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Stylus methods of surface measurement

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The problem to be solved is the assessment of the magnitude of the residual hills and valleys which are found on most manufactured surfaces, and are often of functional significance. Heights may range from 1/50 μm up to 50 μm, and the spacing of the peaks may range from almost molecular dimensions up to the length of the workpiece. Maximum values of height are often found in identifiable wavebands, each associated with some causative aspect of the manufacturing process. Three widely recognized bands cover: (1) the irregularities known as roughness, that often result from well controlled stock removal and have wavelengths up to a few millimeters; (2) longer wavelengths known as waviness that are often caused by improper effects such as vibration between tool and workpiece; and (3) very long waves or curvatures referred to as errors of form. The extremities of these bands are often not well defined.

The relation between surface topography, physical characteristics and function is complex and not yet fully understood. In this state of uncertainty topographic assessment is based largely on conventional parameters (eg the widely used average value of the amplitude in a given waveband) which describe particular aspects of the surface but can give no direct measure of performance.

The earliest stylus instrument is generally attributed to the German engineer Gustav Schmalz, who in 1929 described an arrangement in which a stylus on the end of a pivoted arm tilted a small mirror used as in a reflecting galvanometer, the excursions of the spot being recorded on a moving photographic chart to show the cross section of the surface traced by the stylus. With this arrangement, the maximum possible magnification of the stylus movement is limited by the very small force that can be applied to the sharp stylus to keep it in contact with the surface, which in turn limits the size of the mirror and hence the numerical aperture of the optical system, on which definition of the spot depends. Schmalz' apparatus sufficed to produce some interesting profile graphs of the rougher surfaces, and stimulated further work.

In America, Ernest Abbott developed an electrical instrument in which the output from a coil coupled with the stylus and moving through a magnetic field, was amplified and fed into a voltmeter. Since the output of such a moving coil transducer is responsive basically to velocity, Abbott interposed a circuit attenuating the output inversely as the frequency, so that the meter indicated amplitude regardless of frequency over a controlled range of frequencies wide enough to represent the hills and valleys of 'roughness' at the assigned speed of traverse. The resulting instrument appeared on the market in 1936 as a practical workshop device, under the name 'Profilometer', giving meter readings of amplitude but not graphs. The datum, relative to which the excursions of the stylus were measured, was provided by the locus of a pair of skids of about 6 mm radius which slid over the crests of the roughness texture.

The Talysurf

The series of stylus instruments bearing this name, which was started around 1940 by Taylor Taylor and Hobson (later to become Rank Precision Industries), introduced new features. Kinematic principles have been linked with the progressive availability of new materials and devices to secure improved performance or lower cost.

Until recently these instruments, which from the start gave profile graphs depicting a cross section of the surface together with meter readings of amplitude, have used a small variable inductance transducer. This form of transducer was used in the Admiralty Research Laboratory in Teddington as far back as 1919, for measuring the torsion in ships' propellor shafts. It appeared some 15 years later in the American Pratt and Whitney Electrolimit Gauge, which, with upwards of 100 g force on the stylus tip, gave sufficient output to operate a metal rectifier meter without amplification. The manufacture of this in England by Taylor Hobson provided a starting point for the Talysurf transducer.

In principle, two such inductances are coupled differentially with the stylus, and connected in a bridge circuit supplied from an oscillator giving a carrier frequency f_c substantially higher than the highest frequency f_s to be imparted to the stylus. Displacement of the stylus then modulates the amplitude of the carrier according to the displacement of the stylus, independently of frequency through the range from 0 to f_s.

Preliminary investigation showed that a stylus in the form of a 90° diamond pyramid with its sides meeting at the tip within 2–3 μm could give sufficient resolution of the surface texture for most practical purposes, that the maximum permissible force on it would be about 100 mg and that for practical operation the range of frequencies would extend from 0 to 500 Hz. Fortunately amplitudes on surfaces tend to diminish with the spacing, that is as the frequency imparted to the stylus at a given tracing speed increases.

The requirements set a limit of a few milligrams to the mass transferred to the tip of the moving part of the transducer, and called for an electronic unit to provide a carrier signal, carrier frequency amplification, demodulation and output stages to feed a DC ink recorder and an AC integrating meter able to handle frequencies down to 0·1 Hz in its AC section. The AC frequencies representing

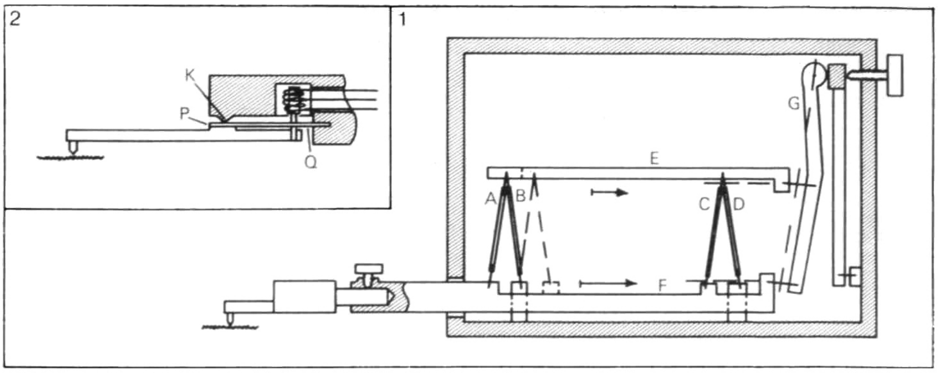

Figure 1 Straight line linkage of model 2 Talysurf giving true datum independent of workpiece
Figure 2 Hinge of very low stiffness for pick up

the desired roughness waveband were selected by a simple type of wavefilter which eventually became standardized. Integration of the amplitude was effected by feeding the filtered and rectified AC signal into a milliampere–seconds meter (Grassot flux meter) for a constant time controlled by the traversing mechanism.

On the mechanical side, a problem lay in generating a datum independent of the surface being examined, suitable for workshop use. It had to be at least 1 cm long (preferably 2 or 3 cm), straight within 0·1 µm per cm, and smooth to better than 0·01 µm. A mechanical slideway could be polished optically to the required limits, but at that time there were no known materials that would slide in contact with it without lubrication, and oil films did not build up to a constant thickness fast enough to permit satisfactory measurement of small workpieces. Attention was therefore given to straight line linkages with ligament hinges, and the arrangement shown in figure 1 was evolved.

If the links A, B and C, D are of equal length, and the bar E is constrained to move at half the speed of the carriage F, it will be seen that by similar triangles the carriage will move in a straight line. A convenient feature of the linkage is that the direction of movement of the carriage is perpendicular to the plane of the links in their coincident position, so that the traverse of the stylus can be tilted about its midpoint and set parallel to the work surface by angular adjustment of the halving lever G. A pick up having a skid of 50 mm radius (convenient but less accurate) could also be used.

For the next version (Model 3) experience showed that a skid type pickup would be acceptable for most workshop purposes, guided by an approximate straight line linkage in the drive unit. This reduced the basic cost. An external, easily replaced optical flat could be attached to provide an independent datum. The former ink recorder was replaced by one which used Teledeltos paper and gave straight linear ordinates by curving the chart paper P to a cylindrical form coaxial with the axis of rotation of the pen. A possibly interesting feature of the pickup lay in the hinge (figure 2) which comprised a knife edge K resting on a plane P across which it was prevented from sliding by a long, substantially coplanar and flexible ligament Q used in shear. This provided a hinge having a very determinate location, combined with much lower stiffness than could be secured by a conventional single or crossed ligament. Strictly, the neutral axis of the ligament should be coincident with the knife edge plane, but the angle of rotation being extremely small, it sufficed to clamp the ligament to the plane and let the knife edge rest on it.

In the recently introduced Model 10 Talysurf, a new approach to the pickup was made possible by the properties of silicon photocells. These cells will stand high levels of illumination substantially without fatigue or drift, so that a very simple optical arrangement will suffice. The cells can be made small in size and exhibit acceptable linearity on a variable area basis. In the Model 10 pickup, designed by D V Elwood, the armature of Model 3 is replaced by a vane which, moving close before a pair of photocells, controls the light falling on them differentially. The light is piped from a source at the back of the pickup through a glass rod. Derivations of PTFE made it practicable for the first time to generate a true independent datum by means of an optically polished shaft sliding through dry bearings. This provided up to 5 cm traverse straight within 0·2 µm.

The Talystep

A requirement arose to measure the thickness of the thin (generally evaporated) films used in the making of microminiature circuits. These films are sometimes soft, and may be as little as 50 Å thick. Test specimens are prepared by masking a small part of the substrate so as to form a well defined edge. The height of the resulting step can be measured by multiple beam interference methods, but this calls for overcoating with a highly reflective layer so as to avoid losses and make the optical properties of the two levels identical. The inconvenience of having to overcoat each specimen before it could be measured led to the use of stylus methods and the Talystep instrument. This instrument is a development of the Talysurf in which, in return for a greatly reduced range of workpiece acceptance, it was found possible to increase the maximum magnification from × 100 000 to × 1 000 000, and simultaneously to reduce the force on the probe from 100 mg to around 1 mg.

The pickup is carried on a frame hinged by widely separated ligaments to a vertical column, and traverses the flat specimen in an arcuate path. This provides a very smooth datum. Slight residual curvature of the specimen can be compensated for by tilting it.

Apart from the question of adequate stability at the high magnifications required, it was not known, before the prototype Talystep was made, whether small steps could be measured accurately enough by a contacting probe. It seemed that the coating might often be harder or softer than the substrate, and that an error would then arise according to the

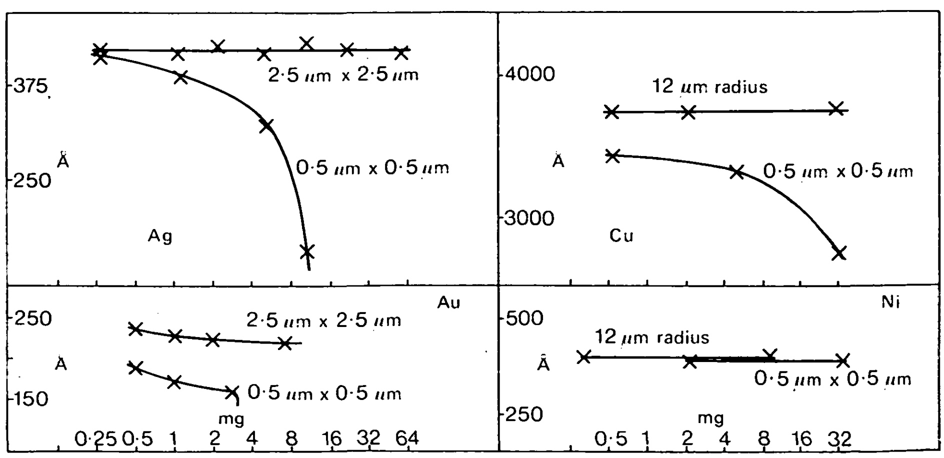

Figure 3 Relationship between thickness of coating evaporated on glass and force stylus tips, two being four sided 90° pyramids truncated to 0·5 µm and 2·5 µm square respectively and the third having a nominal 12 µm radius

difference in the depth of elastic penetration of the probe into the two surfaces. The point was checked by measuring a variety of steps each with two probes of different sharpness under a range of loads. It seemed reasonable to accept the measured step height to the extent that it was not affected by the load. The surprising results shown in figure 3 were later confirmed at the National Physical Laboratory by comparison with two optical interference methods. Some of these results are shown in table 1.

A point to note, when comparing these methods, is that they assess the height in three different ways. The stylus measures in a cross section normal to the surface. The multiple beam interference method measures in an oblique cross section inclined at only a few degrees to the surface. The wave front shearing interferometer operates on two small closely adjacent areas of the surface, one on each side of the step. Unless both levels of the step are perfectly smooth and parallel over the area involved, some small divergence between the results obtained could be expected.

It was also found possible to take advantage of the low force and use, for measuring the finest degrees of roughness, a stylus having a tip width reduced in the traversing direction from 2 μm to less than 0·1 μm. In this form the instrument provides resolution in width to better than half a wavelength of green light, and in depth to a thousandth of a wavelength.

The Talyrond

Measurement of roundness received early attention, and from this emerged the Talyrond instruments shown diagrammatically in figure 4. In the first form, the periphery of the workpiece is traced by an indicator mounted on the end of a precision spindle. A spherical bearing at the lower end of the spindle, in combination with a very slow taper at the upper end, both being optically polished, provided accuracy of rotation better than 0·05 μm. The spindles run with full hydrodynamic lubrication at 3 rpm, the oil film being around 0·3 μm thick. More recently, for inversions in which the workpiece is mounted on a rotating work table, dry bearings are being used.

After closely centring the workpiece relative to the spindle, the variations in radius are conveniently presented in polar form. However, the mean diameter of the resulting figure is very much less than that of the workpiece scaled up by the radial magnification (which ranges from 500 to 10000), and this results in various forms of distortion, especially in the presence of residual eccentricity of the workpiece relative to the spindle. While the profile is being plotted the instrument determines the radius and the coordinates of a circle that best fits the workpiece on a least squares basis, eccentricity being represented by the addition in correct phase, of a sine wave having a frequency of one cycle per revolution and amplitude equal to the workpiece eccentricity. The representation of the best fitting circle is then superposed on the chart during a second revolution to serve as a reference line for numerical evaluation.

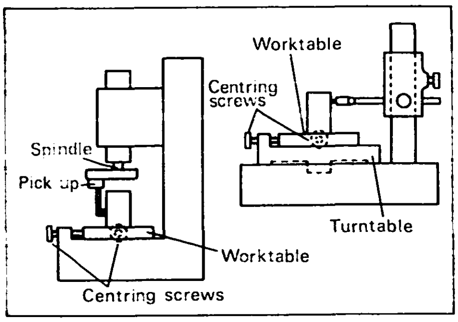

Figure 4 Basic forms of roundness instrument; rotating pick up and rotating workpiece

Study of the statistical and functional properties of surface topography has been greatly helped by the use of digital recording methods, followed by computer evaluation of topographic parameters. Using ordinates of the profile spaced from 2 to 10 μm apart, each expressed to three significant figures, exact comparison became possible of meter readings derived from analogue circuits and the values calculated from the formulae the circuits represent. Furthermore, the accurate study of statistical relationships became practicable, and this in turn has found use in the study of functional properties, for example surface wear, and in manufacturing considerations, for example tool life. It has also encouraged the conception and study of new parameters able to exend the descriptions of surface topography, for example the concept of the average wavelengths of a random profile.

Calibration

In the case of instruments responsive to static displacement of the stylus, calibration starts, fundamentally, from the interferometrically determined difference in thickness of two gauge blocks wrung down side by side on a platten, so as to form a step which can be traced by the stylus. The smallest permissible step must be such that the percentage uncertainty in its determination is negligible, for example less than 1%. Thus the height of the step should be not less than 2 μm. When the magnified value of this step is greater than the chart width, it or a larger step is reduced by a mechanical lever having a ligament hinge and a reduction factor of 10 or 20. The principle is described in BS 1134/1972. Magnifications up to ×100000 can then be calibrated. Having calibrated an instrument in this way, instrument calibration specimens having grooves of convenient depth made by etching or evaporation are calibrated and used as the practical devices for workshop control.

Table 1 Comparison of step height measurement by optical interference and the Talystep

		TALYSTEP Unaluminized Å	TALYSTEP Aluminized Å	INTERFERENCE Shearing Å	INTERFERENCE Multiple beam Å
Magnesium fluoride	1	94	96	99	103
	2	408	411	405	405
	3	775	784	786	794
Gold	1	110	108	105	115
	2	203	209	198	208
	3	392	392	367	370

In the case of the Talystep, which at ×1000000 requires a groove 0·03 μm deep, a specimen having an 0·3 μm groove calibrated from the lever is used to calibrate the ×100000 magnifications, and a final factor of 10 is then obtained by electrical calibration of the gain control, whence instrument calibration specimens for the Talystep can be calibrated, apparently to within about 2%.

Calibration of the AC part of roughness measuring instruments is effected by means of a calibration specimen having a grid of nominally repetitive grooves, which may be accurately calibrated by recording the profile digitally and computing the departure from mean line or other values ■

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