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to the Documentation of Damage to Smooth
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The Application of Angular Resolved Scatter
to the Documentation of Damage to Smooth Mirrors

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Abstract

Mirrors designed to survive exposure to damaging radiation are being irradiated and then measured to determine the mechanisms of failure and to improve the ability of analysis codes to predict an exposure damage threshold. The differences between survival and catastrophic failure are easily recognized and recorded by macro photography. However, the goal of this project is to quantify the onset of mirror degradation utilizing non contact methods that have good measurement sensitivity to small changes in reflectivity (material properties) and light scatter (roughness). A new angular resolved scatterometer is described that has an extended dynamic range and integrated analysis capable of displaying the surface power spectral density (PSD) over large bandwidths of surface spatial frequencies. Graphical displays of the scattered light power before and after exposure to the radiation are compared and integrated over equivalent spatial bandwidths of sensitivity for other instruments to compare calculated RMS roughness values.

Program Description

Mirrors are being designed and tested for their ability to withstand harsh environments including exposures to x-ray and thermal radiation. The mirrors consist of an aluminized fused silica substrate with a multi-layer dielectric protective overcoat. Coating survivability is improved by interposing metallic layers of low Z material between the reflector and the substrate to distribute prompt thermal loads over larger volumes. These design concepts are being tested by fabricating the mirrored substrates and exposing them to varying energies and sources of radiation (1). Of primary interest is the melt fluence due to the production and stopping of photoelectrons within the dielectric mirror stack and substrate. Failure often includes stress cracks at thermal gradients, enhanced chemical pitting, then melting and vaporization and sometimes catastrophic eruption of the surface with increasing exposure. A goal of this study is to better understand the damage mechanisms and improve codes which when given a set of coating parameters will predict the onset of failure. It is possible that for many applications where the substrate is designed to be a heat sink, it need not be of infinite thickness, allowing coatings to replace difficult fabrication steps.

The fabrication methods are not a part of these ongoing experiments. So, as much as possible, well established procedures are being employed to produce

superfinished fused silica substrates with high reflectivity coatings. The substrates are 3.8 cm diameter by 1 cm thick. They are polished flat with pitch and cerium oxide. Care is taken to remove any damage from the roughing operations by continuing the polishing operations two or three times longer than is required to remove visible defects. The edges and large chamfers are also polished for cleanliness and to remove stress. The substrates are then cleaned with soap and water, and transported into a clean room where they are acetone wiped prior to mounting in the coating chamber.

A few of the initial experiments are listed in Table 1 with surface roughness as measured by the Optical Heterodyne Profilometer (2) before coating. The substrate number and its heat sink material (the underlined number and letter code) are placed in the table according to heat sink thickness and enhanced coating design. The entry after surface roughness (in RMS angstroms) is the additional roughness due to coating. In some cases, the surface appeared smoother after coating as indicated by a minus sign. The beryllium coatings were produced by both evaporation and sputtering and in some cases mixed with Boron (Be/B) to achieve a smoother surface. Coating stress is also measured by duplicating the design on thin substrates. These are also exposed and later fractured for microanalysis of the coating structure.

Several instruments capable of noncontact measurement are used on this project. Microscopic examination and photography provide adequate graphic documentation of mirror failure; however, it is necessary to numerically quantify each exposed site with traceable parameters that can be related to the exposure. Statistical evaluation of several point measurements or line profilers requires many measurements when encountering widely dispersed cracks or pits. The exposed area of these experiments is well defined, and can be fully illuminated by an interferometer or scatterometer which will evaluate the entire area illuminated with one or two measurements. The Angular Resolved Scatterometer (ARS) previously described (3) is well suited to these experiments because the measured scattered light profile is directly traceable to the surface roughness. Before and after exposure Power Spectral Density Functions (PSD) (4), (5) are compared to evaluate the effects of the damaging radiation.

	Al: (A)	Be: (B)	Si: (C)	Be/S: (D)
	Thickness in Nanometers			
	<u>0</u>	<u>250</u>	<u>500</u>	<u>1000</u>
Al:Bare	<u>54A</u> 1.5 - 0.1	<u>56C</u> 2.3 - 0.3	<u>58C</u> 2.6 - 0.1	<u>48B</u> 2.6 - 3.4 <u>05B</u> 3.5 - 1.4
Al ₂ O ₃	* <u>80A</u> 2.2 - 0.4	<u>78B</u> 2.2 - 0.1	<u>76B</u> 1.7 + 1.5	<u>49B</u> 2.5 + 5.0
		<u>80C</u> 2.5 - 0.5	<u>62C</u> 1.8 + 0.4	<u>12B</u> 2.4 + 0.1
		<u>24D</u> 3.7 - 0.7	<u>53C</u> 1.6 + 0.6	<u>74D</u> 3.7 - 0.2
			<u>72D</u> 1.8 + 0.1	
Al ₂ O ₃ , TiO ₂			<u>67C</u> 2.2 - 0.1	<u>13B</u> 2.0 + 0.9
				<u>26D</u> 1.9 + 0.8
(Al ₂ O ₃ , TiO ₂) ²			<u>65C</u> 2.0 + 0.6	<u>23B</u> 2.1 + 0.5
SiO ₂ , Al ₂ O ₃			<u>66C</u> 2.1 + 0.0	<u>37D</u> 2.0 + 0.8

Table 1 The substrates are located on the table by the thickness of heat sink layer (material is the letter code) and design of multi-layer overcoat. After the substrate serial number, is the roughness in RMS Angstroms then the additional roughness (for smoothness indicated by a negative sign) as measured after coating.

ARS Description

The ARS measurement provides in a single display the combined simultaneous effects of all the surface irregularities. Individual surface features are area dependent and only produce recognizable spikes in the Power Spectral Density Function (PSD) when facets are large enough to produce a specular reflection or become periodic in the direction of the measurement and contribute little to the calculated RMS roughness. By comparison the Optical Heterodyne Profilometer (OHP) and Wyko Interferometer (6) display a calculated line profile of the reflecting surface analogous to the amplified motion of a contact stylus tracing separate surface irregularities which can appear quite different when measured nearby in the same area. In these instruments the RMS roughness is calculated by a surface transfer function consisting of measured heights and a auto covariance of the measured lengths. Conversely for the ARS, scattered light is measured directly in the Fourier plane and integrated to obtain RMS roughness. The scatterometer detects a differential fraction of

the incidence light scattered into the solid angle collected. Unlike the other measuring instruments, this angle of collection can be adjusted to measure one Fourier component. When the data is integrated over the 2 π hemisphere the result is Total Integrated Scatter (TIS).

$$TIS = \left(\frac{4\pi\sigma}{\lambda} \right)^2 \quad 1$$

where (σ) squared is the RMS roughness and λ is the wavelength light.

The PSD is calculated in a coordinate system from any specular direction. In order to perform this calculation the machine coordinates, which are fixed in the hardware, must be transformed into angles appropriate for the analysis. Upon startup all the axes are "homed" and distances along each axis is sensed by calibrated encoder signals. The angle of incidence θ_i is selected by the operator and light is scattered into the machine horizontal axes θ_r (in plane) and vertical axis α (out of the plane of incidence). The scatterometer geometry is shown in Figure 1 with the α axis rotating on the θ_r axis. The transformations of machine angles to fixed coordinates from mirror normal (θ_s and ϕ_s) are

$$\theta_s = \cos^{-1} (\cos \theta_r * \cos \alpha) \quad 2$$

$$\phi_s = \tan^{-1} (\sin \theta_r^{-1} \tan \alpha) \quad 3$$

In the simplest case, periodic surface roughness scatters light in accordance with the grating equation given by

$$\sin \theta_s = \sin \theta_i + \lambda f \quad 4$$

where λ is the wavelength of illumination, and f is the grating spatial frequency. Mirror surfaces will have a two dimensional surface spatial frequency with components f_x and f_y and the two dimensional grating equations are:

$$f_x = (\sin \theta_s * \cos \phi_s - \sin \theta_i) / \lambda \quad 5$$

$$f_y = (\sin \theta_s * \sin \phi_s) / \lambda \quad 6$$

each scattering over 2π . The PSD (power spectral density) is the roughness power per roughness frequency so

$$PSD [f] = [2\pi f_x^2 + 2\pi f_y^2]^{1/2} \quad 7$$

There are three PSD solutions, given in references (4), (5) and (7) depending upon the surface topography: A general case where a large fraction of the

observation sphere is covered by detector sweeps, a one dimensional case such as a diamond turned or periodic surface, and the isotropic distribution of scatter radially from the normalized specular reflection.

It has been predicted (8) that three scaling, or invariance, rules are true of diffractive scattering. If the angle of incidence is fixed ($\sin \theta_i$) and the product of any other two variables of Equation 4 is constant the third will be known. This seems elementary at first glance, but it is an important tool to the system designer because it allows extrapolation of a measurement to other wavelengths, angles or surface roughnesses. It also allows comparisons among different instruments which calculate roughness values that are valid only within spatial bandwidths where the instrument is sensitive.

The surfaces produced for this project all appear isotropic, even after damage. This reduces the number of measurements necessary to a single horizontal scan of each exposed site and by fixing the polarization and incident angle the data set is further reduced. However, the multi-layer dielectric coating is an important consideration. There are analytic methods to correct for interference from multiple reflecting surfaces in transparent coatings at a given angle of incidence and wavelength (9). Another solution is to overcoat with aluminum any transparent coating. This allows use of a single set of optical constants for all the measurements and is also necessary for comparison between instruments.

Instrument Description

Operation of the scatterometer is outlined in Figure 2. It incorporates LSI control and operator interfaces for 5 axes of motion. There are cursor controlled windows on pages of instructions with default values and error messages for the operator to position a test mirror and perform the scans. Vectors and velocities are calculated for D. C. motor control of the photomultiplier (PMT) position and position encoders provide in-flight correction with equal division of data points within a scan. The scan options include raster and circular multiple sweeps. Both soft and emergency shutdown are provided by limit switches. Shown also is a dynamic feedback loop to the PMT power supply which extends the linear dynamic range.

The optical path is sketched in Figure 3. Important features include placement of the reference detector after the spatial filter along with a relay lens and a second aperture at the first null in the diffraction produced by the spatial filter. This well defined diffraction free field is Fourier transformed by a low scatter projection lens onto the entrance pupil of the sensor to obtain total power. The scattering mirror is then added as shown and the differential scattered light measured. Surface spatial resolution is determined by the area illuminated, the entrance pupil area and the number of data points per scan length. Height information is limited by noise free PMT gain, magnetic and RF shielding, and instrument baffling. The sensor telescope pupils are aligned so only scatter from the illuminated area of the mirror is transmitted. Then the alignment eyepiece is replaced by a turning mirror onto the PMT. The filters shown are to bring the detector into a linear dynamic range, to reject other wavelengths, and to diffuse bright spots over a larger area of the PMT face. Physically the filters are a neutral density filter glass, a narrow band pass wavelength filter, and a ground glass

diffuser.

Alignment of the optical paths through the instrument axis of motion and apertures is important, as is the calibration of PMT linearity. Because a calibrated PSD requires measuring the source and the specularly reflected energy, and because super-smooth mirrors scatter less than one part in 10^{-10} at large angles, dynamic feedback of PMT sensitivity or of the attenuation is necessary. There is a removable, calibrated neutral density (N. D.) 4 filter at the PMT face for measurements of the specular reflection and the first one-half degree of a scan. The remaining range is covered by diffusing the small aperture over a large area of the PMT and controlling the operating voltage (bias) to the PMT. The linear dynamic range is 10^{-4} using constant current control and an additional 10^{-2} at 2000 volts allowing the current to vary. To measure highly damaged mirrors, it is often necessary to add calibrated N.D. filters and insert the attenuation value into software. The efforts to characterize the source and detector have been more rewarding than depending upon secondary standards and substitution techniques of calibration and algorithm testing.

Fig. 1

ARS Axis of Computer Controlled Motion.

Fig. 2. Flow of ARS Control.

Fig. 3. ARS Optical System

Summary

In this application, scattered light is measured as a function of scattering angle and the resulting data are displayed as the PSD function. With this approach, differences in surface roughness are easily recognized over a broad range of spatial frequencies. The ARS surface frequency band limits depend upon the wavelength of illumination and the area illuminated. For other instruments that measure line profiles or a statistical set of points, the band limits are not so clearly defined. In order to determine height (amplitude) information on highly damaged mirrors, an ARS sensor with a large linear dynamic range is required. To determine small changes in smooth undamaged surfaces requires a sensor with high sensitivity. Integrating the PSD function over a specified range of spatial frequencies provides RMS surface roughness and slope that are valid for the range. By confining the integration within band limits that are equivalent to those for some other instrument, a comparison can be made between the ARS data and the calculated RMS roughness and slope derived from the other instrument. With the extended band limits, dynamic range and sensitivity, along with the computer control and data reduction capability, the ARS is an optimal instrument for documenting smooth mirror damage.

The data for several PSD functions in Figure 4 was taken from exposed areas on substrate 80A which is indicated by a star in Table 1. The roughness on exposure Number 1, a smooth surface, varies between 2 and 10 Angstroms RMS. On exposure Number 7, a nearly diffuse surface, roughness values are over 60 Angstroms RMS. (A straight horizontal line would indicate a perfect diffuser.) The source of illumination was an S-Polarized 633 nanometer wavelength laser scattering from a 4mm illuminated area. The PMT with a 2mm entrance aperture acquired 800 data points from .5 to 80 degrees from the specular reflection at a radius of 38 cm. The exposure energy varied from a low level in Number 1, which showed no change from the before exposure scan, through a high level in Number 7, which destroyed the mirror. Numbers 2, 5 and 6 low angle scattering is due to small cracks observable under a low power microscope. The high angle scattering in Number 2 is observed as a silver fog under strong illumination.

Fig. 4. PSD measurements of seven exposed areas on a single substrate (*80A).

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