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OPTICAL SURFACE FINISH MEASUREMENT

H. S. Corey

UNION CARBIDE CORPORATION
NUCLEAR DIVISION
OAK RIDGE Y-12 PLANT

operated for the **ATOMIC ENERGY COMMISSION** *under* **U. S. GOVERNMENT** **Contract W-7405 eng 26**

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ABSTRACT

An optical method of measuring surface finishes in the range of 10 to 100 microinches, AA, has been developed. An infrared laser is used to produce diffraction patterns which are directly related to the surface finish.

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SUMMARY

An optical method has been developed to measure the surface finish of machined parts over the range of 10 to 100 microinches, AA. The method employs an infrared laser which is used to generate a diffraction pattern from surface finish (texture) blocks. It has been shown that the area of the curves of the diffraction patterns is directly proportional to the surface finish.

INTRODUCTION

The present mechanical contact methods of measuring surface finish have several objectionable features. First, the equipment is not adaptable for on-line measurements in conjunction with machine tools. Secondly, in many instances the mechanical contact required is damaging to the measured surface. A third, but not final, objection is that a detailed study of lengthy charts is often required to obtain the value of the surface finish. Therefore, a program was initiated at the Oak Ridge Y-12 Plant^(a) to find a more satisfactory method of measuring surface finish.

The literature gives support to optical means of measuring surface finish. Bennett and Porteus⁽¹⁾ state that "long wavelength specular reflectance measurements ... provide a simple and sensitive method for accurate measurement of surface finish". Piper and Callis⁽²⁾ state that "reflection-type photoelectric instruments ... are extremely sensitive to small changes in surface finish, especially on finely finished work".

There are several important factors to be considered in making measurements of this type. The proper wavelength for the light source must be determined. Also, it must be determined if it is necessary for the light beam to be coherent and/or monochromatic. Another major factor is whether to work with diffuse or specular reflectance. Bennett and Porteus felt the reflectance should be specular. However, Crane⁽³⁾ gives equal consideration to diffuse and specular surfaces. Also, the angle of incidence is given great importance in the literature.

Even though Crane's work was confined to narrow ranges and, for the most part, to finely finished surfaces, it was felt that it did offer enough encouragement to make it worthwhile to undertake a development program to determine the feasibility of measuring surface finishes optically.

(a) Operated for the U.S. Atomic Energy Commission by the Union Carbide Corporation-Nuclear Division.

OPTICAL SURFACE FINISH MEASUREMENT

VISUAL PATTERNS

As the first step in undertaking a study of surface finish versus reflectance, a series of photographs were taken showing the reflectance patterns obtained from various surfaces using a 0.6328-micrometer gas laser as a light source. Figure 1 gives a view of the experimental setup. The laser beam is aimed through a 1/2-inch-diameter hole in the screen onto the test surface; the reflectance pattern is then projected back onto the screen. With this setup, the angle of incidence is near the normal.

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Figure 1. VISUAL-PATTERN EXPERIMENTAL EQUIPMENT.

The first series of tests were conducted with spherical surfaces having a surface finish of two microinches, AA,^(b) and a radius of two inches. The reflectance patterns were spectacular in that a perfect projection of the surface of the part was reflected onto the screen. Such imperfections as tool marks, dents, and scratches were evident. Figure 1 shows a small portion of the surface of the ball reflected in such a manner as to produce a variance in the

(b) All surface-finish measurements referred to in this report are in terms of the arithmetic average, AA.

magnification. (The magnification is greatest at the top of the screen.) The polar area of a spherical part is seen in Figure 2, while Figure 3 shows that a fingerprint on the mirror surface of the spherical part is easily detected. All reflectance in this first series of tests was specular.

Figure 2. REFLECTANCE PATTERN OF THE POLAR REGION.

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The second series of tests were conducted using a sphere with a two-inch radius having a surface finish of 32 microinches. In these tests, as was expected, the light was diffused along a line 90 degrees to the lay of the part. Diffusion of the light produces an interesting pattern as the part is rotated so the light from the source falls on the part ever nearer the pole. Their reflectance patterns are seen in Figures 4 through 7.

Tests were next conducted using cylindrical parts. Specular reflectance produced an elongated pattern parallel to the lay of the part. When the surface was rough enough to diffuse the light, the pattern was spread perpendicular to the lay. Specular reflectance on a cylindrical surface is indicated in Figure 8 and diffused reflectance in Figure 9. A mixture of specular and diffused reflectances is seen in Figure 10.

The final surfaces that were visually studied were flat master standard surface finish blocks. Figure 11 shows the reflectance pattern from a two-microinch standard, pointing out that the reflectance is almost 100 percent specular. Figure 12 reveals the reflectance pattern

Figure 3. FINGERPRINT ON A POLISHED SURFACE.

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Figure 4. DIFFUSE REFLECTANCE PATTERNS FROM THE EQUATOR TO THE POLE. (At the Equator)

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Figure 5. DIFFUSE REFLECTANCE PATTERNS FROM THE EQUATOR TO THE POLE. (15 Degrees from the Pole)

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Figure 6. DIFFUSE REFLECTANCE PATTERNS FROM THE EQUATOR TO THE POLE. (5 Degrees from the Pole)

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Figure 7. DIFFUSE REFLECTANCE PATTERNS FROM THE EQUATOR TO THE POLE. (At the Pole)

Figure 8. SPECULAR REFLECTANCE FROM A CYLINDER.

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Figure 9. DIFFUSE REFLECTANCE FROM A CYLINDER.

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Figure 10. DIFFUSE AND SPECULAR REFLECTANCE FROM A CYLINDER.

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Figure 11. SPECULAR REFLECTANCE FROM A TWO-MICROINCH SURFACE.

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Figure 12. DIFFUSE REFLECTANCE FROM AN EIGHT-MICROINCH SURFACE.

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from a block with a surface finish of eight microinches. Note that the light is completely diffused. A block with a surface finish of four microinches still has some specular reflectance, as can be seen in Figure 13.

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Figure 13. DIFFUSE AND SPECULAR REFLECTANCE FROM A FOUR-MICROINCH SURFACE.

The aforementioned experiments indicate that specular reflectance is limited to surface finishes of 2 microinches or better when the angle of incidence is near the normal and when a light source of 0.6328 micrometer is used.

WAVELENGTH EXPERIMENTS

In order to learn more about the effect of wavelength versus reflectance, ground surface finish standard blocks of 2, 4, 8, 16, 32, and 64 microinches, AA, were run on an infrared spectrophotometer whose wavelength was varied from 2.5 to 15 micrometers. Figure 14 shows the results of these tests. It can be seen that reflectance is a measure of surface finish in the 3-micrometer-wavelength region for all samples. However, as the wavelength is increased, resolution is lost for the lower values of surface finish, but resolution increases with wavelength for the rougher surfaces.

The experiment just described was repeated using shaped or turned surface finish standard blocks of 32, 64, 90, and 125 microinches, AA. The results are summarized in Figure 15. It

Figure 14. INFRARED SPECTROPHOTOMETER REFLECTANCE CURVES. (From 2, 4, 8, 16, 32, and 64-Microinch Blocks)

can be seen from these curves that reflectance is not a measure of surface finish in this range. It is also noted that reflectance crossovers occur at certain wavelengths.

Figure 15. INFRARED SPECTROPHOTOMETER REFLECTANCE CURVES. (From 32, 64, 90, and 125-Microinch Blocks)

REFLECTANCE SUMMARY

In order to get a composite picture of reflectance as a function of the surface finish, a family of curves were drawn (Figure 16) to show the results of the aforementioned tests plus reflectance data taken using a 3.4-micrometer infrared laser, a 0.6328-micrometer laser, and a 0.9-micrometer gallium arsenide diode as light sources. Also included are readings obtained using a MIT surface finish comparator (white light).

The curves are extremely random and inconclusive concerning whether a relationship exists between surface finish and reflectance. In addition, in the feasible operating range (light sources with a wavelength of 5 micrometers or less), resolution is lost above 32 microinches, far short of the required upper limit of measurement. At this point it was decided that a direct measure of reflectance would not give a satisfactory indication of surface finish over the desired range.

Figure 16. REFLECTANCE DATA SUMMARY.

REFLECTANCE PATTERNS

In searching for an optical indication of surface finish other than direct reflectance measurement, it was obvious that it would be necessary to generate some type of reflectance pattern. A new test setup was arranged so that the flat master standard surface finish blocks could be rotated, as indicated in Figure 17. This arrangement made it possible to produce a reflectance pattern by scanning the reflected beam across the sensing element of the detector. Simple curves were generated, as shown in Figure 18, when the various standard blocks were rotated in the laser beam. It was felt that these curves were so dependent on direct reflectance that they would be of little use in obtaining a measure of surface finish.

DIFFRACTION PATTERNS

Another optical phenomenon which could produce useful light patterns is diffraction. If a light source and test surface could be aligned in such a manner as to cause the light to be diffracted, a relationship might be found to exist between the surface finish and the diffraction pattern. This modification would be similar to the operation of a grating spectrograph except that the test surface (grating) would be varied rather than the light source to produce different light patterns.

It was felt that in order to produce satisfactory diffraction patterns, it would be necessary to maintain specular reflectance. Since a long wave-length light source has the advantage of extending specular reflectance to rougher surfaces, the 0.6328-micrometer laser used in the previous experiments was converted to operate in the 3.39-micrometer infrared region. With an infrared laser as the light source, it was necessary to use a radiometric microscope in

place of the laser power meter as the detector. A view of the new experimental setup is given in Figure 19.

Experimentation began using an angle of incidence of 45 degrees. Reflectance patterns were generated (Figures 20 and 21) by rotating the standard block through an angle of approximately 10 degrees. It can be seen from the curves that specular reflectance prevailed for surfaces of 2, 4, and 8 microinches. However, a scatter pattern emerged for the standard blocks with a surface finish of 16 and 32 microinches. Although there was an obvious visual difference in the patterns for surfaces of 8, 16, and 32 microinches, it was felt that it would be difficult to assign numerical values to the data. Also, there was no discernible difference in the patterns produced for surfaces rougher than 32 microinches.

Figure 17. REFLECTANCE-PATTERN TEST EQUIPMENT.

The angle of incidence was decreased to as near the normal as possible with the existing setup. A new set of curves was then generated (Figures 22 through 24). With these new curves it was possible to visually distinguish between 32 and 64 microinches, but no quantitative improvements were noted.

Figure 18. SIMPLE REFLECTANCE CURVES. (Angle of Incidence is 40 to 50°)

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Figure 19. OVERALL VIEW OF THE REFLECTANCE-PATTERN TEST EQUIPMENT.

The experimental setup was again modified, this time to increase the angle of incidence to the maximum value of 80 degrees that was possible with the existing equipment. A new set of curves were generated. These new curves were dominated by a limited number of well-defined peaks, which is characteristic of diffracted light. Also, resolution was extended to 100 microinches, and the area of the curves appeared to be a function of the surface finish.

Further experimentation demonstrated that if the gain was adjusted so that the predominate peak of each of the samples was made numerically equal, and if the samples were rotated through the same angle in the same period of time, the area of these curves appeared to be directly proportional to the surface finish. At this point, the surface finish of each of the standard blocks was measured on a Clevite Surfanalyzer to establish an accurate value of the surface finish in the area traversed by the laser beam. These values of surface finish, rather than those stamped on the blocks, were used to identify the curves generated by the previously described experimental procedure (see Figures 25 and 26).

The area of these generated curves was measured and plotted against the surface finish of the blocks (Figure 27). As can be seen from this plot, the surface finish is directly proportional to the area under the generated curves.

Figure 20. REFLECTANCE PATTERNS FOR 2, 4, AND 8-MICROINCH SURFACE FINISHES. (Angle of Incidence is 45°, Norm; Test Specimen Angle of Incidence, ± 5° of the Norm)

Figure 21. REFLECTANCE PATTERNS FOR 16 AND 32-MICROINCH SURFACE FINISHES. (Angle of Incidence is 45°, Norm; Test Specimen Angle of Incidence, ± 5° of the Norm)

Figure 22. REFLECTANCE PATTERNS FOR 2, 4, AND 8-MICROINCH SURFACE FINISHES. (Angle of Incidence is Near the Normal; Test Specimen Angle of Incidence, ± 5° of the Norm)

Figure 23. REFLECTANCE PATTERN FOR A 16-MICROINCH SURFACE FINISH. (Angle of Incidence is Near the Normal; Test Specimen Angle of Incidence, ± 5° of the Norm)

Figure 24. REFLECTANCE PATTERNS FOR 32 AND 64-MICROINCH SURFACE FINISHES. (Angle of Incidence is Near the Normal; Test Specimen Angle of Incidence, $\pm 5^\circ$ of the Norm)

Figure 25. REFLECTANCE PATTERNS FOR 12, 30, AND 50-MICROINCH SURFACE FINISHES. (Angle of Incidence is 80° from the Normal; Test Specimen Angle of Incidence, $\pm 5^\circ$ of the Norm)

Figure 26. REFLECTANCE PATTERNS FOR 80 AND 100-MICROINCH SURFACE FINISHES. (Angle of Incidence is 80° from the Normal; Test Specimen Angle of Incidence, $\pm 5^\circ$ of the Norm)

Figure 27. SURFACE FINISH CORRELATION CURVE.

These experiments demonstrate that surface finish can be measured optically. However, further experimentation and engineering will be required to develop instrumentation that is suitable for on-line use on machine tools.

A complete calibration and test procedure is given in the Appendix.

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APPENDIX

OPTICAL SURFACE-FINISH MEASUREMENT - TEST PROCEDURE

Equipment Required

1. Infrared laser, wavelength 3.39 micrometer.
2. Infrared detector.
3. Strip-chart recorder.
4. Rotating test-specimen mount.
5. Set of surface finish blocks, 10 - 100 microinches, AA.

Initial Alignment Procedure

1. Place a 2-microinch surface-finish standard block in the rotating mount so that the center of the standard coincides with the center of rotation of the mount.
2. Center the rotating mount so that an equal angular deflection can be obtained on each side of the initial set point.
3. Align the laser and rotating test-specimen mount so that the laser beam strikes the center of the standard with an angle of incidence of 80 degrees.
4. Align the detector so as to receive the maximum reflected signal from the standard. This step completes the initial alignment (see Figure 19, Page 23).

Calibration

1. Replace the 2-microinch standard block with a standard block whose surface finish is not less than 10 microinches. The lay of the block must be parallel to the center line of rotation of the mount.
2. Make minor alignment adjustments to the rotating mount to peak the received signal.
3. Rotate the specimen mount 5 degrees on each side of the aligned center. When the maximum signal is received, stop the rotation and set the gain of the detector so that this signal is 90 percent of full scale.
4. Rotate the specimen mount 5 degrees counterclockwise from the aligned center.
5. Start the strip-chart recorder and rotate the specimen mount clockwise through 10 degrees in five minutes.

6. Stop the strip-chart recorder and remove the record (see typical records, Figures 25 and 26, Page 25).
7. Determine the area under the curve generated during the rotation of the specimen mount.
8. Repeat Steps 1 through 7 for several standard blocks up to a maximum of 100 microinches.
9. When completed, plot the areas of the curves as functions of the values of the surface-finish standard blocks on semilog paper. The areas are plotted on the log scale.

These nine steps will generate a calibration curve for the test equipment (see Figure 27, Page 26).

Determination of Surface Finish

1. Place a machined specimen whose surface finish is unknown on the rotating test-specimen mount. Align the specimen so that the lay of the specimen is parallel to the center line of rotation of the mount.
2. Follow Steps 2 through 7 of the calibration procedure.
3. The surface finish of the unknown specimen is obtained from the calibration curve by determining the value of the surface finish corresponding to the area of the curve generated in Step 2.