TITLE: A COMPARISON OF TWO COMMON METHODS OF SURFACE-
TOPOGRAPHY EVALUATION

MASTER

AUTHOR(S): Allen L. Gauler
Los Alamos National Laboratory
P.O. Box 1663, MS-474
Los Alamos, New Mexico 87545

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University of California

LOS ALAMOS SCIENTIFIC LABORATORY

Post Office Box 1663 Los Alamos, New Mexico 87545

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ABSTRACT

This paper compares some of the advantages and limitations of two methods used for surface topography evaluation, the dual beam interference microscope and the stylus type profiling instrument. Consideration is primarily limited to diamond machined or other high quality surfaces, such as are commonly encountered on optical elements. Parameters discussed include horizontal and vertical resolution, horizontal and vertical range, and surface damage.

I. INTRODUCTION

The purpose of this paper is to compare two of the more conventional methods of surface finish measurement, the dual-beam interference microscope and the stylus-type profiling instrument. The discussion will be concerned primarily with diamond-machined or other high quality surfaces.

II. THE INSTRUMENTS

In the dual-beam interference microscope (Fig. 1), light (usually monochromatic) is divided by a beam splitter into a reference and a measurement beam. In one common design (Fig. 2), these beams are then directed along separate paths, passing through matched objective lenses. One of these objective lenses is focused on a highly polished reference surface, the other on the surface under study. After reflecting from these surfaces, the beams are recombined to produce a magnified image of the surface with interference fringes superimposed on it. This image can be photographed and measured.

The stylus-type profiling instrument (Figs. 3,4) operates by traversing a stylus across the surface of interest. Force on this stylus is kept to a minimum (in some instruments, as low as 0.00001 newton or less). The vertical motion of the stylus with respect to a reference surface in the instrument, such as an optical flat (Fig. 5), is amplified electronically and recorded on a strip chart or other device. Various styli are available, the most common being spherical in shape.

III. COMPARISON

A. Dual-Beam Interference Microscope

1. Advantages

a. Non-contact:

Because no contact is required between the measuring instrument and the surface under examination, the dual-beam interference microscope offers a clearly non-destructive measurement.

b. Gives area information at a glance:

Another advantage and perhaps the most useful aspect of this instrument, is that the height information presented is superimposed on an area view of the actual surface in the form of an easily interpreted "contour map." Such an area view can be invaluable when evaluating a surface about which little is known. Figure 6, for example, is a microinterferogram of one of the early diamond-machined surfaces produced at Los Alamos. A long wavelength pattern can easily be discerned on top of the fairly rough overall surface. This pattern would be less apparent without the large area view. Calculation of the frequency of the pattern lead to the determination of its cause, floor noise transmitted through a faulty isolation pad.

Perhaps more illustrative of the value of an area view are Figs. 7 and 8. These show two diamond-machined surfaces, one copper (Fig. 7) and one aluminum (Fig. 8), on which one might expect to see structure in only one direction due to the processing method. This is true for the

copper. The aluminum surface, however, shows point defects (later found to be raised areas), which are immediately seen to be such in the photo.

Figure 9 shows a third example of a surface which would be hard to evaluate without an area view. This surface was diamond-machined and then hand polished. The photo shows clearly that the lapping has removed the original surface features and replaced them with a random pattern; some idea of the frequency and depth of the larger scratches can also be obtained.

c. Good horizontal resolution:

The diffraction limit for horizontal resolution of the best oil-immersion type microscopes is about 250 nm; for conventional microscopes it is about 500 nm. In practice, usable resolution (that is, the smallest measureable increment) is on the order of about 500 nm at 1000x viewed through an eyepiece, or 1000 nm measured from a photograph.

2. Limitations:

a. Limited field of view:

The advantage of an area view decreases with increasing magnification due to the narrowing field of view. Typically, field of view may vary from about 2 mm with a 10X objective to a somewhat limited 0.2 mm with a 100X objective.

b. Limited vertical range:

Vertical range is limited to about one micrometer or less, since beyond this point the interference bands become too closely crowded to read.

c. Limited vertical resolution:

Vertical resolution is limited to about one fifth of the distance between successive interference fringes, or 50 nm. A surface with a roughness of this magnitude is very difficult to evaluate from a microinterferogram (Fig. 10). Figure 11 shows an attempt at 300X to measure the

height of one of the defects noted on the aluminum surface of Fig. 8. This measurement is also clearly limited by poor vertical resolution.

B. Stylus-Type Profiling Instruments

1. Advantages

a. Surface need not be reflective:

Because reflectivity is not required, a larger variety of surfaces can be examined, including replicas made from otherwise inaccessible surfaces. For example, it was desired to make contour measurements of a radioactive beam collimator from a linear accelerator at Los Alamos in order to determine the shape of an axial swelling in the part. By replicating the part and making many tracings across the axis (Fig. 12), it was possible to arrive at the axial profile shown in Fig. 13.

b. Large horizontal range:

One of the major advantages of the stylus instrument is that its horizontal range is limited only by the length of the instrument's reference surface, and is not dependent on magnification. Long wavelength effects can therefore be investigated. Figure 14 is a tracing made on a part that had been jet-blasted with small particles to obtain a diffusely reflecting surface. The uniformity of this surface over a one centimeter diameter area was studied by means of such tracings.

c. Large vertical range:

The vertical range of stylus instruments may extend up to 400 micrometers or more, which allows virtually any surface texture to be investigated. This range is also useful in measuring contours, such as that of the beam collimator shown in Figs. 12 and 13. This type of measurement yields a continuous tracing of the contour, which may disclose features that would not be visible in a point-by-point coordinate measurement.

d. Good vertical resolution:

Electronic amplification of the stylus motion yields vertical magnifications up to one million times, making vertical resolution better than 2 nm possible. Figure 15 is a tracing of the aluminum surface shown in Fig. 8. Comparison of this tracing with Fig. 11 illustrates the increased resolution available with the stylus instrument.

Figures 16 and 17 show microinterferograms of two surfaces that were diamond-machined from copper. The copper shown in Fig. 17 was annealed prior to cutting. With the exception of the grain structure visible in this photograph, the two surfaces appear to be very similar. However, tracings made at high magnification (Figs. 18 and 19) show marked differences between them.

e. Allows statistical calculations:

Because the surface profile is available for measurement, parameters such as average roughness, autocorrelation function, and others

can be computed easily. Figure 20 shows a tracing of a faulty "O"-ring from which average roughness was computed.

f. More flexible:

In general, the stylus instruments are adaptable to more types of measurements, such as inside diameters, keyways, etc., than are interference microscopes.

2. Limitations

a. Give line information only:

In many cases, the extent of a surface feature in a direction perpendicular to stylus travel is of interest, as in the case of the defects in the aluminum surface shown in Fig. 8. The overall nature of such features is difficult to assess from stylus tracings, unless many parallel tracings are made.

b. Resolution limited by stylus shape:

The horizontal distance between the two sides of a trough of depth "d" on a surface cannot be less than a certain value "h", or the stylus will ride between the sides and not contact the bottom, as shown in Fig. 21. Vertical resolution is thereby limited by the horizontal extent of a feature. Table 1 lists the maximum depth "d" a feature of horizontal extent "h" may have without causing this type of vertical error (see Appendix 1). It can be seen from this table that with the proper stylus choice, excellent resolution is possible.

Another consideration is cosine error, or vertical inaccuracy caused by the finite stylus radius, as shown in Fig. 22. Table 2 lists some values of this error for various surface angles. It may be seen that at higher surface angles, distortion of the surface profile can be appreciable when using large radius tips. This source of error is not usually very important, since surface angles on most high quality surfaces, both lapped and machined, are typically

in the range of one to three degrees or even less. Even at these angles, however, error caused by the stylus shape can be enough to offset the advantage of increased vertical amplification unless care is taken in the choice of a tip.

As an example of how the loss of detail due to use of a large radius tip may in some cases be insignificant, Fig. 23 shows a tracing of a diamond-machined surface made using a 12.5 micrometer radius stylus. Comparison of this with Fig. 18, the same surface traced with a chisel-tip (0.1 micrometer wide) stylus, shows only a small gain in detail, which would not influence analysis of the surface in most cases.

c. Possible surface damage:

The possibility of surface damage caused by the high contact stresses at the stylus tip must also be considered. Table 3 lists the depth of expected permanent deformation for various materials based on the assumption that the surface yields over the entire area of contact

with the tip (see Appendix 2). This table shows that a problem may exist with higher stylus forces and softer materials, but that if these parameters are correctly chosen, damage may be reduced or eliminated in nearly every case.

Tests at Los Alamos have shown evidence of damage to copper surfaces at the 0.0009 newton stylus force listed in Table 3, though the observed depth of permanent deformation was not as large as the predicted value. Figure 24 shows a tracing taken with a chisel-tip stylus under a 0.00002 newton gage force over an area damaged by a 2.5 micrometer radius stylus under a 0.0009 newton load. The depth of damage is about 20 nm, far smaller than anticipated.

Damage caused by styli at 0.00002 newton gage force or less has not been detected by examination of the tested surface. However, repeated tracings of the same line on a copper part have shown a slight change in recorded contour, which may be due to a burnishing effect (see Fig. 25, which is the third tracing repeated over the same line as that of Fig. 23). This effect is very small.

IV. SUMMARY

The dual-beam interference microscope offers one major advantage: its output is an easily interpreted area view of a surface. It yields a qualitative, as well as quantitative, assessment of the surface.

However, when detailed knowledge of a surface is desired, the stylus-type instrument, in most cases, offers a superiority in range and resolution, with minimal damage to the surface of interest, provided stylus shape and gaging force are correctly chosen.

ACKNOWLEDGEMENTS

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typical stylus designs

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APPENDIX I

VERTICAL RESOLUTION:

For a concave feature of horizontal extent h , the depth d at which a stylus of radius R will just contact both sides and the bottom of the feature is the depth of the circle segment whose chord is h . This is given by:

$$d = R \left[1 - \cos \left[\sin^{-1} (h/2R) \right] \right] \quad (1)$$

APPENDIX 2

STYLUS DAMAGE:

A spherical tip of radius R will sink into the surface it rides on to the depth D at which the upward forces from the deformed surface equal the downward gage force F on the stylus tip. Assuming all portions of the surface in contact with the tip are stressed to their yield point S , the depth D of permanent deformation may be estimated as follows:

Forces will be in equilibrium when

$$F = SA \quad (2)$$

Where A is the projection of the area of contact in the vertical direction. But

$$A = \pi \left(R \sin \left\{ \cos^{-1} \left[(R-D)/R \right] \right\} \right) \quad (3)$$

Substituting and rearranging,

$$D = R \left[1 - \cos \left(\sin^{-1} \left\{ \left[F/(\pi S R^2) \right]^{1/2} \right\} \right) \right] \quad (4)$$

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Figure 2. Diagram of typical dual-beam interference microscope

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Figure 17

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Figure 21. Distance from a horizontal
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extent of a concave feature

$$x = R \left(\frac{1}{\cos \theta} - 1 \right)$$

Figure 22. Diagram showing the origin
of cosine error

Figure 23. Tracing of diamond-
machined surface shown in Figure 18

Figure 24. Tracing of a diamond-
machined copper surface showing
stylus damage

Figure 25. The third tracing over the same path shown in Figure 23

Stylus Type	Design	h Horizontal Extent of Feature (nm)	d Maximum Depth of Feature (nm)
12.5 μm Radius		2000	40
		1000	10
		500	2.5
		200	0.4
10.0 μm Radius		2000	50
		1000	13
		500	3.1
		200	0.5
2.5 μm Radius		1000	50
		500	13
		200	2.0
		100	0.5
Chisel-tip		1000	450
		500	200
		200	50
		100	0.0

Table 1. Resolution limits for
typical stylus designs

Stylus Type Surface Angle	12.5 μm Radius	10 μm Radius	2.5 μm Radius	Chisel- Tip
1°	1.9 nm	1.5 nm	0.4 nm	0.9 nm
3	17	14	3.4	2.7
5	48	38	10	4.4
10	193	154	39	8.8

Table 2. Values of cosine error
for typical stylus designs

Material	Tensile Yield Strength MPa	Expected Depth of Permanent Stylus Damage (D)				
		F = 0.0009 N R = 12.5 μ m	F = 0.0009 N R = 2.5 μ m	F = 0.00002 N R = 12.5 μ m	F = 0.00002 N R = 2.5 μ m	F = 0.00002 N Chisel-tip
Copper, hard	345	33 nm	172 nm	1 nm	4 nm	0 nm
Aluminum, 6061-T6	275	42	218	1	5	3
Copper, annealed	240	48	251	1	5	0
Gold	125	92	510	2	10	0
Lead	14	847	Large	18	93	230

D = Permanent Stylus Damage Depth

F = Gage Force

R = Stylus Radius

Table 3. Calculated depth of stylus damage for typical stylus designs and gaging forces