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Surface Topography Measurement and Analysis*

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Abstract

Topography is one of the most important of the physical characteristics of surfaces influencing their significant technical properties. The systematic study of the fine structure of surfaces only became possible when instruments with sufficient magnification to resolve the vertical structures became available. A résumé is given of current and prospective quantitative techniques for determining surface topographical properties. The topics of modelling and the interpretation of data which are mainly in the form of time series are discussed.

1. Introduction

Topography has a major influence on the functional properties of surfaces despite their complex physical nature in other respects. Electrical and thermal conductivity are critically dependent on the *true* area of contact; additionally, the actual nature of the topography determines the current carrying capacity; the mechanisms of friction (adhesive and/or ploughing) and wear (abrasive, adhesive, fatigue etc.) are influenced by topography; and bonding is a further example. The microstructure or roughness of surfaces often determines their macroscopic properties. Apart from the fields in which the significance of topography is already accepted, there is a growing number of topics where topography is becoming recognized as important: the efficiency of solar absorbers can be improved significantly by giving the surface an appropriate roughness and, as a result of ion implementation, changes in surface topography that alter physical properties can be brought about.

The study of the fine structure of surface topography became possible when instruments with sufficient magnification to resolve the vertical structures were developed. The introduction of precision stylus profiling instruments in the late 1920s made it possible to establish the nature of surface topography comprehensively and on a quantitative basis. Profilometers using a fine stylus are still the principal means for gathering detailed quantitative data. The subject has grown very rapidly: a bibliography by Thomas and King (1977) contains 651 entries. The first is dated 1921/22; for the 20 years 1921–41, 11 papers are listed, and for the 20 years 1957–77, there are 532.

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2. Measurement

The roughness range of magnitudes is a continuum in the height of vertical structures and their surface distribution, extending from heights and spacings measured in millimetres to tenths of nanometres. A wide variety of instrumentation has been developed to meet various needs. Digital techniques have influenced the development of stylus instrumentation to a marked extent and the newest generation is based on microprocessors.

Recent activity has centred on the use of light scattering and holographic techniques. There has always been an intrinsic interest in optical methods of measuring roughness, and this has generated a formidable literature: two recent reviews are by Welford (1977) and Vorburger and Teague (1981). Apart from these techniques there is a current need for practical transducers for the adaptive control of machining operations in automatic production processes. Two methods seem to have good prospects for general use, namely direct optical Fourier transformation in reflection (Thwaite 1979, 1980) and speckle pattern contrast (Sprague 1972). There are no practical devices available as yet, but the need for them in automatic control is acute.

Modern data logging techniques have made it possible to collect large quantities of data and a number of workers have recently developed apparatus for the three-dimensional mapping of surfaces (Snaith *et al.* 1981; Idrus 1981).

A class of instruments has been developed especially for the measurement of form. Roundness and straightness measuring instruments are used for the measurement of spheres, cylinders and other precision dimensional measuring tasks. The roundness instruments have a very accurate bearing. An arm attached to the bearing carries a stylus displacement transducer which remains in contact with the workpiece as the arm rotates. With the best of these instruments a truly round object can be measured to within 25 nm. The straightness instruments work along the same lines as the roundness devices but use a straight datum instead of a bearing. Combined roundness and straightness instruments are available for the measurement of the full form of cylindrical objects.

Non-contacting profiling techniques based on triangulation methods for the measurement of profiles with large amplitudes and long wavelengths (waviness) have many applications in industrial processes, such as rubber extruding, clay products, steel and building products. A review of these methods has been given by Loewen (1980) and a prototype instrument for measuring the roughness of rollers used in sugar milling has been described by Thwaite and Bendeli (1980). The principal methods of measuring surface topography are listed as follows:

(*a*) *Light Microscopy*

Optical microscopy. There are many microscopic techniques for the examination of surfaces: bright field illumination; dark field illumination; the Nomarski and other shearing systems, which give the contrast related to local shape etc.; and taper sectioning. The visual methods of greatest interest are the Schmaltz profile microscope and interference microscopy.

Schmaltz profile microscope. This technique is used for examining fairly rough surfaces in the range $0 \cdot 5$–$50\ \mu$m and is available commercially from a number of sources (Edensor 1965).

Interference microscopy. Both two-beam and multiple-beam systems are available. Instruments with magnification of $\times 750$ can give height differences by visual interpolation to better than $0 \cdot 05\ \mu m$. Other systems available are the Nomarski and shearing (Zeiss Epival Interphako) techniques (for a discussion of interference microscopy see Beyer 1974).

Table 1. Limitation on light scattering techniques

Technique	Limitation
Specular reflection	$R_q < \lambda$
Total integrated scatter	$R_q \ll \lambda$
Angular distribution of scatter	$R_q \ll \lambda$
Speckle contrast	$R_q < 0 \cdot 1\lambda$
Polychromatic speckle contrast	$\frac{1}{5}\lambda < R_q < \lambda^2/\Delta\lambda$[A]
Speckle correlation	$\lambda < R_q < 10\lambda$

[A] $\Delta\lambda$ is the bandwidth.

(*b*) *Light Scattering Techniques*

Many techniques have been investigated and, in the main, they give measures of the r.m.s. roughness R_q and are limited by the wavelength λ of the radiation used. These techniques are summarized in Table 1. Ellipsometry is another technique that has been partly investigated. Interference fringe contrast has also been suggested for $R_q < 0 \cdot 2\lambda$.

(*c*) *Profiling Instruments*

Contacting instruments. A profiling device using a sharp stylus attached to a displacement transducer to trace a surface is by far the most common instrument. Magnifications in ordinary commercial instruments go as high as $\times 200\,000$, and there are also low magnification instruments of $\times 10$ or so with long ranges. Most stylus instruments give a measure of roughness in terms of the arithmetic mean deviation R_a of the profile from a reference line. With this technique, even the finest stylus will not fully penetrate the grooves in the sample surface which ultimately (on the most sensitive ranges) limits the validity of the measurements.

To ensure reproducibility of results and consistency, it is necessary to standardize a number of features of the instruments in an arbitrary way. All major industrial nations, including Australia, have standard specifications which define parameters such as stylus radius and force, the minimum traversing length and the all-important bandwidth. Thomas (1982) has written a useful general introduction to stylus techniques.

Optical profiling. A few specialized methods have been developed which can be used in place of the ordinary stylus instruments (Mitsui and Sato 1978). Long range, low resolution devices have a variety of uses.

Ultra-high resolution profiling. At high resolutions it is natural to think of imaging devices such as transmission and scanning electron microscopes (TEM and SEM). These instruments along with interference microscopes do not readily provide detailed quantitative information on topography. The TEM can give resolutions of better than 3 nm and the SEM better than 10 nm, with some improvements in these values with the right specimen.

The prospect of obtaining fringe fields by the interference of electrons similar to those produced by visible light has been present for some time. A recent review of electron interferometry and electron microscopy has been given by Missiroli *et al.* (1981). Fig. 1 shows interferograms of glass surfaces due to Lichte (1980). Resolutions of 0·2 nm for sinusoidal objects with wavelengths of 1 μm have been reported.

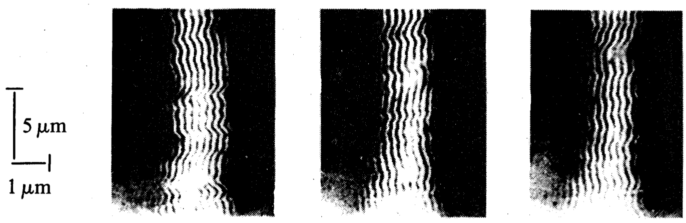

Fig. 1. Electron interferograms of optical polished glass surfaces. [Lichte (1980).]

Other very high resolution techniques are (i) stylus instruments giving a magnification of $\times 10^6$ (Moody 1968), (ii) a projected light spot profiling instrument with a resolution of 1 nm (Dupuy 1967), and (iii) a fine-point field emission instrument for use in a vacuum, known as the 'Topografiner' (Young *et al.* 1972). These high resolution profiling devices are very useful for the measurement of the thickness of thin films (King *et al.* 1972), and they rival the interferometric techniques.

3. Topography of Surfaces

Topography means the distribution of heights across a surface; microgeometry and roughness are substitute terms. A 'surface' is in reality a transition region going from the bulk properties of one material to those of another. The location of a surface depends upon the means used to detect it, and thus an operational definition is involved so that there can be major or minor differences in interpretation. For most technical surfaces examined by stylus profilometry the distinction is unimportant, but for the detection of dislocations, for example, the means of detection would be critical. Another important example is the difference in the location of a finely lapped surface, of the type used for precision length standards, as determined by optical interferometry in one case and by mechanical contact in another.

Over the range of surfaces there is a continuous spectrum of amplitudes and spacings of structures. Fig. 2 shows the profiles and amplitude spectra of (*a*) a periodic surface produced by diamond turning and (*b*) a random surface produced by grinding.

For many surfaces it is the distribution in heights of the highest asperities that may be of importance and this distribution is often claimed to be gaussian. The height distribution is sometimes skew, particularly when it results from sequential finishing techniques. As well as having a wide range of height distributions, the wavelength content of surfaces varies greatly.

The approximate ranges of asperity parameters for tribological surfaces are:

Density	10^2–10^6 mm^{-2}	Height	2·5–7·5 μm
Spacing	1–75 μm	Radii	10–20 μm
Slopes of sides	5°–10° (some $<2°$; others $>35°$)		

The density values show that asperity is a rare event, while slope values show that the 'aspect' of the structures is low.

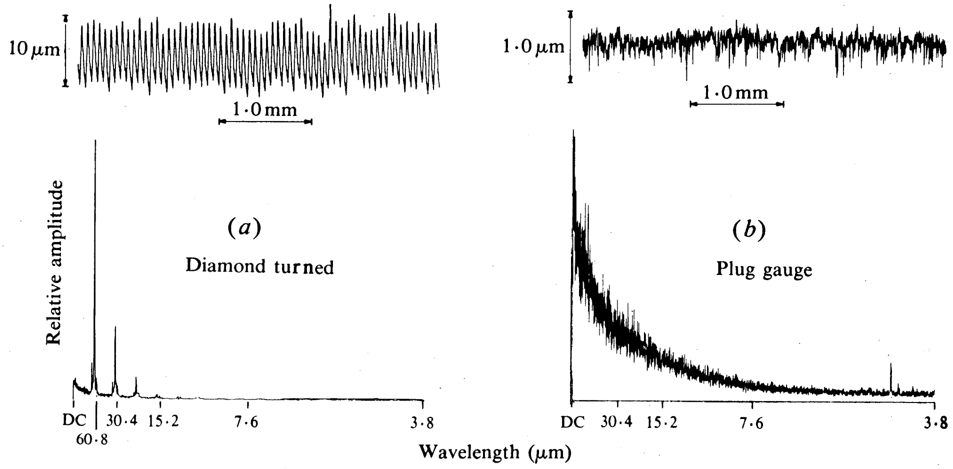

Fig. 2. Profile (*above*) and amplitude spectrum (*below*) of (*a*) a periodic surface produced by diamond turning and (*b*) a random surface produced by grinding.

4. Surface Models and Analysis

Surfaces are described in precise numerical terms with a multitude of ends in view: these range, for instance, from the highly complex problem of explaining and predicting the behaviour of frictional pairs to the more direct but practically important task of controlling the finish of production surfaces in an *ad hoc* manner. The topics involved are modelling, sampling problems (the relation of a restricted set of measurements to the surface as a whole), and numerical analysis of profile records (for a summary of numerical interpretation see Thwaite 1978).

(*a*) *Modelling*

The work of Longuet-Higgins (1957) in developing a model for sea surfaces established a basis for analysis in a comprehensive and rigorous manner. Greenwood and Williamson (1966) were among the first to propose random models for surfaces in order to derive their macroscopic properties from the microstructure. A *three-point asperity model* developed by Whitehouse and Archard (1970) was used by Onions and Archard (1973) to develop a theory of contact.

A comprehensive and accurate contact theory is a major goal of surface analysis and one that remains unsatisfied; a review of contact and modelling problems was given by Archard *et al.* (1975). The most satisfactory approach to date has been the development of the Longuet-Higgins work by Nayak (1971, 1973*a*, 1973*b*) and the application by numerous authors of a basic description of surfaces in terms of the moments of the *power spectral density function* $f(\lambda)$:

$$\gamma_n = \int_{-\infty}^{+\infty} \lambda^n f(\lambda)\, \mathrm{d}\lambda ,$$

for the nth spectral moment. Applications have included adhesion (Bush *et al.* 1975) and static contact (O'Callaghan and Cameron 1976).

The gaussian model has played a central role in deriving practical results but its appropriateness has often been questioned. It is argued in any case that for properties involving contact it is the distribution of the heights of the uppermost asperities that are important. A recent work (Adler and Firman 1981) developed a two-dimensional non-gaussian random surface model which gives χ^2 marginal height distributions for the surface.

(*b*) *Sampling*

One of the most interesting problems related to the quantitative measurement of surface topography is the relationship between the surface properties and measured profile properties. It is possible to classify surfaces into broad classes and, in some cases, to infer the relationship. The division into homogeneous and nonhomogeneous (stationary and nonstationary) is the fundamental division, with further breakdowns into isotopic and non-isotopic, deterministic and random, gaussian and non-gaussian. The extension from isotopic to non-isotopic surfaces presents few new problems but there is a large increase in complexity. The role played by nonhomogeneity in the topography of technical surfaces is still not clear; many large discrepancies in measurements of surface parameters reported in the literature may well be due to the specimens rather than instrumentation.

The relation between the surface ϕ^{s} and profile ϕ^{p} power spectral densities is given by (Nayak 1971)

$$\phi^{\mathrm{p}}(k_{\mathrm{p}}) = 2\int_{k_{\mathrm{p}}}^{\infty} \frac{k_{\mathrm{s}}\,\phi^{\mathrm{s}}}{(k_{\mathrm{s}}^2\,k_{\mathrm{p}}^2)^{\frac{1}{2}}}\,\mathrm{d}k_{\mathrm{s}},$$

with the somewhat less tractable expression

$$\phi^{\mathrm{s}}(k_{\mathrm{s}}) = \frac{1}{\pi}\int_{k_{\mathrm{s}}}^{\infty} (k_{\mathrm{p}}^2 - k_{\mathrm{s}}^2)^{\frac{1}{2}}\left(\frac{\phi''^{\mathrm{p}}}{k_{\mathrm{p}}} - \frac{\phi'^{\mathrm{p}}}{k_{\mathrm{p}}^2}\right)\mathrm{d}k_{\mathrm{p}}.$$

Here $k_{\mathrm{p,s}} = 2\pi/\lambda_{\mathrm{p,s}}$ are the propagation constants at wavelengths λ_{p} and λ_{s}, and

$$\phi''^{\mathrm{p}} = \partial^2\phi^{\mathrm{p}}/\partial k_{\mathrm{p}}^2, \qquad \phi'^{\mathrm{p}} = \partial\phi^{\mathrm{p}}/\partial k_{\mathrm{p}}.$$

(*c*) *Time-series and Numerical Analysis*

Since the bulk of data available for analysis is in the form of the digital ordinates of profiles taken at finite spacings, time-series and numerical analysis techniques are used, and their limitations are highly relevant. In estimating spectra all the usual restrictions apply (see e.g. Jenkins 1961). The variance does not go to zero as the record becomes longer; successive estimates of the spatial density are not correlated and result in the highly irregular fluctuations that appear in raw spectral estimates; also, the bandwidth times the variance is a constant. Smoothing and averaging or the use of spectral windows is essential.

As already mentioned in Section 3, estimates of the properties of the extremes are of particular importance and the numerical analysis for maxima and slopes in relation to the bandwidth of the data has been treated by a number of authors, principally Whitehouse (1974) and Whitehouse and Phillips (1978).

5. Conclusions

The topography is, of course, only one element in the characterization of a surface but one that, in a number of cases, can be considered virtually in isolation. It is a topic in which it is difficult to be definitive and the consequences of the *sparse asperity model* are still being worked out in detail. Despite this, our understanding has been at a level to positively influence practical technology for many years.

Stylus techniques have reached a high degree of perfection but suffer from the drawback that only a very small part of a surface is sampled at a time. The instruments are also delicate and not suitable for on-line use, although there have been recent reports of ruggedized stylus equipment (Webster and Kaliszer 1980). There is considerable interest in the development of a practical integrating optical technique both for adaptive control and day-to-day industrial roughness measurement.

Analysis for the important slope and asperity parameters has not progressed much beyond two- and three-point estimators and, for the most part, despite the major effort expended, the limitations imposed by sampling restrictions are only imperfectly understood.

The study of surface topography is a developing one with a variety of physical and mathematical content and a scientific and technical significance hard to rival.

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