

Absolute measurement of surface roughness

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In an interferometer which uses a reference surface, the measured surface heights correspond to the difference between the test and reference surfaces. To accurately determine the rms roughness of supersmooth surfaces, the effects of the reference surface roughness need to be removed. One technique for doing this involves averaging a number of uncorrelated measurements of a mirror to generate a reference surface profile which can then be subtracted from subsequent measurements so that they do not contain errors due to the reference surface. The other technique provides an accurate rms roughness of the surface by taking two uncorrelated measurements of the surface. These two techniques for measurement of supersmooth surfaces are described in detail, and results of the measurement of a 0.7-Å rms roughness mirror are presented. The expected error in the rms roughness measurement of a supersmooth mirror due to instrument noise is 0.02 Å.

I. Introduction

Interferometric measurements of surface roughness are a common means of determining surface finish quality.¹⁻¹⁰ In interferometers which use a reference surface such as the Michelson, Mirau, Linnik, and Fizeau, the measurement yields the relative difference between the test and reference surfaces.^{5,9,10} Typically, reference surfaces have an rms roughness of 5–8 Å making it impossible to measure accurately the roughnesses of surfaces smoother than the reference surface. Current state-of-the-art optical surfaces are being produced with rms roughnesses of 1 Å or less. Although it is possible to make an interferometer reference surface with an rms roughness of 1 Å, it is not easy. Mirau interferometers which are commonly used for these measurements have a small reference surface which must be coated to produce good contrast fringes. It is very difficult to make these coated reference surfaces with an rms roughness of <5 Å. Because of errors caused by the roughness of the reference surface, it is desirable to measure the roughness of the test surface without the roughness of the reference surface affecting the measurement.

When measurements of surface roughness are made, techniques based on statistics can be used to remove the effects of the reference surface.¹¹ It should be noted that these techniques are not meant to be used

when the surface shape needs to be determined. This paper describes and shows examples of two techniques which yield accurate absolute measurements of rms surface roughness. The examples shown are for a flat surface; however, the techniques will work for any shape surface as long as the low frequency figure terms are subtracted or filtered out.

II. Background

Each measurement made with an interferometric optical profiler using a reference surface 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:

$$meas(x) = test(x) + ref(x). \quad (1)$$

Each surface profile is assumed to be an ergodic random process where spatial averages can be considered equivalent to averages over an ensemble of similar surfaces.¹² Assuming that 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:

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

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, the measured rms will be 11.2 Å. The error in the measurement is 1.2 Å or 12% of the actual value.

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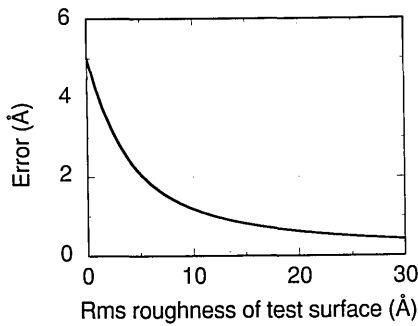


Fig. 1. Error in the rms roughness measured for a reference surface with 5-Å rms roughness.

When the roughness of the test surface is the same as the roughness of the reference surface, the measured value for the rms roughness will be 7.1 Å, which has an error of 2.1 Å or 42%. As long as the rms roughness of the test surface is >2 times the rms roughness of the reference surface, the error introduced by the reference surface will have little effect on the measurement. However, when the rms roughness of the test surface is <2 times the rms roughness of the reference surface, the effect is large enough to have a noticeable effect. A plot of the measurement error for a reference surface with an rms roughness of 5 Å is shown in Fig. 1.

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 <1 Å. Another technique is to create a reference data file which corresponds to the profile of the reference surface by averaging a number of measurements of a smooth mirror, where the mirror is moved by a distance larger than the correlation length of the surface between measurements.¹³ This will be referred to as a generated reference surface. The final technique is useful when only the rms roughness of the test surface is desired.

For this technique, two measurements of the test surface are made with the test surface being moved by more than the correlation length of the surface between measurements. These two measurements are subtracted, and the rms roughness of the difference is divided by the $\sqrt{2}$ to find the test surface rms roughness. This is referred to as an absolute rms roughness measurement. With this measurement, the calculated profile does not represent the surface; however, the statistics of the calculated profile do represent the statistics of the surface.

III. Subtraction of a Generated Reference Surface

A profile of the reference surface can be generated 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. (Typically, good quality mirrors have 5–8-Å rms surface roughness.) Between measurements, the mirror is moved by a distance greater than the correlation

length of the surface.¹³ (For most optical surfaces, the correlation length is <0.1 mm.) 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. However, the generated reference surface becomes invalid if the reference surface is moved. Using this procedure, supersmooth surfaces with rms roughness values of <1 Å can be measured.

One of the N profile measurements used to generate the reference surface can be written as

$$\text{meas}(x)_i = \text{mirror}(x)_i + \text{ref}(x), \quad (3)$$

where this equation is for a single point x in the profile i , the interferometer reference surface profile ref is assumed to be the same for each measurement, and mirror_i refers to a profile measured on the mirror used to generate the reference. To keep $\text{ref}(x)$ constant, the reference surface should not be moved between measurements. The test surface can be tilted, and focus can be adjusted. The generated reference profile which is the average of N measurements is given by

$$\text{genref}(x) = \frac{1}{N} \sum_{i=1}^N \text{meas}(x)_i = \frac{1}{N} \sum_{i=1}^N \text{mirror}(x)_i + \text{ref}(x), \quad (4)$$

where the mirror and reference surface are uncorrelated random variables, and each point x on the mirror profile is averaged over N independent measurements of the surface.

The variance of the averaged profile [Eq. (4)] can be written as

$$\langle \text{genref}(x)^2 \rangle = \left\langle \left[\frac{1}{N} \sum_{i=1}^N \text{mirror}(x)_i \right]^2 \right\rangle + \langle \text{ref}(x)^2 \rangle, \quad (5)$$

where the angle brackets indicate an average over x , and we have assumed that all the variables have zero mean in x for simplicity. (In general, it is not necessary for the variables to have zero mean.) Assuming that the mirror measurements are independent and, therefore, uncorrelated and that they are identically distributed, Eq. (5) can be reduced to

$$\begin{aligned} \langle \text{genref}(x)^2 \rangle &= \frac{1}{N^2} \sum_{i=1}^N \langle \text{mirror}(x)^2 \rangle + \langle \text{ref}(x)^2 \rangle \\ &= \frac{1}{N} \langle \text{mirror}(x)^2 \rangle + \langle \text{ref}(x)^2 \rangle. \end{aligned} \quad (6)$$

Equation (6) can be rewritten in terms of rms roughness to yield

$$\sigma_{\text{genref}} = \sqrt{\left(\frac{\sigma_{\text{mirror}}}{\sqrt{N}} \right)^2 + \sigma_{\text{ref}}^2}, \quad (7)$$

where σ_{genref} is the rms roughness of the generated reference surface, σ_{ref} is the rms roughness of the interferometer reference surface, and σ_{mirror} is the rms roughness of the mirror used to produce the generated reference surface. Note that this equation does not depend on the specific probability distribution of the individual random variables. From Eq. (7), it is obvi-

ous that the effect of the mirror on the generation of the reference surface is reduced as the number of measurements increases.

Measurements of supersmooth test surface profiles can then be made by subtracting the generated reference surface profile from subsequent measurements. This can be written as

$$\text{meas}(x) - \text{genref}(x) = \text{test}(x) - \text{error}(x), \quad (8)$$

where the surface profile error term is given by

$$\text{error}(x) = \frac{1}{N} \sum_{i=1}^N \text{mirror}(x)_i. \quad (9)$$

As long as the mirror profile has zero mean, the error profile height will go to zero as N goes to infinity.

The rms roughness of the actual test surface profile measurement σ_{test} is

$$\sigma_{\text{test}} = \sqrt{\sigma_{\text{meas-genref}}^2 + \sigma_{\text{error}}^2}, \quad (10)$$

where $\sigma_{\text{meas-genref}}$ is the rms roughness of the calculated test surface profile and σ_{error} is the rms roughness error. This rms roughness error is given by

$$\sigma_{\text{error}} = \frac{\sigma_{\text{mirror}}}{\sqrt{N}}, \quad (11)$$

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.

To determine the magnitude of the error, assume that the reference surface has an rms roughness of 5 Å, and a 5-Å rms mirror is used to generate the reference surface profile. When twenty-five independent measurements of the mirror surface are averaged together, the rms roughness error due to the mirror used to generate the reference surface [Eq. (11)] will be $5/\sqrt{25} = 1$ Å. This would be equivalent to the error produced by a single measurement of a 1-Å rms mirror without subtracting the generated reference. This would mean that measurement of a 5-Å rms test mirror obtained by subtracting the generated reference would be 5.1 Å rms. Thus the error due to the generated reference is only 0.1 Å or 2%. This means that the generated reference surface profile is a very good representation of the actual reference surface.

IV. Absolute rms Roughness Measurement

For an absolute rms roughness measurement, two uncorrelated measurements of the test surface are made. To get an uncorrelated measurement, the test surface is moved by a distance greater than the correlation length of the surface between measurements. These two measurements can be written as

$$\begin{aligned} \text{meas}(x)_1 &= \text{test}(x)_1 + \text{ref}(x), \\ \text{meas}(x)_2 &= \text{test}(x)_2 + \text{ref}(x), \end{aligned} \quad (12)$$

where x refers to a single point on a single profile. The

reference surface effect on the measured profile should not change from the first to the second measurement. This means that the reference surface should not be tilted relative to the optical axis between measurements. (Focus can be adjusted between measurements.) When the difference in these two measurements is taken, the effects of the reference surface profile cancel out and yield

$$\text{diff}(x) = \text{meas}(x)_1 - \text{meas}(x)_2 = \text{test}(x)_1 - \text{test}(x)_2. \quad (13)$$

If Eq. (13) is rewritten slightly as

$$\text{diff}(x) = \text{test}(x)_1 + [-\text{test}(x)_2], \quad (14)$$

this calculation can be thought of as the sum of two random variables. If we assume that the probability distributions of each of the random variables test_1 and test_2 are uncorrelated, the rms roughness of the difference profile can be written as

$$\sigma_{\text{diff}}^2 = \sigma_{\text{test}_1}^2 + \sigma_{\text{test}_2}^2. \quad (15)$$

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

$$\sigma_{\text{test}_1} = \sigma_{\text{test}_2}. \quad (16)$$

Finally, the rms roughness of the test surface is given by

$$\sigma_{\text{test}} = \frac{\sigma_{\text{diff}}}{\sqrt{2}}. \quad (17)$$

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.

V. Results

These two statistically based techniques have been implemented on an interferometric optical profiler using a 10× objective with a Mirau interferometer. Phase-measurement techniques are used to obtain the surface profile.¹⁴ The optical profiler has a linear detector array with 1024 elements, and the output is digitized to 12 bits. The sample is put on top of a tip-tilt stage so that the relative tilt between the test and reference surfaces can be adjusted without touching the reference surface. The interference fringes are adjusted to be parallel to the detector. Tilt and curvature are subtracted from the measurements so that only surface roughness is analyzed.

Figure 2 shows a single measurement of a supersmooth mirror made using no absolute measurement techniques. The rms roughness of this measurement is 5.6 Å (0.56 nm). When a reference is generated using sixteen measurements of this supersmooth mirror, an rms roughness of 5.3 Å is obtained. This generated reference corresponding to the Mirau reference mirror is shown in Fig. 3. Note that the surface features are similar to those in Fig. 2. The difference between Figs. 2 and Fig. 3 is shown in Fig. 4. This

MIRROR

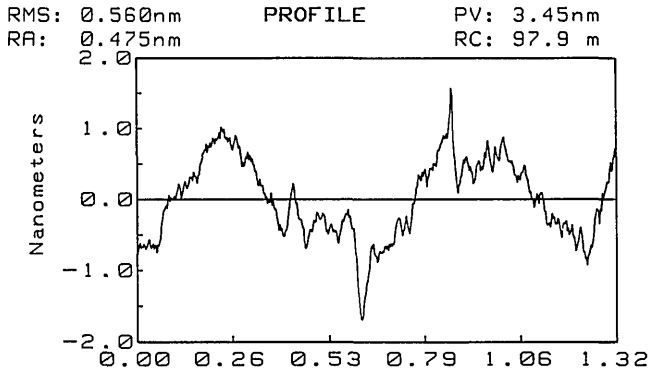


Fig. 2. Measurement of supersmooth mirror including the reference surface.

MIRROR

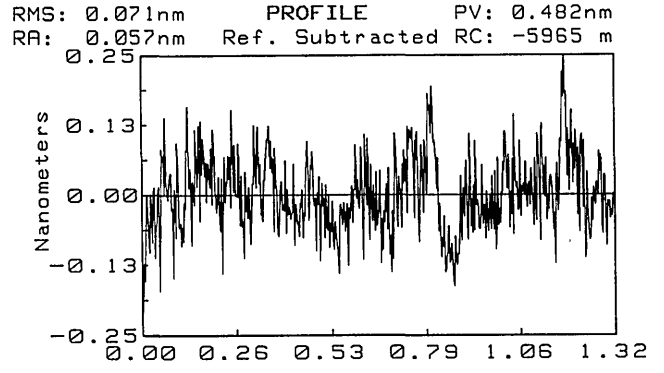


Fig. 5. Same as Fig. 4 plotted on a different height scale. Profile and roughness of surface can be seen.

REFERENCE

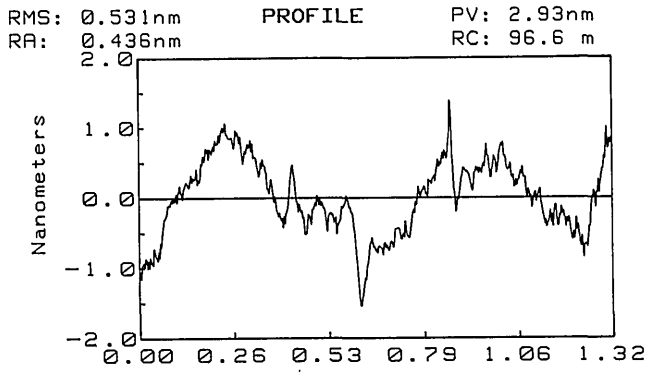


Fig. 3. Profile of reference surface generated by averaging sixteen uncorrelated measurements of the supersmooth mirror.

Difference

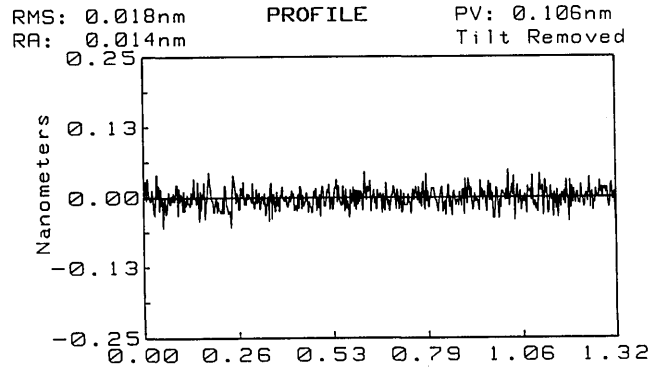


Fig. 6. Difference between two consecutive data sets taken at a single location on a mirror indicating the noise level of the measurements.

MIRROR

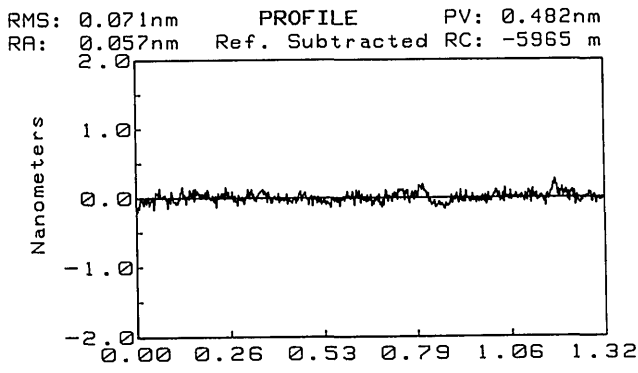


Fig. 4. Difference between Figs. 2 and 3 showing the supersmooth mirror without the effects of the reference surface on the same scale as Figs. 2 and 3.

Absolute

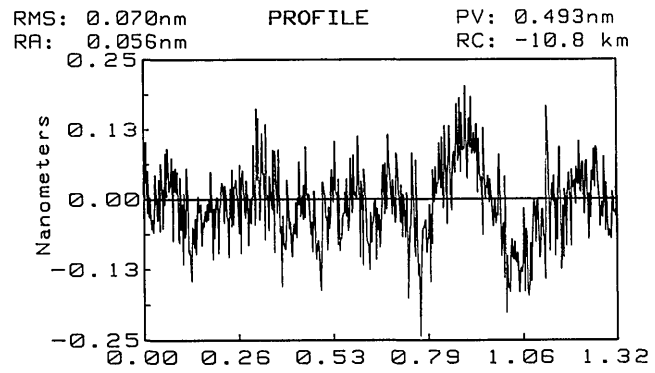


Fig. 7. Absolute measurement of the supersmooth mirror made with two uncorrelated measurements.

corresponds to the actual surface without effects due to the reference surface and is plotted on the same scale as Figs. 2 and 3. The rms roughness of the test mirror is 0.71 Å, which is much less than the 5.3-Å rms roughness of the Mirau reference mirror. Figure 5 shows Fig. 4 on a different height scale. Note that the roughness of the test surface is very random and looks a lot different than the reference surface. From Eq. (11), the error in the rms roughness due to the generated reference surface is 0.02 Å, which is approximately the same effect as the instrument noise.

Figure 6 shows that the rms noise of the instrument is 0.18 Å. This profile is found by taking two consecutive data sets at a single location on a mirror, each an average of sixteen measurements, and subtracting the two profiles. The rms of this difference profile is a good indication of the measurement repeatability. The rms instrument noise will affect the measured rms roughness of the absolute measurement a small amount. Assuming that the instrument noise is independent of the surface profile being measured, the rms roughness of the test surface without the contribution from the instrument noise is $\sqrt{(0.71)^2 - (0.18)^2} = 0.69$ Å. Thus the effect of the instrument noise on the measured rms roughness is 0.02 Å.

The absolute rms roughness technique was used to produce the results shown in Fig. 7. The rms roughness obtained using this technique is 0.70 Å. The profile obtained represents the test surface statistically but does not correspond to the profile at the measured location. The rms roughness obtained using this technique only differs by 0.01 Å from that obtained using the generate reference technique, which is in the range of the expected error. These rms roughness values can be measured repeatedly to within ± 0.05 Å.

VI. Conclusions

The techniques of generating a reference surface from a number of averaged measurements of a smooth mirror and of making an absolute rms roughness measurement using two measurements are both viable techniques for determining rms surface roughnesses which are smoother than the reference surface. They enable the effects of the reference surface to be subtracted from the measurements. They can be used to measure surfaces with rms surface roughnesses of <1 Å with an expected error of ~ 0.02 Å. These measurements can also be done repeatedly to within ~ 0.05 Å rms. When a number of surfaces are to be measured, the generated reference technique is very convenient

because the reference only needs to be generated once and can be subtracted from subsequent measurements as long as the interferometer reference surface has not been moved. The absolute rms roughness measurement technique is good to use when a quick measurement of the rms roughness is desired.

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References

1. J. M. Bennett and L. Mattsson, *Introduction to Surface Roughness and Scattering* (Optical Society of America, Washington, DC, 1989).
2. J. M. Bennett, "Comparison of Techniques for Measuring the Roughness of Optical Surfaces," *Opt. Eng.* **24**, 380-387 (1985).
3. W. T. Welford, "Noncontacting Measurement of Surface Roughness," *Proc. Soc. Photo-Opt. Instrum. Eng.* **235**, 118-121 (1980).
4. G. E. Sommargren, "Optical Heterodyne Profilometry," *Appl. Opt.* **20**, 610-618 (1981).
5. B. Bhushan, J. C. Wyant, and C. L. Koliopoulos, "Measurement of Surface Topography of Magnetic Tapes by Mirau Interferometry," *Appl. Opt.* **24**, 1489-1497 (1985).
6. J. M. Zavisland and J. M. Eastman, "Measurement and Effects of Surface Defects and Quality of Polish," *Proc. Soc. Photo-Opt. Instrum. Eng.* **525**, 169-173 (1985).
7. D. Pantzer, J. Politch, and L. Ek, "Heterodyne Profiling Instrument for the Angstrom Region," *Appl. Opt.* **25**, 4168-4172 (1986).
8. F. Laeri and T. C. Strand, "Angstrom Resolution Optical Profilometry for Microscopic Objects," *Appl. Opt.* **26**, 2245-2249 (1987).
9. J. C. Wyant, C. L. Koliopoulos, B. Bhushan, and D. Basila, "Development of a Three-Dimensional Noncontact Digital Optical Profiler," *Trans. ASME, J. Tribol.* **108**, 1-8 (1986).
10. J. F. Biegen and R. A. Smythe, "High Resolution Phase Measuring Laser Interferometric Microscope for Engineering Surface Metrology," in *Proceedings, Fourth International Conference on Metrology and Properties of Engineering Surfaces* (National Bureau of Standards, Washington, DC, 13-15 Apr. 1988).
11. J. C. Wyant, "Measurement of Roughness of Supersmooth Optical Surfaces," *Acta Polytech. Scand., Proc. Image Science '85*, Helsinki, Finland **Ph 150**, 241-244 (1985).
12. P. Beckman, *Elements of Applied Probability Theory* (Harcourt, Brace & World, New York, 1968).
13. Correlation length is defined as the distance over which the autocovariance function falls to 0.1 of its maximum value (ANSI Standard B46.1-1978, Surface Texture, p. 34). It can be calculated from a measured profile of the surface.
14. K. Creath, "Phase-Measurement Interferometry Techniques," *Prog. Opt.* **26**, 349-393 (1988).