A New Light On Quality

INTERPRETING LIGHT SCATTER MEASUREMENTS

Simple Interpretation of BSDF Curves and Raster Scans

In this note, we discuss how light scatter measurements can be used to quantitatively determine the physical condition of a surface or bulk material. By studying typical data from a variety of applications, we will see how scatter measurements offer a fast, sensitive quality check for a variety of industrial and laboratory applications, from detailed evaluations to simple pass/fail quality checks.

WHERE DOES SCATTER COME FROM?

Objects that are opaque, and/or reflective, scatter light from their outer surfaces. A transparent or partially transparent object may scatter light both from its outer surfaces and from its interior (or bulk).

Surface Defects

A perfectly smooth mirror will reflect light according to the simple relationship: angle of reflection = angle of incidence. This is termed specular reflection. If a narrow laser beam is directed at a perfectly smooth mirror, all the reflected light intensity will be in the narrow reflected beam.

In the real world, surfaces are not perfectly smooth and have some types of defects such as dust particles, cracks, residual film, microroughness, etc. These defects cause some incident light to be scattered or diffusely reflected off the surface in many directions. In the case of very rough surfaces, such as a sheet of sandpaper, the well-defined specular reflection disappears and all of the reflected light is scattered.

Bulk Defects

When a beam of light passes through a transparent (clear) material, such as water or glass, it will be almost invisible from most angles. Very little light is scattered out of the direction of beam propagation. However, if the material has small particles or defects in it, some of the light will be scattered, making the beam visible from all directions. The simplest example of this is to consider a search light. It is virtually invisible in a clear night sky but clearly visible if it passes through smoke or a cloud. The reason it becomes visible is that the smoke particles or water droplets scatter the light in all directions.

HOW IS SCATTER RELATED TO THE DEFECTS?

The size, shape, and distribution of the surface features or bulk defects determine how much light is scattered versus how much is reflected in a specular fashion. In addition, the distribution and size of these features determine the angular distribution of the scatter. Measurements of how the material scatters a well-characterized beam of light, such as a laser beam, can therefore be used to determine the size and distribution of the scattering features.

DEFINING AND MEASURING SCATTER, BSDF

Figure 1 shows how light may be scattered both in reflection and transmission. In both cases, the light may be scattered throughout a hemisphere whereas the "specular" beam is confined to a single angle.

The terms most useful in defining or measuring scatter are collectively called BSDF (Bidirectional Scatter Distribution Function). The two most commonly used are BRDF (for reflected scatter) and BTDF (for transmitted scatter). For simplicity, we shall concentrate on the more common BRDF surface measurements here, but similar interpretations apply to BTDF measurements.

The BRDF is a full description of the angular distribution of the reflected scattered light. It assumes a single incident light beam at a fixed angle of incidence. The BRDF value at each scatter angle is the scattered light intensity at that angle, divided by the incident intensity and includes various geometric factors (see Figure 2). BRDF can be measured by an array of detectors arranged in an arc or by a sweeping a single detector through an arc.

Some important general rules to remember are:

The intensity of scatter increases with increased depth and density of the surface defects. The scatter angle (measured from specular) is dependent on the average width (or length) of the surface defects. Wider (longer) defects scatter at angles close to specular, whereas narrower (shorter) defects scatter at angles far from specular.

INTERPRETING SCATTER DATA

1. BRDF ANGLE PLOTS

In this section, we consider the most common type of measurement, BRDF angle scans. During CASI measurements, the angle at which the laser strikes the sample (angle of incidence) is kept constant and the angle of the detector is varied to measure the scattered intensity at different angles. If the sample being tested has an optical use, the chosen angle of incidence may be the specific angle relating to its actual operation.

<u>Surfaces Produced by Random Processes</u>

The BRDF of a surface produced by random wear, such as by grinding or polishing, is simple to analyze in order to obtain valuable information about surface quality (smoothness or finish). The easiest way to understand such a plot is to examine some sample data.

Figure 3 shows the BRDF plot for two randomly polished mirrors. As explained above, this is a plot of scattered intensity versus angle. The 0 degree point on the horizontal axis indicates the direction of the specular reflection. All other directions on the plot are relative to this direction (Ès-Èi in Figure 2). The vertical axis is the BRDF scatter (on a logarithmic scale). BRDF is typically plotted on a logarithmic scale because it changes over several orders of magnitude within a few degrees of the specular beam.

Looking at Figure 3 we can easily see that mirror 2 has a higher BRDF plot than mirror 1 indicating that mirror 2 scatters more light than mirror 1. Without any mathematics whatsoever, we can immediately tell that mirror 1 has a much smoother surface than mirror 2.

BRDF is often displayed in a "log-log" plot. That is to say that both the BRDF and the angle of scatter (horizontal axis) are plotted on log scales. There are two very good reasons for this. First, it allows a more detailed study of the scatter distribution close to the specular direction, and for a polished surface, that is where most of the light is scattered. Second, for surfaces produced by a random process, a log-log plot generally approximates a straight line. The slope of this plot is a characteristic of the process which is used to produce the surface under test. Figure 4 shows log-log plots for the same two mirrors as in Figure 3. These mirrors are both produced by the same process. Although the slopes of the log-log plots are very similar, mirror 2 clearly has a rougher surface finish. Conversely, Figure 5 shows the BRDF plots for two mirrors produced by quite different processes. Mirror 1 has a higher scatter near the specular angle, whereas mirror 2 produces more scatter at higher angles. We can, therefore, deduce that mirror 1 has long surface characteristics than mirror 2, but the surface of mirror 2 has a greater number of short surface characteristics. Generally, for optical surfaces, higher scatter near specular results in a degradation of the resolution of an object or ability to clearly "image" objects very close to each other. Higher scatter at higher angles often produces glare or "noise" in an optical system.

This straight line plot is thus a very powerful diagnostic. If the log-log BRDF plot for a particular sample has an unusual slope or even a curvature, this could indicate that there are problems in the process used to produce that sample. If there are peaks in the curve, then the surface defects are not random.

Machined Surfaces/Periodic Processes

Machined surfaces are inherently different than random wear surfaces in that the surface defects tend to be formed in a regular or periodic manner. A simple example of this is a metal disc produced by a lathe turning process which actually looks like a phonograph record when viewed under magnification.

Periodic surface features, such as tool marks, cause light to be scattered into a few specific angles. This shows up on a BRDF plot as one or more sharp peaks or spikes. The number, height, and angular location of the peak(s) all give valuable information about the regular surface grooves or defects. Simply put, the depth (height) and density of the surface grooves or tool marks determines how high the peaks are in the BRDF plot, whereas the position of a peak on the plot indicates the width (surface wavelength) of the grooves causing that peak (see Figures 6 and 7).

For a simple mathematical analysis:

The angle at which a peak occurs is given by

$$\sin(è_{scat}) = \sin(è_{inc}) + në/L$$

where L is the periodic spacing (length) between successive surface grooves, ë is the wavelength used in the scatter test, $è_{inc}$ and $è_{scat}$ are the incident and scatter angles relative to surface normal, and n is a positive integer (1, 2, 3...). Peak position is determined by the periodic spacing as shown by the equation. The number and relative size of the peaks is determined by tool mark shape. Sinusoidal grooves give a dominant first order peak (n=1) with only very small higher order scatter as long as the groove amplitude (depth) is small compared to a wavelength. Other shapes (square, triangle, cusp, etc.) change the relative size of the peaks (see Figure 7). A convenient parameter used to analyze surface roughness is the inverse scatter wavelength (1/L), which is known as the spatial frequency (f).

To summarize, we can tell the following from a BRDF plot containing sharp peaks:

a. The presence of sharp peaks on a BRDF or BTDF plot indicates regularly space defects or grooves on the surface or within a transparent material.

b. The height of the sharp peaks tells us how deep and dense the scratches or grooves are. Larger peaks indicate deeper surface scratches.

c. The spacing of the grooves (periodicity) can be simply derived from the angle at which the main peak(s) occur using the simple equation given above. The position of these peaks can be used to check that the machine generating the surface is still running at normal speed and feed rates.

d. The number of peaks in a related series and the relative intensity of these peaks are functions of the shape of the grooves or tool marks. Changes in this pattern are an excellent diagnostic for tool wear, chip drag, chatter, vibrations, and a number of other characteristic and potential problems in the machining process.

e. The height of the BRDF curve between the peaks tells us how much random roughness there is on the surface, as discussed on the previous page.

2. RASTER SCANS

The BRDF plots described on the previous pages represent the most common types of scatter measurement. However, this type of measurement essentially measures the average surface properties over an area (or volume) defined by the size of the laser beam used in the scatterometer. Although this spot size can be varied, many applications benefit from information taken over a larger area.

In a Raster area measurement, both the angle of incidence and the detector angle (scatter angle) are fixed. The sample is then moved in predetermined x-y steps (rastered) or rotated until the laser beam has sampled the entire surface (Figure 8). As the sample moves, the scatter intensity is continuously recorded. The data is then presented as a map using multiple colors. Each color represents a certain range of scattered intensity (hence degree of roughness on nontransmitting materials). A raster scan is used for one or more of the following reasons:

(1) To study a large surface or volume and better understand its overall, average, or statistical scatter and roughness.

(2) To study the degree of homogeneity of such a surface.

(3) To detect, locate, or count individual flaws.

In this type of measurement, both the angle of incidence and the detector angle (scatter angle) are fixed. The sample is then moved in predetermined x-y steps (or a raster pattern) until the laser beam has sampled the entire surface (Figure 8). As the sample moves, the scatter intensity is continuously recorded. The data is then presented as a map using multiple colors. Each color represents a certain range of scattered intensity (hence degree of roughness on nontransmitting materials). For example, Figure 9 shows raster scans of 2 mirrors measured at 0.514 microns. All areas shaded darkest have BRDF values below 2.00E-6, and all areas shaded next lightest have BRDF values between 2.00E-6 and 4.472E-6. The areas shaded darkest are therefore smoother than the areas shaded next lightest. For these scans, the detector was positioned at 10° from the specular angle. Notice that 001 has lower scatter than 002. 002 has less variation across its surface, it scatters more evenly. The process for creating 001 created smoother, higher quality regions but also left more high scatter defect areas. Refinement of the 001 process could ultimately lead to an excellent surface relative to the 002 process.

Also printed on the plots are average and standard deviation values of the displayed area. In some applications using scatter as an on-line process control tool, these values can be a signal to correct the process or discard the sample.

3. CALCULATION OF SURFACE ROUGHNESS

We have already seen that the measurement of scatter direction of prominent scatter peaks can be used to find the wavelength (or spatial frequency) of prominent periodic surface features. In addition, as random surface roughness increases the background scatter increases. So it should come as no surprise, that in special cases the measured BRDF can be used to calculate roughness statistics. This is accomplished through the use of diffraction theory. A full explanation is beyond the scope of this tutorial, but the results are fairly easy to understand, and making use of them can provide a lot of insight into the roughness characteristics of reflective samples.

For the special case where reflective scatter comes only from small surface features (sometimes called micro-roughness), the BRDF is essentially proportional to a roughness characterization function known as the surface power spectral density function (or PSD). Except for a change in units, and the fact that it is plotted against spatial frequency instead of scattering angle, a PSD plot looks a lot like the corresponding BRDF plot. Figures 10 and 11 show the BRDF and calculated PSD from a molybdenum mirror. The PSD has the very convenient feature that the surface root mean square roughness (rms) can be found by simply integrating the curve (finding the area under the curve) from some f_{min} to some f_{max}. The rms is equal to the square root of the calculated area under the curve. This is shown in Figure 12 for the PSD of Figure 11. Notice that if different frequency limits are chosen, different rms values will result. It is clear that the rms roughness of a surface depends on the defined bandwidth (f_{min} to f_{max}). This is a fact of life for all roughness measurements whether they are made by scatterometry or profilometry. Thus in order for roughness measurements and specifications to be meaningful, the associated bandwidth must also be given.

As indicated above, scatter can be used to accurately find roughness only if the scatter signal is caused exclusively by micro-roughness. Other sources of scatter, such as surface contamination, bulk defects, and very rough surface features create scatter noise that prevent accurate roughness characterization. Thus the surface must be a smooth (mirror-like), clean, front surface reflector for the technique to be used for accurate roughness calculations. However, scatter remains a sensitive indicator of surface features even when these conditions are not met. Even though a surface is too rough to meet the conditions for roughness calculation, it may still scatter more or less as the roughness changes and the measurement can be used to provide a fast, non-contact method to monitor changes in roughness.

SUMMARY

Excellent insight into surface quality, defects, and bulk purity can be obtained from scatter measurements. Also, astute analysis can result in simple, inexpensive in-process and final QC procedures for production of a variety of surfaces, materials, and optics. As we can see, much can be learned from just visual examination of BRDF plots and raster scans. This is often sufficient for pass/fail tests of product quality. The data can also be analyzed in more detail using various formulas and computer programs. In addition, since the data is digital, it can be rapidly analyzed by computer in on-line process control applications.

Far more detailed information on this subject may be found in Optical Scattering: Measurement and Analysis by John Stover. The second edition of this book is being published by SPIE, will be available during the summer of 1994, and may be purchased from SPIE [(206) 676-3290].

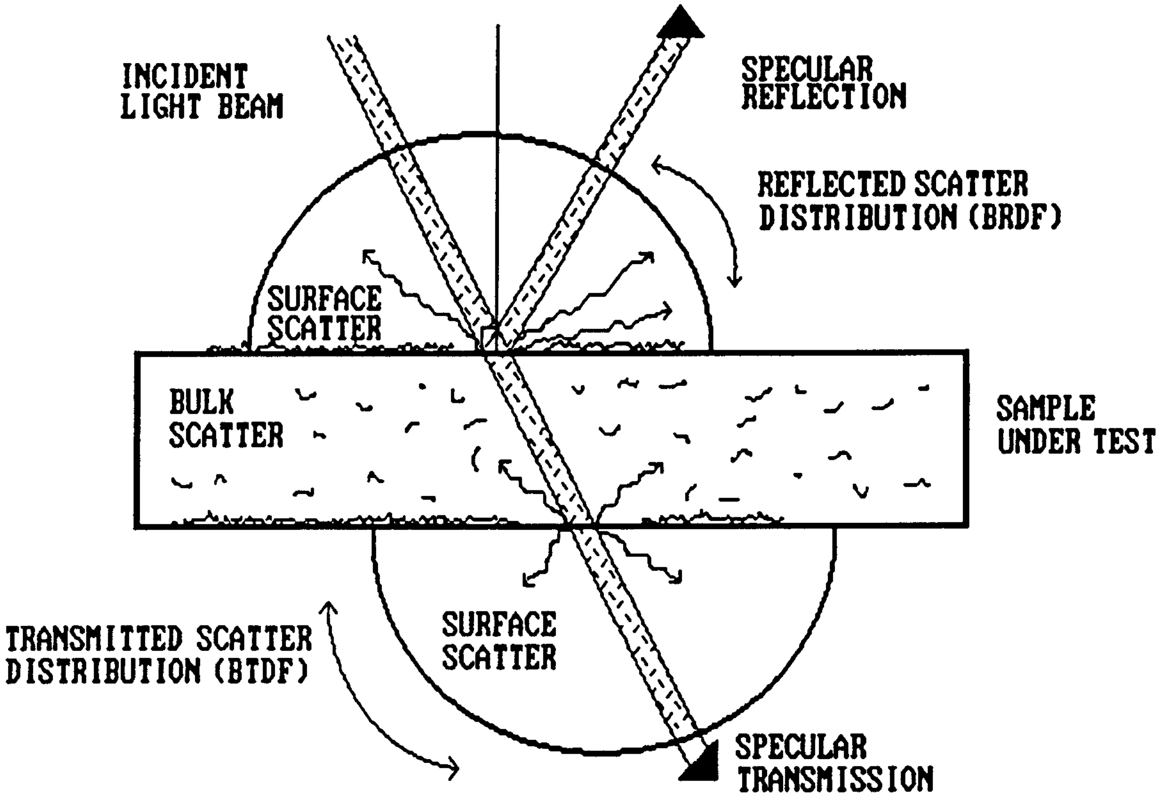

FIGURE 1. BOTH SURFACE AND BULK IMPERFECTIONS CONTRIBUTE TO BOTH REFLECTED AND TRANSMITTED SCATTER

$$\text{BRDF} = \frac{Ps/\Omega}{Pi \cos\theta s}$$

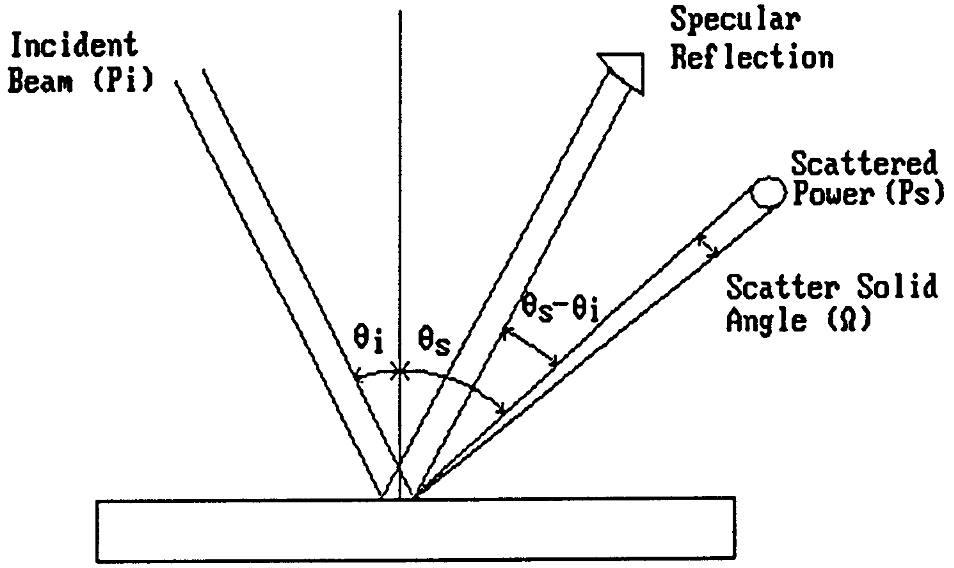

FIGURE 2. DEFINITION OF BRDF

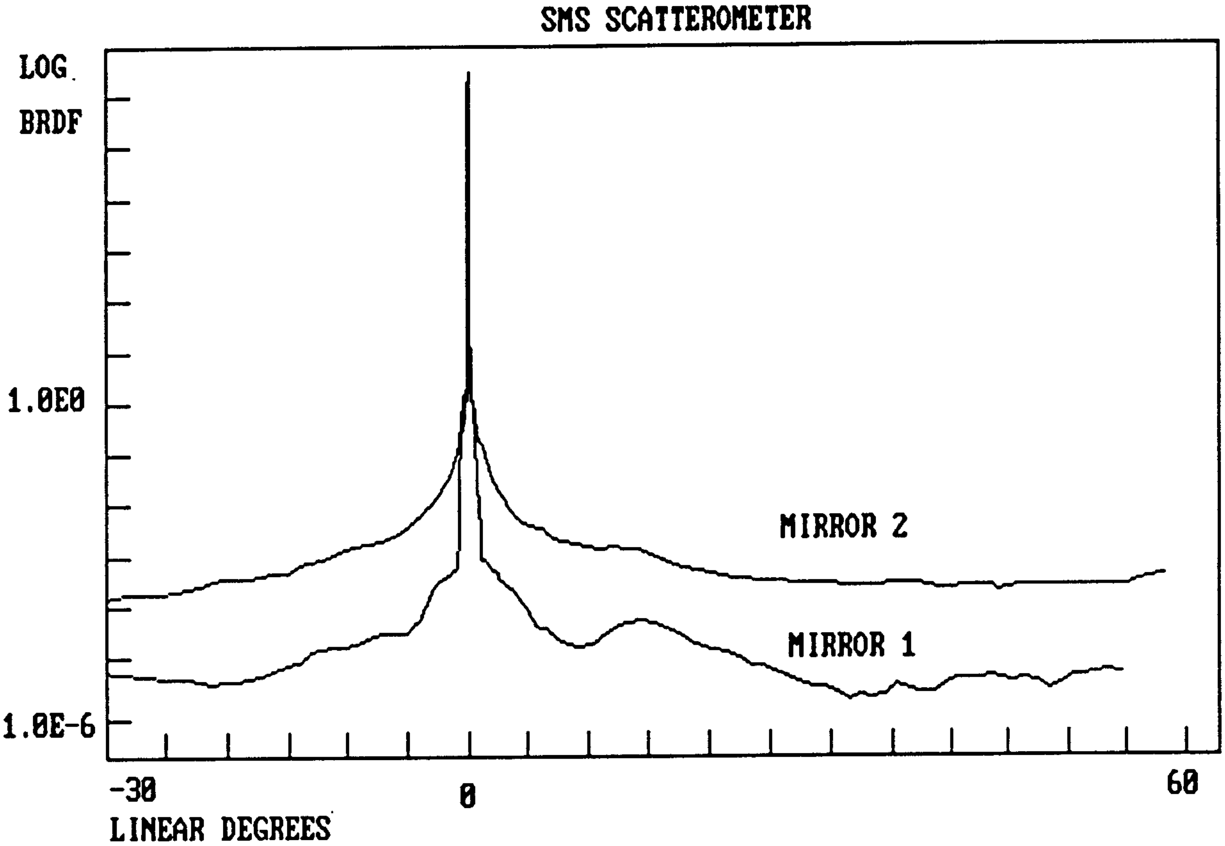

FIGURE 3. BRDF PLOTS FOR TWO MIRRORS

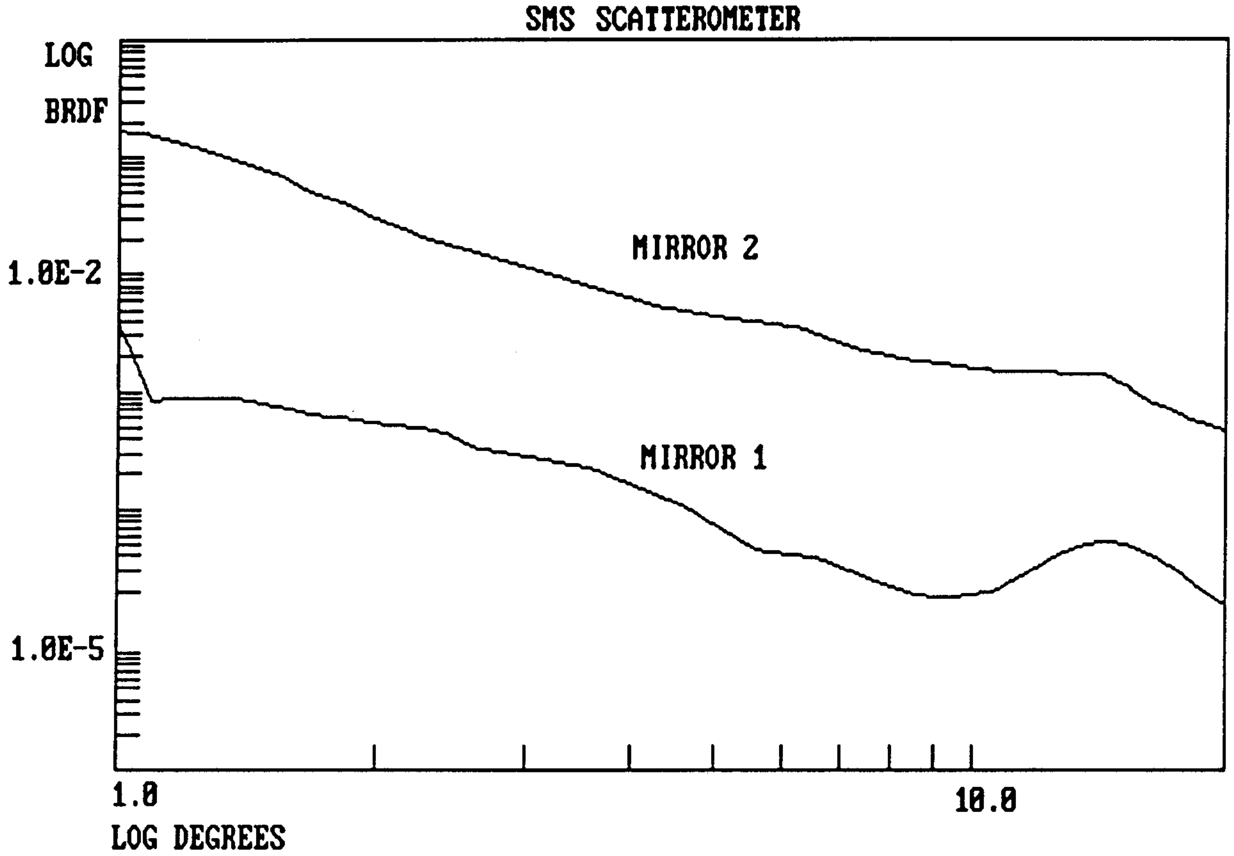

FIGURE 4. LOG-LOG BRDF PLOTS FOR TWO MIRRORS PRODUCED BY THE SAME PROCESS

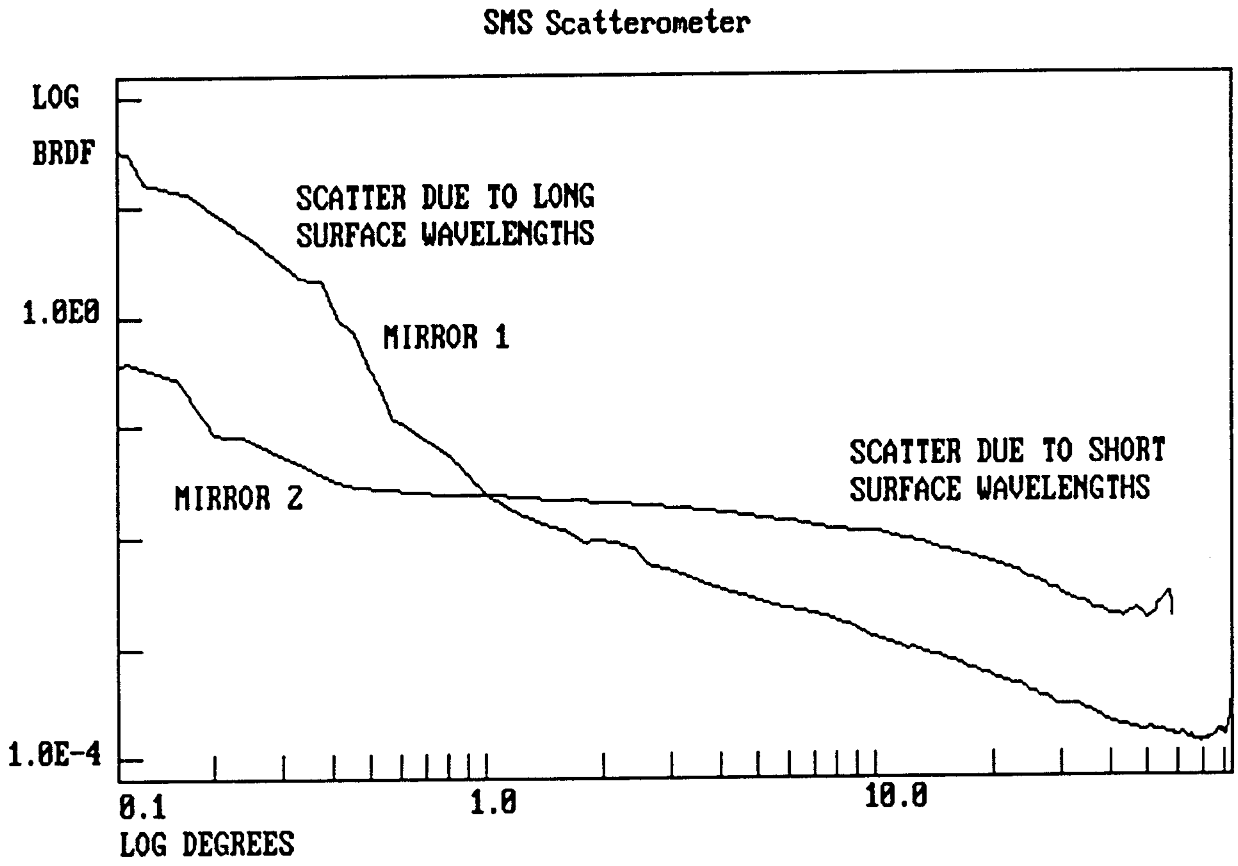

FIGURE 5. LOG-LOG BRDF PLOTS FOR TWO MIRRORS PRODUCED BY DIFFERENT PROCESSES

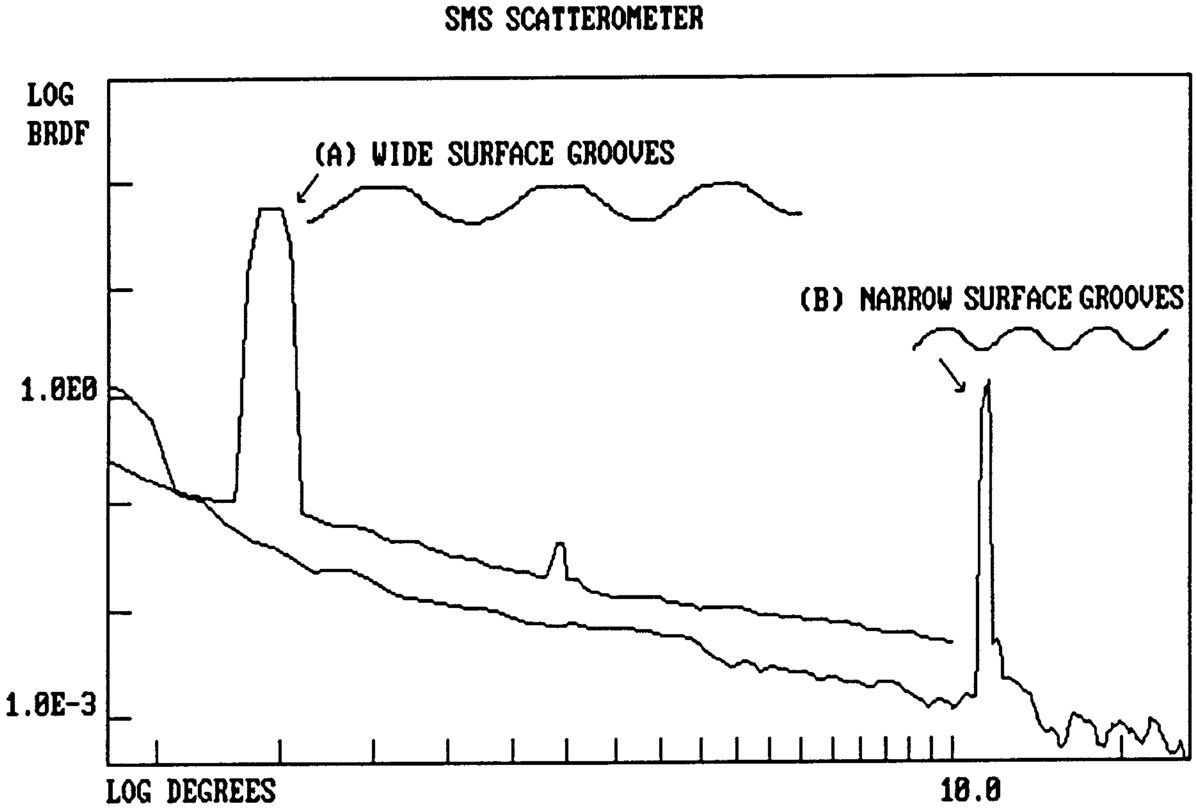

FIGURE 6. THE HEIGHT AND POSITION OF A PEAK ARE RELATED TO THE DEPTH AND WIDTH OF THE SURFACE GROOVES

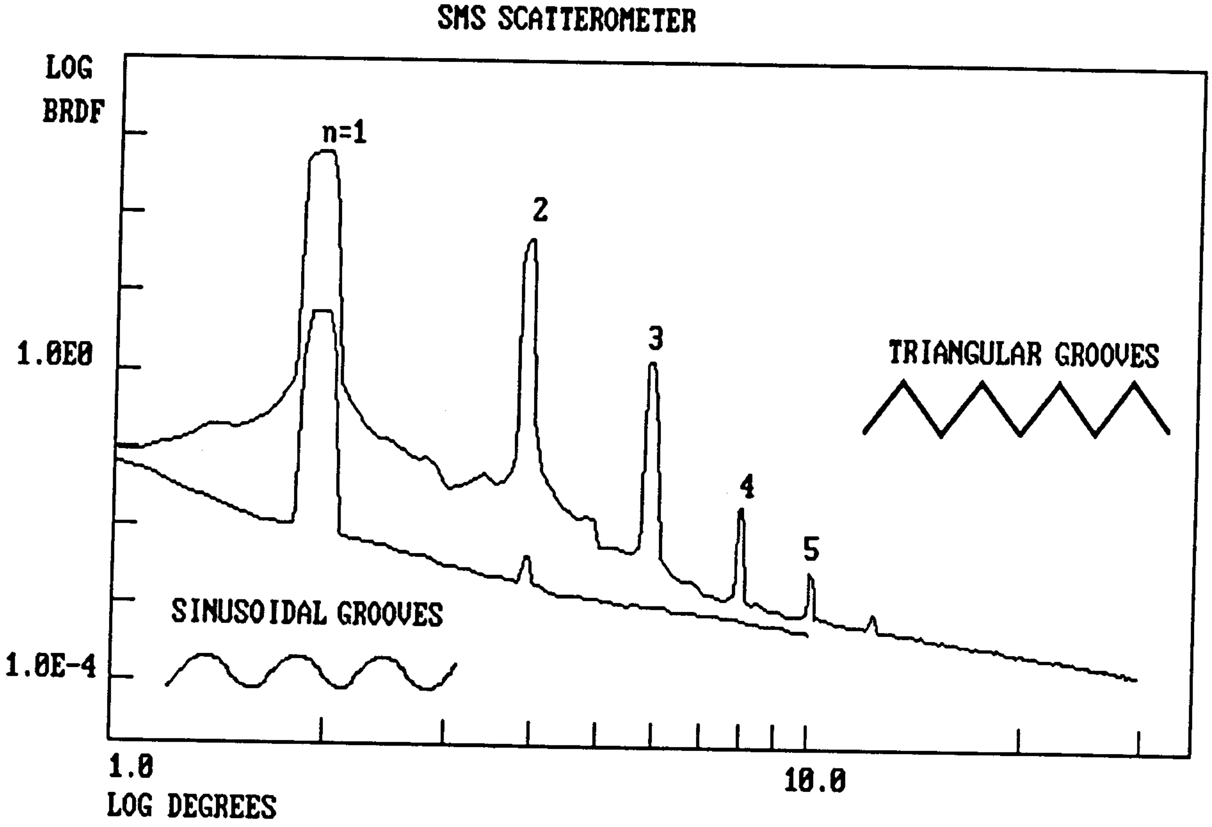

FIGURE 7. DIFFERENT SHAPED GROOVES CAN PRODUCE A SERIES OF PEAKS

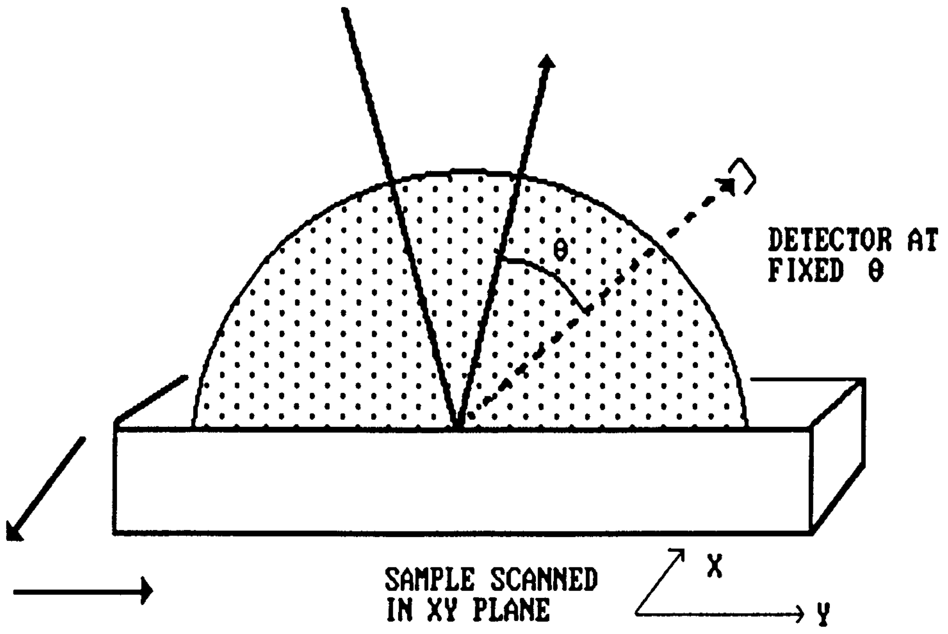

FIGURE 8. IN A RASTER SCAN THE SURFACE MOVES BUT BOTH ANGLES ARE FIXED.

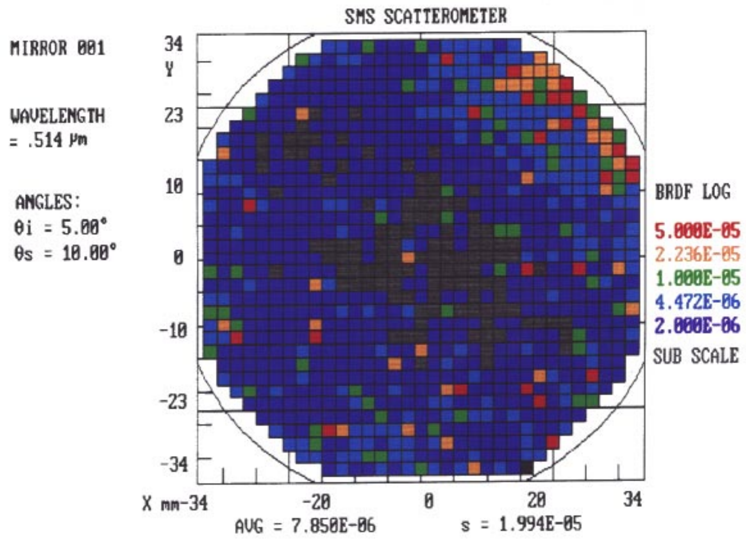

FIGURE 9. RASTER SCAN OF TWO MIRRORS

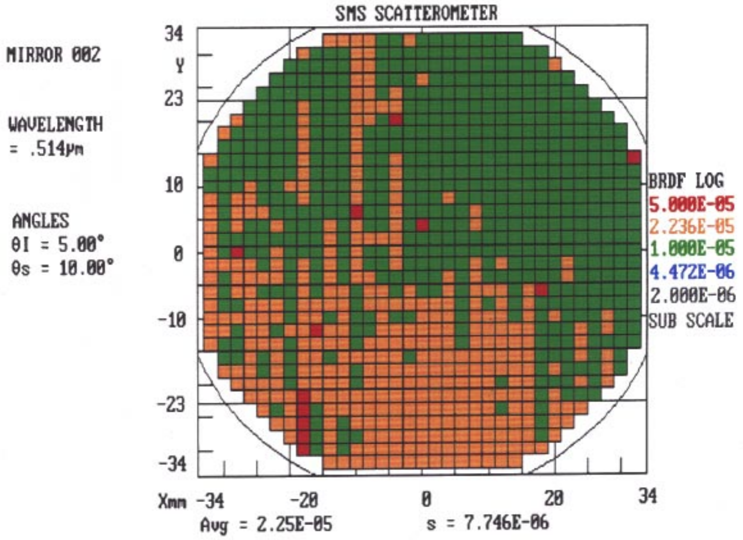

FIGURE 9. RASTER SCAN OF TWO MIRRORS

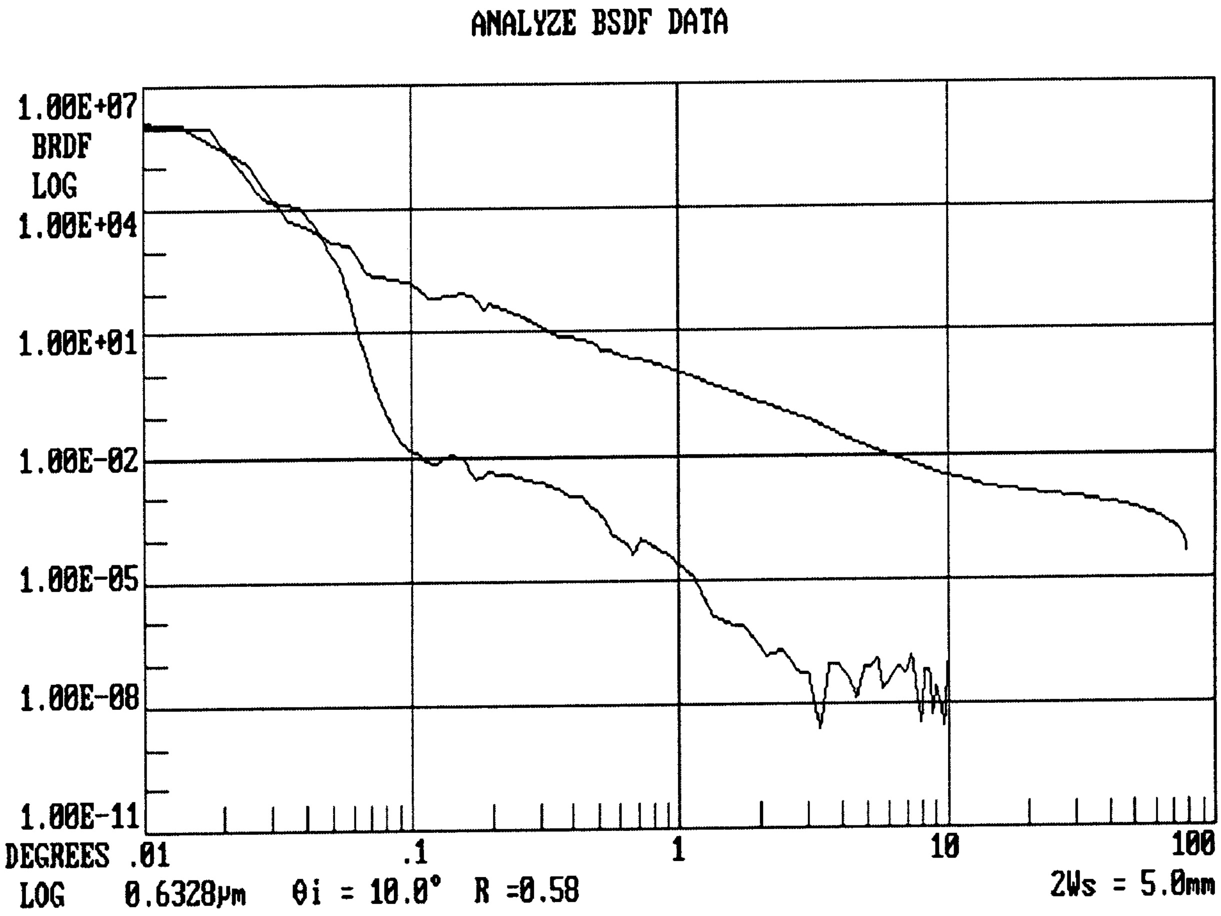
ANALYZE BSDF DATA
1.00E+07
BRDF
LOG
1.00E+04
1.00E+01
1.00E-02
1.00E-05
1.00E-08
1.00E-11
DEGREES .01
.1
1
10
100
LOG 0.6328µm θi = 10.0° R =0.58
2Ws = 5.0mm

FIGURE 10

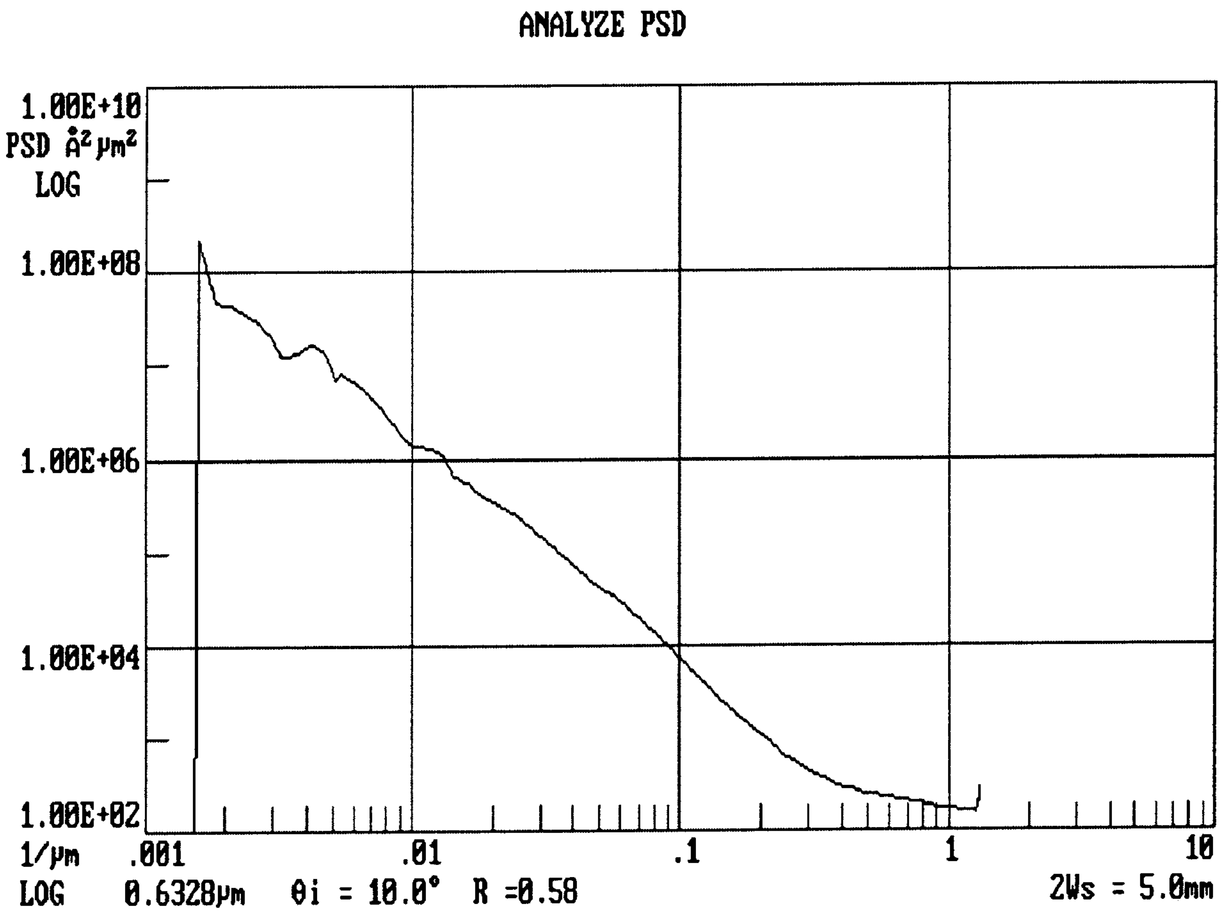
ANALYZE PSD
1.00E+10
PSD Å² µm²
LOG
1.00E+08
1.00E+06
1.00E+04
1.00E+02
1/µm
LOG
.001
.01
.1
1
10
0.6328µm θi = 10.0° R =0.58
2Ws = 5.0mm

FIGURE 11

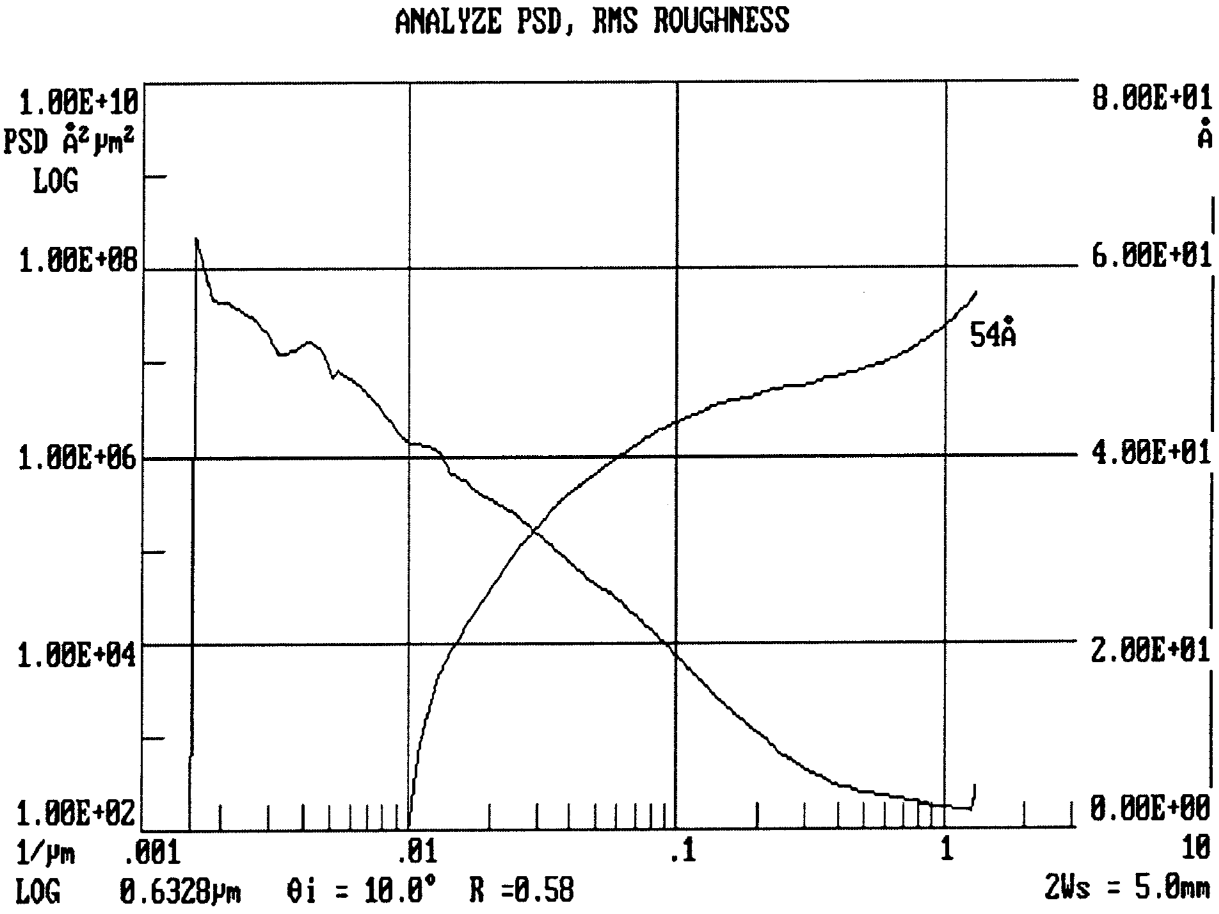
ANALYZE PSD, RMS ROUGHNESS
1.00E+10
PSD Å² µm²
LOG
1.00E+08
1.00E+06
1.00E+04
1.00E+02
8.00E+01
Å
6.00E+01
4.00E+01
2.00E+01
0.00E+00
54Å
1/µm
.001
.01
.1
1
10
LOG
0.6328µm
θi = 10.0°
R =0.58
2Ws = 5.0mm

FIGURE 12

FIGURE CAPTIONS

Figure 1. Both surface and bulk imperfections and contribute to both reflected and transmitted scatter.

Figure 2. The width of the features of defects determines the scatter angle.

Figure 3. BRDF plots for two mirrors

Figure 4. Log-log BRDF plots for two mirrors produced by the same process.

Figure 5. Log-log BRDF plots for two mirrors produced by different processes.

Figure 6. The height and position of a peak are related to the depth and width of the surface grooves.

Figure 7. Different shaped grooves can produce a series of peaks.

Figure 8. In a raster scan the surface moves but both angles are fixed.

Figure 9. Raster scans of two mirrors.