Int. J. Mach. Tools Manufact. Vol. 32, No. 1/2, pp. 5–10, 1992.
Printed in Great Britain

0890–6955/92$5.00 + .00
Pergamon Press plc

ADVANCES IN INTERFEROMETRIC OPTICAL PROFILING

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SUMMARY

This paper discusses some advances in non-contact, interferometric optical profilers. Topics discussed include: (i) The advantages of using a white light source, rather than a laser source, (ii) The tradeoff between the use of Michelson, Mirau, and Linnik interferometers for different fields of view and different lateral resolutions, and (iii) Techniques for removing errors in the reference surface enabling a person to measure sub-Ångstrom surface microstructure in the presence of a much rougher reference surface.

INTRODUCTION

Due to high measurement accuracy and rapid data taking and analysis, non-contact, interferometric optical profilers are widely used for the measurement of surface microstructure. Fig. 1 shows a simplified schematic of a non-contact, interferometric optical profiler. The configuration shown in Fig. 1 utilizes a two-beam Mirau interferometer at the microscope objective.

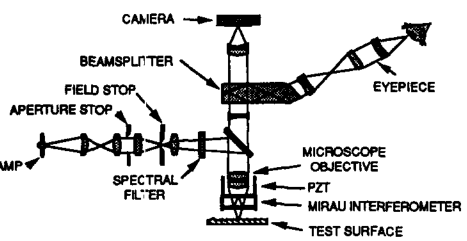


Fig. 1. Schematic of interferometric optical profiler.

A tungsten halogen lamp is used as the light source with a spectral filter of 40 nm bandwidth centered at 650 nm, to increase the coherence length. Light reflected from the test surface interferes with light reflected from the reference. The resulting interference pattern can be viewed through the eyepieces and is imaged onto either a 1024 element linear CCD array, a 256 x 256 photodiode array, or a 1024 x 1024 CCD array. Output from the solid state detector array is digitized and read by the computer. The reference surface of the Mirau interferometer is mounted on a piezoelectric transducer (PZT) so that by applying a voltage to the PZT the reference mirror can be moved during the measurement. During this movement, the test surface remains fixed. Thus, a phase shift is introduced into one arm of the interferometer. By introducing a phase shift into only one arm while recording the interference pattern that is produced, it is possible to perform the direct phase measurement technique described below.

DIRECT PHASE-MEASUREMENT INTERFEROMETRY

An optical profiler can use several phase measurement techniques that yield more accurate height measurements than are possible with the traditional technique, which determines visually how much interference fringes depart from being straight and equally spaced. The profiler described in this paper uses the 'integrated-bucket' technique (Wyant, 1975; Creath, 1988; Hariharan *et al.*, 1987).

For this technique, the phase difference, $\alpha(t)$, between the interfering beams is changed at a constant rate as the detector is read out. Each time the detector array is read out, the phase, $\phi(x,y)$, has changed by 90^{o} for each pixel. The basic equation for the intensity of a two-beam interference pattern is given by

$$I = I_1 + I_2 \cos[\phi(x,y) + \alpha(t)] \quad (1)$$

where the first term is the average intensity and the second term is the interference term. If the intensity is integrated while $\alpha(t)$ varies from $-5\pi/4$ to $-3\pi/4$, $-3\pi/4$ to $-\pi/4$, $-\pi/4$ to $\pi/4$, $\pi/4$ to $3\pi/4$, and $3\pi/4$ to $5\pi/4$, the resulting signals at each detected point are given by

$$A(x,y) = I_1' + I_2' [-\cos \phi(x,y)]$$

$$B(x,y) = I_1' + I_2' [\sin \phi(x,y)]$$

$$C(x,y) = I_1' + I_2' [\cos \phi(x,y)] \quad (2)$$

$$D(x,y) = I_1' + I_2' [-\sin \phi(x,y)]$$

$$E(x,y) = I_1' + I_2' [-\cos \phi(x,y)]$$

From the values of A, B, C, D, and E, the phase can be calculated as

$$\phi(x,y) = \tan^{-1}\left[\frac{2(B(x,y) - D(x,y))}{2C(x,y) - E(x,y) - A(x,y)}\right]. \quad (3)$$

The subtraction and division cancel out the effects of fixed pattern noise and gain variations across the detector, as long as the effects are not so large that the dynamic range of the detector becomes too small to be of use.

Because Eq. (3) gives the phase modulo 2π, there may be discontinuities present in the calculated phase. These 2π discontinuities can be removed as long as the slopes on the sample being measured are limited so that the actual phase difference between adjacent pixels is less than π. This means that the sample height change between adjacent pixels must be less than one-quarter of the wavelength of the light used to make the measurement. The discontinuities are removed by adding or subtracting multiples of 2π to a pixel until the difference between it and its adjacent pixel is less than π.

Once the phase $\phi(x,y)$ is determined across the interference field, the corresponding height distribution, $h(x,y)$, on the test surface is determined by the equation

$$h(x,y) = \frac{\lambda}{4\pi}\phi(x,y). \quad (4)$$

ADVANTAGES OF USING A WHITE LIGHT SOURCE

Lasers are generally used as the light source for interferometers because their long coherence length makes it easy to obtain interference fringes regardless of the path length difference between the two interfering beams. However, there are several advantages of using a filtered white light source in an interferometric optical profiler.

The first advantage is that noise is reduced due to the lack of spurious interference fringes. In almost any optical system, and especially in a high magnification profiler where several optical components are required, spurious reflections exist. In a system using a long coherence length source, such as a laser, these spurious reflections produce spurious interference fringes, which add noise to the measurement. If a short coherence length source, such as a filtered white light source, is used, the spurious reflections still exist, but interference fringes will result only if the beams have path differences of a few microns or less. The result is that generally a filtered white light source produces no spurious interference fringes.

For an optical profiler looking at micro-surface structure, it is extremely important that the sample is in focus, otherwise the measurements will be incorrect. On smooth surfaces it is sometimes difficult to determine focus, because there is no structure on the surface to image. A major advantage of using a white light source is that the presence of interference fringes uniquely defines focus. When a short coherence length source is used, interference fringes are obtained only when the path lengths are nearly matched. The maximum contrast interference fringes are obtained when the path lengths are exactly matched. Assuming the profiler is constructed such that the path lengths are matched when the sample is in focus, the correct focus is obtained by moving the sample through focus and looking for the maximum contrast interference fringes. With the addition of a detector and electronics, an automatic focusing system can be achieved by changing the distance between the objective and sample and sensing the position of maximum fringe contrast (Cohen *et al.*, 1989).

A third advantage of using a filtered white light source as the light source in an optical profiler is that multiple wavelength techniques can be used for the measurement of steps or surfaces having steep slopes (Creath, 1987). As discussed above, if a single wavelength source is used, the largest surface height change allowed between adjacent detectors is one-quarter wavelength. By performing the measurement at two wavelengths, λ_1 and λ_2, and subtracting the two measurements, the limitation in the height difference between two adjacent detector points is now one-quarter of λ_{eq}, where

$$\lambda_{eq} = \frac{\lambda_1 \lambda_2}{|\lambda_1 - \lambda_1|} \cdot \qquad (5)$$

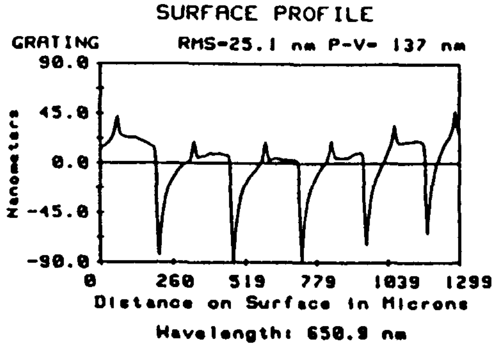
The measurement is essentially tested at a synthesized equivalent wavelength, λ_{eq}. While this approach increases the dynamic range of the measurement, the precision is also degraded by the ratio of λ_{eq}/λ . The precision can be regained by using the equivalent wavelength results to correct the 2π ambiguities of the single wavelength data. In this way the dynamic range of the equivalent wavelength is obtained, but the precision of the single wavelength data is maintained.

Results for measuring a square wave grating are shown in Fig. 2. Fig. 2a shows a measurement of the profile obtained using a wavelength of 650.9 nm. The slopes are too great for a single wavelength measurement and the resulting profile does not look like a square grating. Fig. 2b shows the result for using the profile obtained using two wavelengths having an λ_{eq} of 10.16 µm to correct the 2π ambiguities in the single wavelength profile. The corrected profile shows the correct step heights.

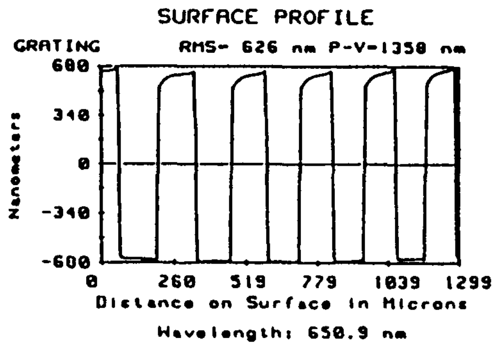
INTERFERENCE OBJECTIVES FOR DIFFERENT MAGNIFICATIONS

A key component in any interferometric optical profiler is the microscope interference objective. Due to the wide range of magnifications used in an optical profiler, no single type of interference objective can be used in a profiler. The Michelson interferometer shown in Fig. 3a is used for low magnifications such as 1.5X, 2.5X, and 5X. An advantage of the Michelson is that only a single objective needs to be used, and hence to first order, aberrations in the objective do not contribute to errors in the measurements. A disadvantage is that a beamsplitter must be placed between the objective and the sample, so only long working distance objectives can be used.

The Mirau interferometer shown in Fig. 3b is used for the medium magnifications such as 10X, 20X, and 40X. The Mirau also has the advantage that only a single objective is required. While some optics must be placed between the objective and the sample, not as much working space is used up as for the Michelson. A disadvantage of the Mirau is that a central obscuration is present in the system. While this is not troublesome for a medium magnification since the size of the obscuration is equal to the field of view of the sample, the obscuration becomes too large for low magnification systems.



(a)



(b)

Fig. 2. (a) Profile obtained using a single wavelength, 650.9 nm, does not resemble a square wave grating. (b) Single wavelength profile after corrected using λ_{eq} = 10.16 µm profile.

The Linnik interferometer shown in Fig. 3c is used for high magnifications such as 100X and 200X. It has the disadvantage that two matched objectives are required. However since no optics are required between the objective and the sample being measured, large numerical aperture, short working distance, objectives can be used. The use of a large numerical aperture, NA, is important because it determines the maximum optical resolution possible. The optical resolution, which can be thought of as the closest that two features can be on the surface such that both features can be detected, is given by $0.61\lambda/(2NA)$, where NA is the numerical aperture of the objective. In practice, due to aberrations in the optical system, the actual resolution is slightly worse than the optical resolution.

As stated above, during the measurement the reference surface is moved so as to vary the phase difference between the two interfering beams. It is important in the design of the interference objective that the distance between the sample and the lens does not change during the measurement because this could cause the sample to go out of focus. Thus, the interference objective must be designed in a manner such that during phase shifting only the position of the reference mirror moves, and the objective to sample distance does not change.

MEASUREMENT OF SUPERSMOOTH SURFACES

Due to powerful computer techniques it is possible to measure surfaces smoother than the reference surface. Techniques are available for removing errors in the reference surface enabling a person to routinely measure sub-Angstrom surface microstructure, even with a much rougher reference surface (Creath and Wyant, 1990).

Each measurement made with an interferometric optical profiler yields the relative point-by-point distance between the reference and test surfaces. Mathematically, we can represent a single point of a single measurement meas(x) as having independent contributions from both the test, test(x), and reference, ref(x), surfaces,

$$\text{meas}(x) = \text{test}(x) + \text{ref}(x) \quad . \qquad (6)$$

Assuming the test and reference surfaces are uncorrelated and independent of one another, the rms roughness σ_{meas} of the interferometric measurement is a combination of the two rms roughness values:

$$\sigma_{meas} = \sqrt{\sigma_{test}^2 + \sigma_{ref}^2} \ , \qquad (7)$$

where σ_{test} is the rms roughness of the surface under test and σ_{ref} is the rms roughness of the interferometer reference surface.

If the rms roughness of the reference surface is 5 Å and the rms roughness of the surface under test is 10 Å, then the measured rms will be 11.2 Å. The error in the measurement is 1.2 Å or 12% of the actual value. When the roughness of the test surface is the same as the roughness of the reference surface, the measured value for the rms roughness is the √2 times the actual value. As long as the rms roughness of the test surface is greater than 2 times the rms roughness of the reference surface, the error introduced by the reference surface will have little effect on the measurement.

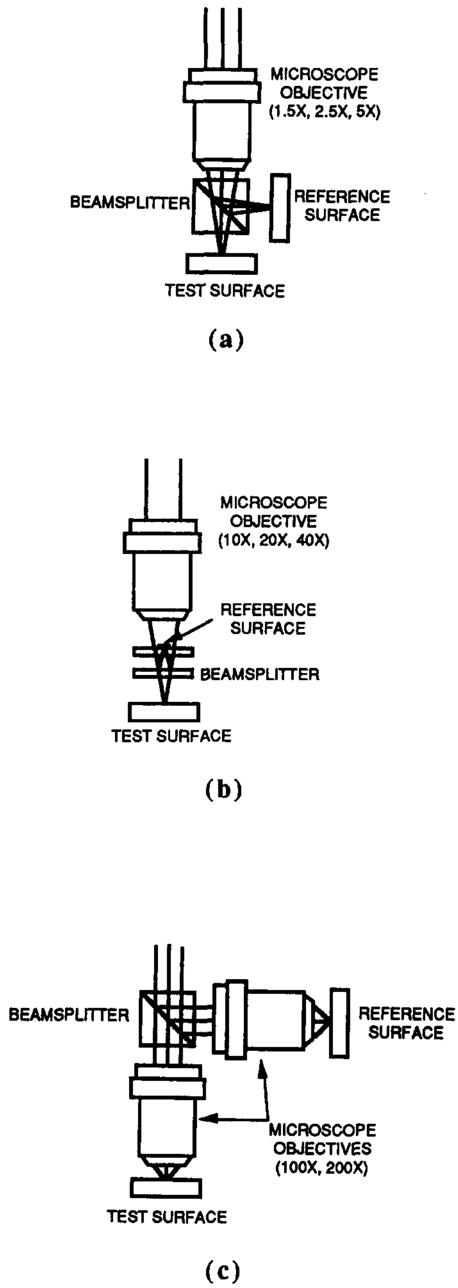


Fig. 3. Interference objectives.
(a) Michelson interferometer, (b) Mirau interferometer, and (c) Linnik interferometer.

In order to subtract the effects of the reference surface in the interferometer, three different techniques can be implemented. A straightforward means of producing a reference surface profile is to measure a supersmooth mirror with an rms roughness of less than 1 Å. This information can be stored in the computer and subtracted from each measurement.

Another technique is to create a profile of the reference surface by averaging a number of measurements, N, of a smooth mirror. The mirror surface used to do the averaging does not need to be supersmooth, but the smoother it is, the fewer measurements will need to be averaged. Between measurements, the mirror is moved by a distance greater than the correlation length of the surface. Once the reference surface profile is generated, it can then be subtracted from subsequent measurements of test surfaces to measure the surface profile minus the reference surface. Using this procedure, supersmooth surfaces with rms roughness values of less than an Ångstrom can be measured. The resulting rms roughness error is given by

$$\sigma_{error} = \frac{\sigma_{mirror}}{\sqrt{N}}, \tag{8}$$

where σ_{mirror} refers to the rms roughness of the mirror surface used to produce the generated reference profile. Thus, the error in the measurement of the test surface rms roughness is reduced by using a smoother mirror to generate the reference and by increasing the number of measurements averaged to generate the reference.

A simple technique for obtaining the rms roughness of a supersmooth surface, but not the profile, is to use the so called absolute rms roughness measurement technique. For the absolute rms roughness measurement, two uncorrelated measurements of the test surface are made. To get an uncorrelated measurement, the test surface is moved between measurements a distance greater than the correlation length of the surface. The reference surface effect on the measured profile should not change from the first to the second measurement. When the difference of these two measurements is taken, the effects of the reference surface profile cancel out. If we assume the two measurements, $test_1$ and $test_2$, are uncorrelated, the rms roughness of the difference profile can be written as

$$\sigma_{diff}^2 = \sigma_{test_1}^2 + \sigma_{test_2}^2 . \tag{9}$$

Because independent measurements of the test surface profile should have similar statistics,

$$\sigma_{test_1} = \sigma_{test_2} . \tag{10}$$

The rms roughness of the test surface is given by

$$\sigma_{test} = \frac{\sigma_{diff}}{\sqrt{2}} . \tag{11}$$

Thus, the rms roughness of the test surface can be easily determined by making two measurements of the surface. When this measurement is made, the effects of the reference surface cancel, and the surface statistics are derived. However, the calculated surface profile does not represent the actual test surface.

Fig. 4 shows measurement results for a supersmooth mirror. Fig. 4a shows the profile of the supersmooth mirror with the effects of errors in the reference surface remaining. Fig. 4b shows the profile of the reference surface obtained by averaging sixteen uncorrelated measurements of the supersmooth mirror. Fig. 4c shows the profile of the supersmooth surface obtained by subtracting the profile shown in Fig. 4b from the profile shown in Fig. 4a. Note that the vertical scale for Fig. 4c is different from that of Figs. 4a and 4b. The supersmooth mirror is found to have an rms surface error of 0.71 nm. Fig. 4d shows the result obtained using the absolute rms technique for measuring the same mirror. The absolute rms technique gives an rms surface error of 0.70 nm. Thus the two measurement techniques give very nearly the same rms.

SUMMARY

During the past decade there have been many advances in non-contact interferometric profilers. It is now possible to perform sub-Angstrom measurements in a matter of seconds. The high precision and accuracy are due to using interferometers having low noise, short coherence length sources, specialized interferometers for different magnifications, and computerized techniques for removing errors in the reference surface. Future advances will probably include more automated systems for use in production applications, rather than the research applications, and increased software for additional analyses. Also, the range of roughness range will be enhanced.

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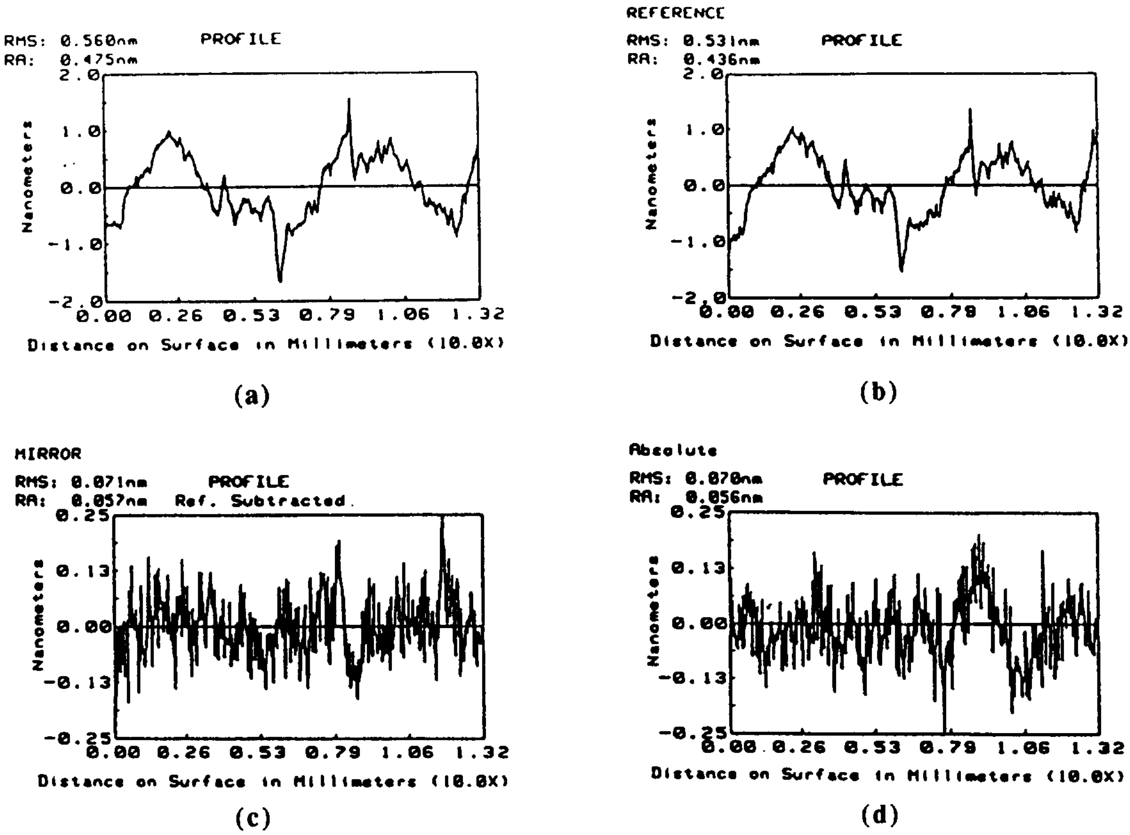

Fig. 4. (a) Profile of a supersmooth mirror including effects of reference surface. (b) Profile of reference surface. (c) Difference between 4a and 4b showing the profile of the supersmooth mirror without the effects of the reference mirror. (d) Absolute rms measurement of the supersmooth mirror made using two uncorrelated measurements.

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