate parameters and on the ability to measure them. We have shown that it is important to know the function to which an optic will be employed, since that determines the tolerances to which it must be made. But without the proper metrology, tolerances are meaningless. Manufacturers will be asked to deliver components far superior to those in use today in order to make use of new high-brightness and high power sources. It is usually the responsibility of the user to develop the metrology capability for his own requirements and pass them on to the manufacturer in some "technology transfer" way. We are actively seeking to further the technology transfer process to advance the state-of-the-art in optical fabrication by applying commercially-available instruments to our problems, by developing new metrology techniques, and by providing feedback to the manufacturing community to inform them of our needs and capabilities in metrology.

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Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise, does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof.

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TABLE I. Materials and surface figures of reflection optics in use or contemplated for use in synchrotron radiation beamlines.

<u>Material</u>	<u>Figure</u>
Fused silica	Plano
Float glass	Spherical
Metals	Cylindrical
Ceramics	Toroidal
Composites	Ellipsoidal
Thin film coatings	Paraboloidal
Multilayer reflectors	Bent mirrors
Replicas	Polynomial surfaces
Plastics	Cylinders of revolution
Soap films	Plane cylinders
	Diffraction gratings

Table II. Metrology required to qualify SR optics

General Requirements

Surface figure
Surface finish
Reflectance
Coating quality - adhesion, uniformity, durability
Thermal stability
Mechanical integrity and stability
UHV compatibility
Reference surface alignment

Specific for Diffraction Gratings

Diffraction efficiency
Groove orientation on blank

Following Exposure to SR Beam

Contamination
Damage assessment

Dynamic Measurement for Bent Mirrors or Actively-Cooled Optics

Figure
Thermal stability
Mechanical stability - coolant flow jitter
UHV compatibility

Table III. Interpretation of a 1 arc second RMS slope error.

(1 arc second = 4.85 μ rad)

Spatial Period D	Amplitude A	RMS Roughness σ
50 cm	562 nm	397 nm
50 mm	56 nm	39.7 nm
5 mm	5.60 nm	3.97 nm
1 mm	1.12 nm	0.79 nm
.5 mm	.56 nm	0.39 nm

Sinusoidal component of surface roughness with amplitude A over period D has the following RMS roughness and slope errors:

$$\sigma = \frac{A}{\sqrt{2}}$$

$$m = \sqrt{2} \frac{\pi A}{D}$$

FIGURE CAPTIONS

- Figure 1. Design process logic diagram for specification of SR optical components and instrumentation.
- Figure 2. Specular reflection and scattering in one dimension from the surface of a reflection optic at grazing incidence ($\sin \theta_i \approx \theta_i$). The angular deviation, θ_s , of a scattered component is related to the surface spatial period, d_s , by the grating equation.
- Figure 3. The scattering process viewed as a generalized diffraction process. The surface profile can be viewed as a phase variation in the exit aperture, and the amplitudes of the diffracted wavefronts calculated by Fresnel-Kirchhoff diffraction theory.
- Figure 4. Relationships among various phenomena in the image plane. Terms are discussed in the text.
- Figure 5. Relationship among image plane phenomena for a "typical" SR mirror used at two different angles of incidence with the following parameters: $\lambda = 1 \text{ \AA}$; length $L = 50 \text{ cm}$; source distance 10 m ; image distance 1 m ; magnification 0.1 ; source size $200 \text{ }\mu\text{m}$. The ordinate indicates the location of various features in the image plane. The region of image space sampled by the surface profiler depends on the function of the mirror and the source size.
- Figure 6. Representation of the departure from the best-fit aspheric surface by a sinusoidal component of amplitude A and period D , with a corresponding root-mean-square roughness $\sigma_{\text{RMS}} = A/\sqrt{2}$ and slope error $m_{\text{RMS}} = \sqrt{2} \pi A/D$.

FIGURE CAPTIONS (continued)

- Figure 7. Surface profilers suitable for making measurements on full size SR optics and the range of surface spatial periods over which they are sensitive. Dashed lines indicate potential extensions of the conventional ranges with appropriate instrument modifications. The upper group are mechanical contact profilers; the lower group are non-contact optical methods (except for the SEM and STM).
- Figure 8. Schematic diagram of the WYKO optical profiler in use at Brookhaven National Laboratory. It is a zero-path-difference interferometer based upon a Mirau microinterferometer objective.
- Figure 9. Point spread function measurement method for assessing the quality of grazing incidence components or systems used with synchrotron radiation. Measurements are made at visible wavelengths and data is analyzed by means of a diffraction integral model. The technique is sensitive to slope errors on the order of 1 arc second.
- Figure 10. **(Upper)** - Point spread function at $\lambda = 632$ nm for the U4 PGM P5 collimator mirror alone: solid line = measured data; dashed line = model with 2.7 arc sec RMS surface slope error.
- (Lower)** - PSF at $\lambda = 442$ nm for the U4 PGM system using the P3 focusing mirror: solid line = measured data; dashed line = model with 3.8 arc seconds surface slope error; dotted line = ideal PSF. All curves are normalized to their peak values.

FIGURE CAPTIONS (continued)

- Figure 11. Calibration of a mirror-bending mechanism using the PSF measurement technique with a He-Ne laser source. Inclusion of a gravity-sag term and a residual slope error of 1.7 arc seconds RMS is essential to reproduce the asymmetry in the measured profiles: solid line = measured data; dotted line = model results with the indicated focal distance parameter. The observation point is always constant at 10.0 m from the mirror.
- Figure 12. Surface profile measurement made by the WYKO optical profiler along the major axis of a fused silica toroid. Upper panel is prior to removal of curvature by the detrending process; lower panel is the residual roughness after removal of the curvature, measured to be 4.01 Å RMS. This illustrates the ability to estimate local surface curvature on smooth aspheric optics with the optical profiler.
- Figure 13. Surface profile measurement along the major axis of an electroless nickel-plated Al toroid. The surface profile is substantially different from the fused silica surface, with an RMS roughness of 6.68 Å.
- Figure 14. Surface profile and corresponding power spectral density for a gold-coated float glass surface, taken with the X10 objective. The measured roughness is 3.50 Å over the bandpass of the profiler.

FIGURE CAPTIONS (continued)

Figure 15. Surface profile and corresponding PSD for a REFEL silicon carbide toroidal surface coated with a thin rhodium layer. Measurements were made with a X2.5 objective; sample trace length is 5.3 mm. Grain pull-outs during the polishing process limit the achievable roughness to about 60 Å RMS for this material.

Figure 16. Angle-resolved scatter measurement (dotted line) and PSD computed from the surface profile (solid line) for a 4.0 Å RMS gold-coated float glass mirror. Scatter measurements made at $\lambda = 1$ Å at 3 mrad grazing incidence angle. The PSD is scaled by the appropriate geometric factors and compares favorably with the measured scattered intensity. The PSD computed from the profile measurements can be used to predict scattering performance at x-ray wavelengths for smooth surfaces.

Figure 17. Angle-resolved scatter measurement (dotted line) and PSD function for a REFEL SiC mirror surface. (Same parameters as in Fig. 16). The large roughness value of the SiC surface exceeds the limits of smooth surface scalar scattering theory, and the comparison between measured and predicted scatter breaks down.

Figure 1

$$\theta_s = \frac{\lambda}{d_s \theta_i}$$

Figure 2

Figure 3

Figure 4

$\theta = 90^\circ$ (normal incidence)

$\theta = 3 \text{ mrad}$ (grazing incidence)

Figure 5

Figure 6

PROFILERS SUITABLE FOR SR OPTICS

Figure 7

Figure 8

Figure 9

Figure 10

Figure 11

Figure 12

Figure 13

Figure 14

Figure 15

Figure 16

Figure 17