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Roughness measurement of highly polished, mirror-finished surfaces

A. Prakash* and K. Struijk†

This paper describes the use of optical and digital methods for the roughness measurement of very fine surfaces. The equidensity photograph of the interference fringe pattern of the surface is video-scanned and the information is stored in a 256 x 512 (or 512 x 512) dot matrix. The information is further retrieved in digital form using appropriate grey values and analysed to calculate various roughness parameters in ISO terminology.

Highly polished or mirror-finished surfaces pose problems in the measurement of their roughness by stylus (contact type) measuring instruments even at high sensitivity. The profile of the surface is distorted by chatter and vibrations of the stylus and other environmental effects such as the electrical noise of the instrument. The least count of the apparatus also has a limiting effect on the measurement. The effect of the datum surface characteristics becomes dominant when measuring surfaces having roughness values close to the apparatus' least count. The information given by commercial instruments is mostly a measure of the height of the surface irregularities, which, in the case of such surfaces, does not vary sufficiently to enable any realistic and comparative assessment of their roughness.

However, the limitations of the stylus type instruments, when used for measuring very fine surfaces, can be minimised and better results are possible by using a finer stylus and a higher data sampling rate. But increase in pressure at the stylus tip due to finer geometry may scratch the surface and sampling at points too close together yields correlated and highly redundant data. Optical methods (non-contact type) alone do not give a complete roughness assessment of such surfaces; they are more a measure of the surface reflectivity, depth of scratches and grooves rather than texture.

The differentiation between local scattering and total reflectivity also needs to be considered when using optical methods and any non-conventional method of roughness measurement should give results in parameters which are comparable to the accepted ISO roughness terminology. A combination of optical and digital methods has therefore been investigated. The results given by this non-contact, opto-digital method have been satisfactory, comprehensive and in ISO terminology, thus enabling a realistic comparison of the roughness of very fine surfaces.

Principle behind the method

In interference microscopy, light is reflected by two planes, one the surface to be studied, the other a reference plane. These are normally situated in different parts of the microscope, but are optically imaged close together. The light output corresponding with a certain plane on the surface is a function of the distance between the two planes:

\[ I = I_0 \left[ 1 - \sin^2 \frac{2\pi d}{\lambda} \right] \]

where \( a \) is a modulation parameter \( < 1 \) and \( f \) is given by

\[ d = \frac{k - f}{2} \frac{\lambda}{2} \]

where \( d \) is the distance between the planes, \( \lambda \) the wavelength, \( k \) an integer and \( f \) a fraction \( < 1 \). In practice, the reference plane is tilted in such a way that interference fringes result which, given suitable conditions, are seen on the surface to be studied.

The relation between photographic density (= grey value) and light intensity is such that in a certain region a monotonous, approximately linear relationship exists. (For low intensities there is a threshold, for high intensities saturation). It is clear that in principle this relationship can be determined by calibration and the height distribution on the surface to be studied can then be determined. This height distribution is to be taken from the reference plane and, as such, depends on the adjustment of this reference plane. The results can be made independent of the reference plane, however, by the simple expedient of calculating a best fitting plane.

In practical interference microscopy the very complete information about the surface which is contained in the interference pattern is not used. Normally the interference fringes are interpreted as height curves which is acceptable if the surface structure is more or less constant along the surface.

To facilitate this method of visual inspection narrow fringes are normally sought by (a) the use of photographic material having a steep density curve, (b) use of multiple beam interferometry or (c) by a photographic technique called equidensity interferometry. In all cases higher accuracy is traded for less information over the major part of the surface. (The very fine photographs of Tolansky are notoriously empty). This drawback, together with the frustration of being unable to use the total information of the pattern, led us to the preliminary experiments described below.

In this experiment, we had to accept limited communication between the video apparatus and the computer, so a lot of information was left unprocessed. This, however, obviated the need to determine the density curve, as only one grey value was used. The resolution of the method seems to be around 1%, which is sufficient, as the spread of roughness parameters over...
the surface is normally much higher. The spatial resolution is limited by the aperture of the objective lenses of the microscope, and is around 1 μm. Both are adversely influenced by the granulation of the photographic image which, however, at the moment is of little consequence.

**The method**

Fig 1 shows the technique employed. An equi-density photograph of the interference fringe pattern is prepared using a commercial interference microscope. The magnification used is such so that one complete fringe could be enclosed in the photo frame of length to breadth ratio 2:1 for 1 512 x 256 dot matrix or 1:1 for a 512 x 512 dot matrix. Alternatively, the photograph could be covered by a thick paper so as to expose only one of the interference fringes.

The photograph is then scanned by an ordinary video camera with the image projected onto a television screen. After routine contrast and gain adjustments of the image on the screen, the information is stored in the system memory. The stored information represents the grey value of darkness (or whiteness) in numerical form for each dot of the matrix. The grey value can vary from 0 to 255 for a totally dark or totally white spot (dot) respectively. A computer program picks up spots of the desired grey value from the information stored on the diskette and punches its position (distance from the base line along y-axis) on the paper tape. The information on the tape thus represents digitally the values proportional to the departure of the surface profile from a reference line. These departures termed as profile ordinates, denoted as \( y_1, y_2, y_3 \) (Fig 2) have been used for the calculation of roughness parameters by the main computer. Fig 3 shows the actual set-up of the total system.

**Calculation of roughness parameters**

Given the numerical data, an almost unlimited number of parameters can be computed. Information on useful parameters and on the details of calculation are given elsewhere \(^1,^2\) and also in the draft recommendation to the CIRP Technical Committee Surfaces Meeting, February 1977 \(^3,^4\) and are therefore not dealt with here.

**Results**

Computer outputs (line prints and plots) for various surfaces and test specimens have been shown (Figs 4–6).

Fig 4(a) shows acme threads drawn purposely to test the computer output for a known profile. From the computer output (Fig 4(b)) for acme threads, it will be observed that the results compare favourably with the
calculated ones. The discrepancy between the results given by other standards as ISO-2RC filter and the phase corrected filter is due to the fact that the cut-off length is about equal to the periodicity of the surface profile, hence there is a phase shift for the ISO-double RC filter.

Fig 5(b) shows the output of a Taylor Hobson stepped test specimen (Fig 5(a)) using the opto-digital method. Fig 5(c) shows the output of the same test specimen when measured by the stylus-contact method using a 'Talysurf'. Comparison of the roughness results given by these two methods (Figs 5(b) and (c)) shows close agreement. The output shown in Fig 6 is of the measurements done on an aluminium surface by the opto-digital method.

Of the various curves drawn from the application of Fourier transformation eg slope distribution, power spectrum and auto-correlation functions, the slope distribution curve is the most important. Unlike lapped and polished surfaces, the mirror finish surface produced by conventional machining keeps the typical geometrical configuration representative of the machining process employed. In such very fine surfaces, the variation in the usual parameters such as $R_a$, $R_t$, auto-correlation functions etc is not sufficient to enable any realistic and comparative assessment of their roughness. Slope values and the slope distribution curve for very fine machined surfaces vary appreciably and so are more suitable for their roughness assessment. The slope distribution function can also be employed for determining the optical properties of these surfaces as it measures the directional changes of the surface profile curves and is suggestive of their reflectivity. A relationship between the reflectivity index and the slope distribution function of a surface can possibly be established enabling a quicker assessment of its reflectivity index. However, differentiation between the scattering and total reflectivity has also to be considered while establishing the above relationship.

Problems and errors
The following points need deeper consideration for optimum and accurate results from this opto-digital technique of roughness measurement.

Effects of photographic process
Since the digitisation starts only after the video-scanning of the photograph, it is rather important that the photograph should be a true representation of the actual interference image of the surface. The effect of various elements of the photographic process, such as emulsion resolution, grain size, type of paper, Eberhart effect and variation in density, needs to be precisely controlled, but with the advanced photographic techniques available, the error introduced by one or many of these parameters is negligible.

Phase shift
It was observed that results were not identical for surfaces having similar roughness but of different materials, such as brass and aluminium. This is due to the distortion caused in the molecular structure of the material by the production process. The problem becomes acute when the distortion in the molecular size is greater than half the wavelength of the light used for interference fringes, in which case there is a phase shift between the incident and reflected beam resulting in an unrealistic fringe image.

Local black spots
The microscopic examination of the aluminium surface revealed cracking of molecules, which caused black spots to appear on the fringe photograph, giving possible error spots during video scanning. Boundary sharpness of the picture can also cause error in the results. However, these two possible causes of error can be easily overcome by programming for more than one fringe band and ignoring spots whose position falls outside the expected limits (Fig 2).

Modifications
Problems associated with photographic processing of the fringe patterns can be entirely overcome by directly
interfacing the interference microscope to the video generator via the camera. The suggested system is shown in Fig 7.

The data can be stored in a video ram or a microprocessor memory and can be retrieved for calculating roughness parameters or for dot displaying on the television monitor. Systems are now commercially available* which can be directly plugged into a microprocessor or other compatible devices. Such matrix storage facility of the roughness data gives an important advantage of measuring roughness over an area rather than on a line which has been a restriction until now. The roughness of the area covered by fringes 1, 2, 3, 4 etc (Fig 7) can be easily and economically calculated and the dots in the matrix having near equal roughness can be located and marked for assessing correlation of the roughness characteristics of different portions of the surface under observation.

**Conclusions**

This opto-digital technique overcomes most of the problems associated with the roughness measurement of very fine surfaces by both conventional and non-conventional methods. The results obtained are not only accurate and convenient for comparison but also predict better the surface functional behaviour. The roughness assessment thus available is realistic, detailed and complete compared to the limited results available from commercial instruments and being a non-contact method, there is no risk of spoiling the surface.

**Acknowledgements**

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*Matrix microprocessor displays, Matrix Ltd, Montreal, Canada*
Fig 6 Aluminium surface: results of roughness measurement by the opto-digital method

Eindhoven University of Technology for the help rendered in the use of their video scanning equipment. Initiation of the idea and helpful suggestions during the investigation by Prof. drs. J. Koning, Head of the Metrology Section, is gratefully acknowledged. The production of equi-density fringe photographs by Mr H.G. Sonnemans, Metrology Group, is appreciated.

References
4. ISO Recommendations on Roughness Measurements. ISO/R 468, 1878, 1880, TC 57

 CALCULATION OF ROUGHNESS PARAMETERS. MAIN PROGRAM.

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<th>ISO-R468 STANDARD DATA</th>
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| FILTERED WITH ISO-2RC FILTER (=ISO STANDARD DOUBLE RC FILTER). C.O. = 0.064 MM |
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| RMIN = -0.0090 SKEW = -0.9902 KURT = 4.1827 |

| FILTERED WITH PHASE CORRECTED FILTER. C.O. = 0.064 MM |
| RT = 0.0111 RMS = 0.0023 RA = 0.0018 RP = 0.0053 |
| RMIN = -0.0058 SKEW = -0.2651 KURT = 2.9733 |

Fig 7 System using video digitiser
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