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APPLICATIONS FOR A WIDE RANGE STYLUS INSTRUMENT IN SURFACE METROLOGY*

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Summary

Some applications in the field of surface metrology are described for a new stylus instrument incorporating a transducer with a wide dynamic range. The transducer has a range of 2.0 mm and a resolution of 5 nm enabling the measurement of both the fine surface texture and the surface form of a highly formed component to be made in a single traverse. The form is separated from the texture mathematically by the calculation of certain dimensional parameters relating to that form. The examples outlined in this paper specifically refer to the form being either a circular arc, giving the radius, or a straight line, giving the angle of tilt.

Applications include the measurement of form errors, surface finish and radius of circular formed components such as ball bearing raceways, diamond turned mirrors, a diamond turning tool and the surface geometry of a Rockwell C hardness indenter.

Some of the implications of this technique are described especially in relation to its measurement of surface finish.

1. Introduction

The ever-increasing demands that are required of engineering surfaces [1] are placing more and more importance on surface metrology. The digital computer has provided the ability both to control the measurement cycle of a stylus instrument and to accept the electrical data for the evaluation of complex analytical results which are only possible by digital techniques. Thereby there is a reduction in the measurement cycle time whilst the accuracy and, in some instances, the ability to use less skilled operators, are retained.

However, a conventional surface finish instrument, principally on account of the limited dynamic range of the pick-up, can be designed only

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to measure a highly curved component in respect of either its form or its surface texture. Either property requires a setting-up procedure which can become quite tedious and time consuming. This is especially true when measuring the texture on such a component, as the instrument requires a curved datum which has to be matched to the component before any measurement can be made. The problem is more acute with smaller components.

The new instrument has been developed to alleviate these problems. Setting up a curved component is considerably easier because in the instrument's operation a wide dynamic range is combined with accuracy and data is yielded as profile points in exact (x, y) coordinates, enabling form, texture and radius to be measured in a single traverse.

2. Implications of a wide range transducer

To measure the form, surface texture and radius of the component depicted in Fig. 1 in a single traverse, a pick-up is needed which can measure in the y direction with a range of at least h and a resolution high enough to detect the surface texture detail. Accurate measurement of the pick-up traverse, in the x direction, is essential.

The side-acting pick-up comprises a pivoted lever; on one end of this is the stylus which contacts the surface to be measured. On the other end is a cube corner reflector which acts as the measurement arm of a miniature polarization-coded interferometric transducer [2] to give a direct digital output with a range of 2 mm, a resolution of 5 nm and a frequency response of about 300 Hz.

The light source for the Michelson-type interferometer is a commercially available He–Ne laser of 1 mW output. The output beam from the interferometer derived from both measurement and reference arms is split into four, enabling four photodiodes to detect the fringe pattern. These signals, indicating the stylus displacement y, are fed into a preamplifier board producing the conventional quadrature signals which enable bidirectional counting and interpolation to $\frac{1}{64}$ of a fringe [3]. This gives a range-to-resolution ratio of 5×10^5, *i.e.* equivalent to 19 bits.

Certain factors need to be taken into account when using a transducer with these capabilities: some of these are now described.

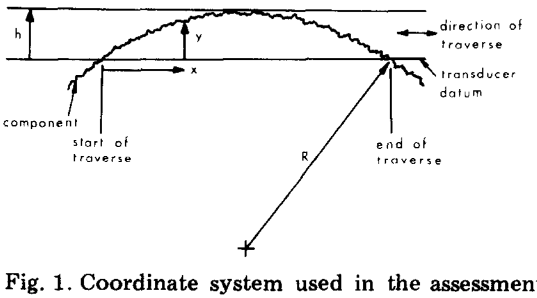


Fig. 1. Coordinate system used in the assessment of both form and texture of a curved surface.

2.1. Transducer linearity

Firstly, the stylus arm pivot needs to have a precise axis of rotation which introduces minimal friction and allows for the wide measuring range. The variation in static stylus force over this range must also be minimal. These constraints help to ensure that the stylus arm moves accurately over the wide range. However, the normal assumption of linearity of stylus movements will no longer apply in either the y or the x direction, and a small correction is made by the computer for the cross-axis relationship of the pick-up geometry.

The corrected value of y is given by

$$Ay + By^2$$

where A is nominally 1 and $b = a/2b^2$, and the corrected value of the horizontal stylus movement x is given by

$$Cy - Dy^2$$

where $C = a/b$ and $D = 1/2b$.

Here a is the dimension from the stylus tip to the stylus arm and b is the dimension from the stylus to the pivot.

2.2. Digital sampling of the data

The sampling of data in a digital system may be controlled temporally or spatially. The use of temporal sampling to measure the x direction in Fig. 1 is not advisable as any speed fluctuations in the traverse give related errors E in the sampling distance. Referring to Fig. 1, if the best-fit arc was calculated using temporal sampling and then subtracted from the data the resulting surface detail would show this error with amplitude $e = E \tan \alpha$, where α is the angle at which the stylus is traversing (*i.e.* the tilt of the component being measured) relative to the true datum of the instrument. To avoid this, spatial sampling is employed which is more reliable although less convenient.

A conventional moiré fringe grating transducer is attached to a traversing table which holds the workpiece. The grating pitch is 10 μm, and the quadrature signals from the transducer were fed into an interpolator that divides by 20 to provide a data-logging pulse at every 0.5 μm displacement of the table.

Cyclic errors in the signals from the transducer limit the performance; the effect is similar to that described above for temporal errors but is considerably less. These errors can be isolated from the true data by the use of a 10 μm digital notch filter.

3. The instrument system

Figure 2 shows a schematic view of the system, which is built around a standard Rank Taylor Hobson product (Talydata) embodying a Data General

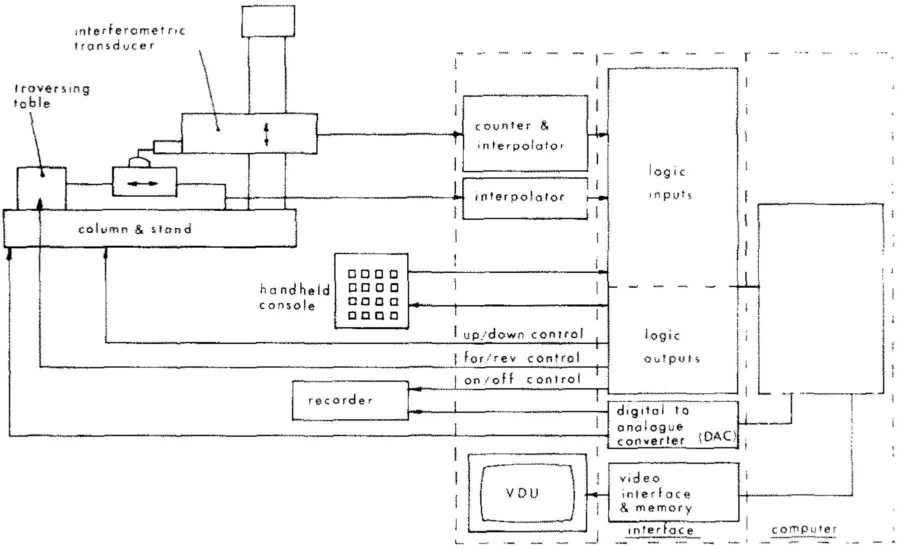


Fig. 2. Schematic view of the wide range stylus instrument system.

microNova computer. Nineteen of the logic inputs are used for the data of the interferometric transducer. The digital-to-analogue converter provides an analogue signal to the recorder and an analogue signal derived from the interferometric transducer that is used in a servo to control the column drive. Instrument operation is controlled by the handheld console responding to menu-type messages displayed on the visual display unit (VDU).

3.1. Reference lines and calibration

Considering the component in Fig. 1, to fit accurately a reference line conforming to a best-fit circular arc [4, 5] to the data collected by the transducer, a calibration routine is required. It is not sufficient to use a conventional "three-line" or "R_a" standard. A round smooth ball of known radius is traversed under the stylus. After the best-fit arc has been calculated and subtracted from the data, the modified data should show minimum form error and the calculated radius should agree with the true radius of the ball, enabling the calibration referred to in Section 2.1 to be achieved.

This calibration is absolute and will be true for other measurements whether the reference line is a circular arc, a straight line or any other curve. The accuracy in radius measurement or parameter of any curve depends mainly on the calibration accuracy, traverse length chosen and the surface texture present.

Because the stylus tip has a finite width (about 2 μm) its value has to be taken into account as it passes the valley on a concave component or the peak on a convex component.

The stylus is not always normal to the surface being measured; the inclination has to be compensated for to give valid form error and surface finish height information.

When the best-fit arc is calculated the ordinate spacing is based on the chord of the arc: after the arc has been subtracted the residual data are referred to the arc itself, to give valid form error and surface finish wavelength information.

Similar corrections are necessary if a straight-line reference is used to remove large angles of tilt when measuring a flat component. The accuracy of the measured angle of tilt of the straight-line reference again depends on the calibration accuracy, traverse length chosen and the surface texture present.

3.2. Surface texture measurement

Surface texture comparisons were made between a Rank Taylor Hobson Talysurf 4 instrument and the wide range instrument by making measurements on components with different finishes: milled, turned and ground. Table 1 shows the set-up for each measurement.

For each measurement three traverses over similar parts of the component were taken and the results were averaged. A best-fit least-squares straight line was subtracted from the sets of data and the data from the turned and ground surfaces were further modified by a standard 2CR high pass filter with a 0.25 mm cut-off to obtain the surface texture parameters and power spectra shown in Fig. 3.

TABLE 1

Measurement	a	b	c	d
Instrument	Talysurf 4	Wide range instrument	Wide range instrument	Wide range instrument
Component tilt	$<0.01^\circ$	$\leqslant 0.1^\circ$	$\leqslant 0.1^\circ$	$\approx 25^\circ$
Comments	Without skid	Without 10 μm notch filter	With 10 μm notch filter	With 10 μm notch filter

3.2.1. Results from the milled surfaces (Fig. 3(a))

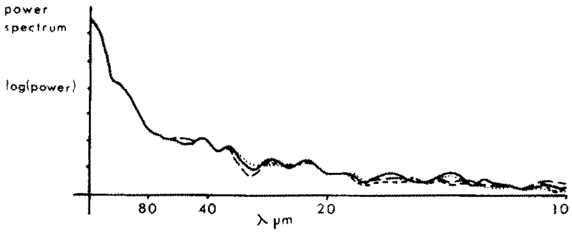
The parameters and power spectra for all four measurements show good correlation.

3.2.2. Results from the turned surface (Fig. 3(b))

The power spectra and parameters given by measurements a and b show good correlation. The power spectra show the effect of the 10 μm notch filter on measurements c and d which will affect both amplitude and wavelength parameters.

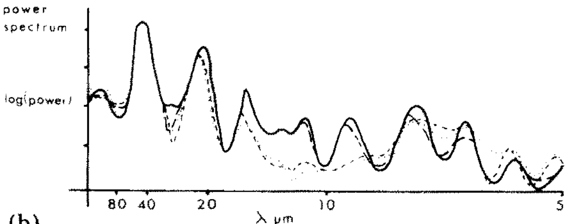
3.2.3. Results from the ground surface (Fig. 3(c))

The power spectra of measurements a and b show that surface detail with a wavelength of about 10 μm is predominant. There will therefore be larger parameter differences between a or b and c or d. This surface shows



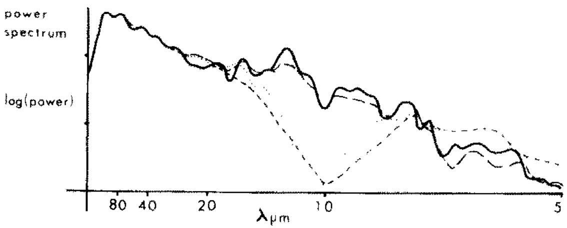
(a)

Measurement and symbol	a; ——	b; — — —	c; - - - -	d; ·······
Tilt (deg)	0.01	0.1	0.1	25
R_t (μm)	18.2	18.0	18.0	17.7
R_a (μm)	4.50	4.53	4.50	4.45
Δ_a (deg)	3.00	2.95	2.88	2.86
λ_a (μm)	540	553	562	560



(b)

Measurement and symbol	a; ——	b; — — —	c; - - - -	d; ·······
Tilt (deg)	0.01	0.1	0.1	25
R_t (μm)	1.45	1.46	1.35	1.33
R_a (μm)	0.262	0.260	0.244	0.240
Δ_a (deg)	3.12	3.02	2.75	2.80
λ_a (μm)	30.2	30.9	31.9	30.9



(c)

Measurement and symbol	a; ——	b; — — —	c; - - - -	d; ·······
Tilt (deg)	0.01	0.1	0.1	25
R_t (μm)	4.32	4.40	3.95	3.33
R_a (μm)	0.488	0.500	0.424	0.408
Δ_a (deg)	8.40	8.35	4.60	4.45
λ_a (μm)	20.9	21.4	33.2	33.0

Fig. 3. Comparisons between Talysurf and wide range stylus instruments on three surfaces: (a) milled; (b) turned; (c) ground.

a high average slope Δ_a which will tend to influence to a lesser extent the parameters given by d because of the tilt of the component.

3.2.4. Summarizing remarks

Considering the three given types of surface both amplitude and wavelength parameters considered in Fig. 3 show good correlation between measurements a and b.

The 10 μm notch filter which is employed to isolate the grating transducer cyclic errors will also filter real surface detail around this wavelength. Therefore the correlation between parameters for measurements b and c will be dependent on the amount of surface detail at this wavelength.

Measurements c and d show good correlation considering the large component tilt that exists for d.

4. Applications

Figure 4 shows a measurement over a ball of diameter 25.4 mm. The profile contains the form errors and texture after the best fit arc has been subtracted from the data. The peak-to-valley (P–V) distance is taken over the assessment length L (P–V) and the R_a and R_q values are taken over $L(R_a)$. The difference in these lengths is the settling distance for the filter (twice the cut-off).

This ball was used to calibrate the instrument, and all subsequent measurements made in this section are taken with respect to this one calibration.

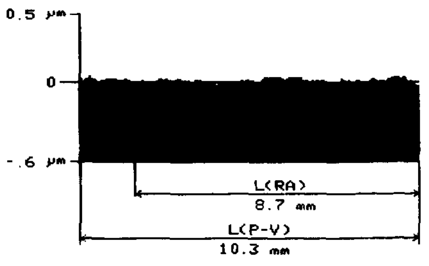


Fig. 4. Measurement of ball (ball radius, 12.701 mm; R_a = 0.008 μm; R_q = 0.010 μm; P–V = 0.10 μm).

4.1. Ball bearings

An important application is the measurement of the cross-track curvature of bearing raceways. One traditional method of measuring the radius is to project the arc onto the screen of an optical comparator at an appropriate magnification and to compare it with arcs drawn on a template. This method has a number of disadvantages, one being that the measurement is very subjective and depends on operator interpretation.

Figures 5(a) and 5(b) show results taken with the wide range instrument giving form errors, surface texture and radius. The component in

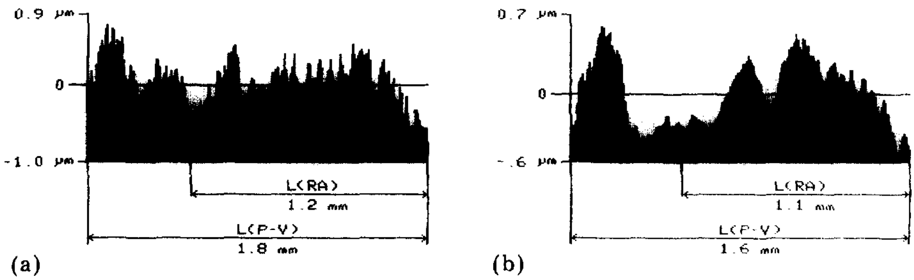


Fig. 5. Measurement of cross-track curvature on bearing races: (a) ground race (radius, 1.347 mm; $R_a = 0.18$ µm; $R_q = 0.23$ µm; P–V = 1.78 µm); (b) lapped race (radius, 1.348 mm; $R_a = 0.091$ µm; $R_q = 0.11$ µm; P–V = 1.19 µm).

Fig. 5(a) has had the track ground whereas that in Fig. 5(b) has been lapped; this shows that not all the grinding marks have been removed and it also shows the form errors due to lapping. The range of radii of interest is usually between 0.4 and 15 mm. The measurement accuracy on the radius has been found in practice to be better than ±5 µm for this range.

Further applications include the measurement of the balls (Fig. 4) and rollers that make up the rest of the bearing.

4.2. Optical components

Diamond turning is becoming highly important in the manufacture of mirrors and some lenses. The traditional method of measurement is by interferometry, with problems of interpretation and setting up. This technique cannot be used for many modern types of IR lenses.

Figure 6 shows results taken by the wide range instrument on a toroidal diamond-turned aluminium mirror. The differences in radius values show the toroidal form. The machining marks predominate in Fig. 6(b) as this measurement is taken across the lay, whereas Fig. 6(a) is along the lay.

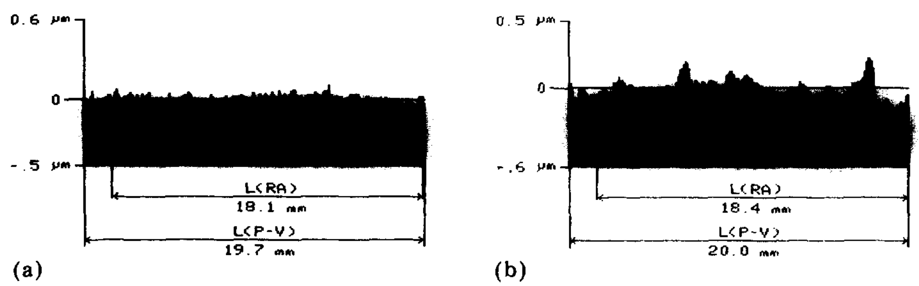


Fig. 6. Measurement of a diamond-turned toroidal mirror: (a) along the lay (radius, 109.94 mm; $R_a = 0.022$ µm; $R_q = 0.029$ µm; P–V = 0.20 µm); (b) across the lay (radius, 111.26 mm; $R_a = 0.026$ µm; $R_q = 0.036$ µm; P–V = 0.52 µm).

The radii of interest are usually between 20 and 600 mm with a measurement accuracy of the radius that is better than 0.1% of the nominal value.

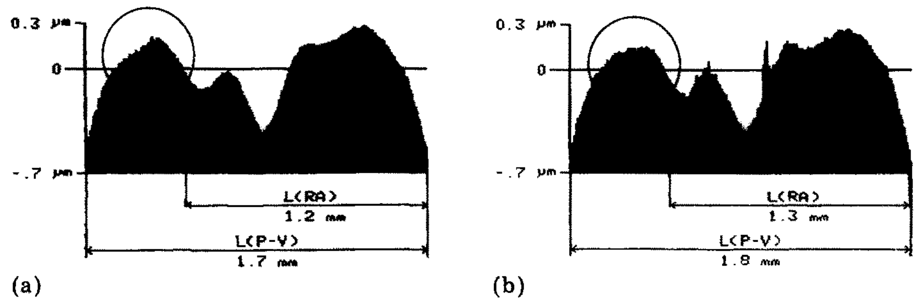


Fig. 7. Measurement of a diamond turning tool: (a) new tool (radius, 2.510 mm; R_a = 0.051 µm; R_q = 0.064 µm; P–V = 0.93 µm); (b) used tool (radius, 2.508 mm; R_a = 0.053 µm; R_q = 0.077 µm; P–V = 0.94 µm).

The diamond tools that are used to generate these surfaces can have an arcuate cutting surface. Figure 7 shows a measurement of such a tool after the best-fit arc has been subtracted. Figure 7(a) shows the tool as new whereas Fig. 7(b) shows the same tool after many cuts have been taken and hence the slight wear on one side of the cutting edge, shown encircled in Fig. 7(b).

Aspheric mirrors and lenses could also be measured; with the best-fit arc subtracted the resulting asphericity will be displayed. Where the aspherity is large, it will not be easy to measure small aspherity deviations. However, if this deviation is not of interest high pass filtering will enable the surface finish detail to be obtained.

4.3. A Rockwell C hardness indenter

The surface form and texture of this indenter should conform to British Standards [6], the relevant parts being as follows.

(1) The indenter should be polished over an area sufficient to ensure that no unpolished part of its surface makes contact with the test piece when indenting to a depth of 0.3 mm.

(2) There should be no discontinuities in the spherical and conical profiles and they should blend tangentially.

(3) The contour of the tip in any axial section should be part of a sphere of radius 0.2 ± 0.01 mm.

(4) The included angle of the conical section should be 120° ± 0.33°.

(5) The axis of the diamond cone should be square to the seating surface to within 0.5°.

The recommended way of examining the spherical tip is by the use of optical projection. Figure 8(a) shows a cross-sectional view of the indenter taken by the wide range instrument. This would tend to satisfy requirements (1) and (2), depending on the definition of "smooth" in this context.

Figure 8(b) shows the form errors and surface texture after the best-fit arc has been subtracted from the data over the assessment length L_1 = 0.2 mm, the radius of this arc being R = 0.25 mm which is beyond the limits stated in requirement (3).

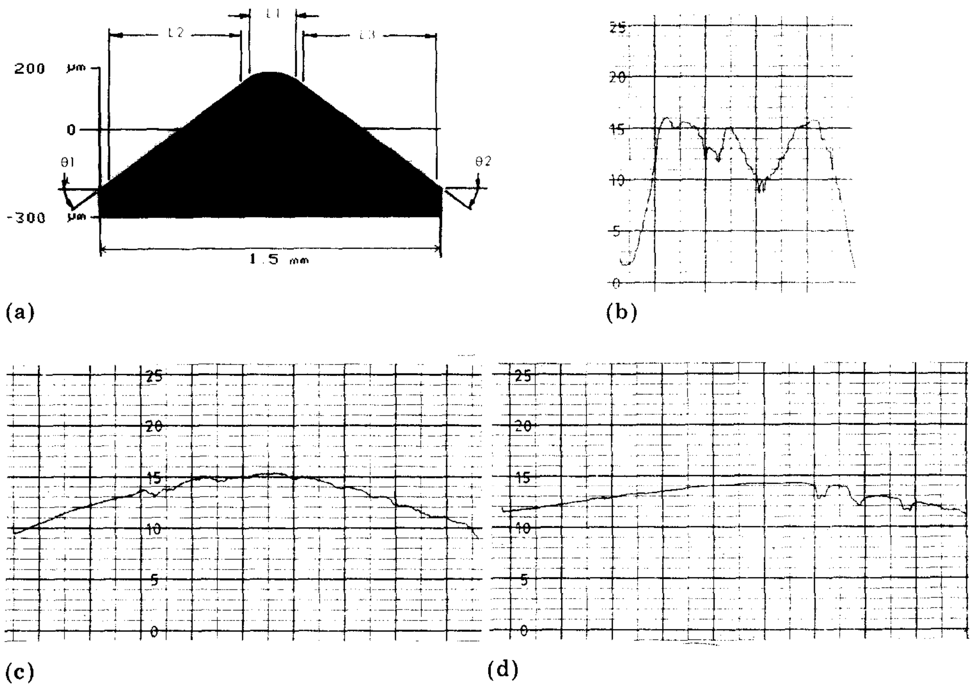


Fig. 8. Measurement of a Rockwell C hardness indenter: (a) cross-sectional view; (b) form and texture over L_1; (c) form and texture over L_2; (d) form and texture over L_3. (Magnifications for (b) - (d): vertical, 6700X; horizontal, 134X.)

Figures 8(c) and 8(d) show the profiles of the conical section of the indenter after the best-fit least-squares straight line has been subtracted: the angles θ_1 and θ_2 obtained will give the included angle θ_{in} for that section to a measured accuracy of 0.1% of the nominal angle, which is well within the tolerance required by (4):

$$\theta_{in} = 180° - \theta_1 + \theta_2$$

where $\theta_1 = 29.18°$, $\theta_2 = -30.84°$. Therefore $\theta_{in} = 119.98° \pm 0.06°$ which is within the value required by (4).

The requirement (5) can be met by measuring the seating surface of the indenter and subtracting the best-fit straight line to obtain the offset angle θ_0: the squareness is

$$\frac{\theta_1 + \theta_2}{2} - \theta_0$$

where $\theta_0 = -0.606°$. Therefore the squareness is $-0.22° \pm 0.03°$ which is within the value required by (5).

To obtain a more comprehensive study of the indenter, measurements of more cross sections are required. This application illustrates the use of both a best-fit arc and a best-fit straight line that can be fitted to different parts of the data collected in a single traverse. The definition of the word "smooth" in the Standard is not quantified but in this instance the cone (Figs. 8(c) and 8(d)) can be seen to be "smoother" than the spherical tip (Fig. 8(b)).

5. Concluding remarks

A new wide range stylus instrument has been described which in a single traverse can measure the form and texture of a highly formed component. There is a mathematical separation of the two properties, so that the associated dimensional parameters are accurately evaluated. In this paper examples of a circular-arc form, giving form errors, surface texture and radius, and a straight-line form, giving form errors, surface texture and angle, have been dealt with. Other forms such as parabolic, elliptical, hyperbolic and aspheric are the subject of continuing investigations.

The instrument provides a distinctive and useful advance in measurement by the stylus method, offering possible solutions to many obdurate problems in the field of surface metrology.

Further improvements in technique are planned such as alleviating the need for a 10 μm notch filter which at present can affect surface texture measurements.

Acknowledgments

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References

1 D. J. Whitehouse, The measurement and analysis of surfaces, *Tribol. Int.*, *7* (December 1974) 249 - 259.
2 J. D. Garratt, An interferometric transducer for surface metrology, *M.Sc. Thesis*, University of Aberdeen, 1977.
3 F. Duffin, Electronic interference fringe counter and divider, *M.Sc. Thesis*, University of Aberdeen, 1974.
4 D. J. Whitehouse, Computational replacement of curved datum and the measurement of radius on Talysurf 5, *RTH Tech. Note T52*, 1974 (Rank Taylor Hobson, Leicester).
5 P. J. Scott, Statistic analysis of circular profiles, *M.Sc. Thesis and DIC Rep.*, Imperial College, London, September 1980.
6 Method for Rockwell hardness test, *BS 891*, Part 2, 1964.
Method for Rockwell superficial hardness test (N and T scales), *BS 4175*, Part 2, 1970.