Characterization of surface roughness

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Proliferation of redundant parameters for characterizing surface roughness is explained as a historical consequence of the predominating influence of instrument manufacturers over users. Problems of roughness characterization are introduced: high and low-pass filtering, transitional topographies, sampling error. The needs of three classes of user, the machinist, the researcher and the quality control engineer, are discussed. Three kinds of descriptor, namely statistical height, extreme-value height and texture are identified, and examples of each are defined and critically compared, with applications. It is suggested that a classification comprising average roughness, skewness, high-spot count and extrema density might suffice for many engineering purposes

The present proliferation of roughness parameters is at least partly the consequence of the history of surface roughness measurement. In many other fields, needs for measurement were perceived by users and under pressure from them instrumentation was developed to satisfy these needs. In roughness measurement, on the other hand, for many years the technical competence of the instrument manufacturers so far outstripped the sophistication of the users that the former were able to impose parameters on the latter whose definition owed more to their own convenience than to the users' real requirements.

The extreme-value parameters, for instance, which are so ill-adapted to measurement by analogue electronics, originally came into being because it was impossible to measure anything more useful with a Schmalz light-section microscope. The slit whose image was focussed on the surface with the instrument happened to be 0.8mm long, for reasons of optical convenience, so this figure became incorporated into national roughness standards as the preferred filter cut-off for stylus instruments. Subsequently the instrument manufacturers conveniently discovered that 0.8mm was the optimum cut-off[1], a claim never subjected to impartial scientific scrutiny. The average roughness parameter R_a, which has no functional significance whatever, is written into standards rather than the more useful root-mean-square roughness R_q because the integrating circuit which computes it is simpler. These examples suggest that it might be more profitable to examine the needs of the user. Before this can be done it is necessary to examine some of the possible pitfalls in surface characterization.

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Problems of roughness characterization

No list of roughness parameters can safely claim to be exhaustive, but references to a reasonably comprehensive list can be found[2]. Some order can be imposed on this list by returning to first principles. Whitehouse and Archard[3] showed that the statistical geometry of many random profiles, that is the distributions of slopes, curvatures, peak heights and so on, could be represented completely by only two parameters, the standard deviation of the height distribution R_q, and the correlation length β^* (see below). It was later show by Nayak[4] that this was a special case of a more general treatment in which the statistical geometry of a random surface could be represented by the first three even moments of the power spectrum of a profile of the surface, and this has been confirmed experimentally[5].

Unfortunately, it turns out that none of these parameters is an intrinsic property of a real surface. The numerical values of almost all parameters depend on the scale of measurement because of the phenomenon of 'self-similarity'[6] whereby real surfaces reveal new complexities in their structure as this is examined in finer and finer detail. It has been argued elsewhere[7] that this is an inescapable consequence of the mechanism of their formation.

The consequences may be expressed in terms of filter cut-offs. Stylus instruments usually have a range of high-pass filters whose cut-offs have numerical values prescribed in national standards.

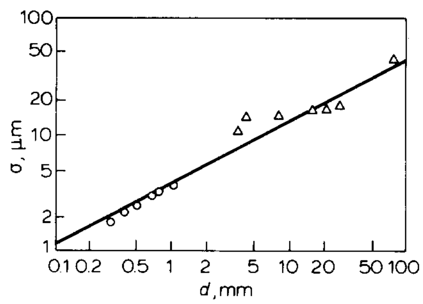

Fig 1 Variation of R_q with high-pass cut-off for a profile from a grit-blasted surface[9]. Solid line is best fit of slope ½

All height descriptors R_a, R_z or whatever, depend on the high-pass cut-off, and for many surfaces their values increase as the square root of the cut-off (Fig 1). Extreme-value height descriptors such as R_z depend also, if determined digitally, on the interval at which the profile is sampled by the analogue-to-digital converter (ℓ in Fig 4). If this sampling interval is decreased, for instance, a single peak may be resolved into two separate peaks, thus changing the value of R_z or whatever[8].

Most texture parameters such as slope and curvatures, on the other hand, depend solely on the low-pass cut-off. In digital systems this is fixed at twice the sampling interval (the so-called Nyquist criterion). It can be shown that for many surfaces the mean slope decreases as the square root of the sampling interval, while the mean peak radius of curvature increases as the 3/2 power (Fig 2). Correlation length, however, is extremely sensitive to the high-pass cut-off[9]. These difficulties have still not dawned on the committees responsible for drafting standards; the draft ISO standard[10], for instance, still talks about the "instantaneous slope of the profile".

0141–6359/81/020097–08 $02.00

Table 1 Summary of surface roughness parameters

Parameter name:	Symbol:	Definition in words:	Mathematical definition:	Digital implementation:
Statistical height descriptors				
Average roughness (Fig 4)	R_a	Average absolute deviation from mean line over one sampling length; this value usually averaged over several consecutive sampling lengths, depending on standard	$R_a = \frac{1}{L}\int^{L} \lvert z \rvert \, dx$	$R_a = \frac{1}{n}\sum_{i=1}^{n} \lvert z_i \rvert$
Root-mean-square (rms) roughness (Fig 4)	R_q	Root mean square deviation from profile mean over sampling length	$R_q = (\frac{1}{L}\int^{L} z^2 \, dz)^{1/2}$	$R_q = (\frac{1}{n}\sum_{i=1}^{n} z_i^2)^{1/2}$
Skewness (Fig 5)	Sk	Third central moment of profile amplitude probability density function, measured over sample length	$Sk = \frac{1}{R_q^3}\int_{-\infty}^{\infty} z^3 p(z) \, dz$	$Sk = \frac{1}{nR_q^3}\sum_{i=1}^{n} z_i^3$
Kurtosis (Fig 5)	K	Fourth central moment of profile amplitude probability density function, measured over sampling length	$K = \frac{1}{R_q^4}\int_{-\infty}^{\infty} z^4 p(z) \, dz$	$K = \frac{1}{nR_q^4}\sum_{i=1}^{n} z_i^4$
Extreme value height descriptors				
Ten-point height (Fig 4)	R_z	Mean separation of 5 highest peaks and 5 lowest valleys in 1 sampling length; peak (valley) defined as local maximum (minimum) above (below) profile mean line	$R_z = (\sum_{i=1}^{5} P_i - \sum_{i=1}^{5} V_i)/5$	Additional condition that $P_i > 0, V_i < 0$
Average peak-to-valley height (Fig 6)	R_z	Separation of the highest and lowest peak in a single sampling length, averaged over 5 consecutive sampling lengths	$R_z = \sum_{i=1}^{5} (P_i - V_i) / 5$	
Average roughness depth (Figs 4 and 6)	R_{3z}	Separation of the 3rd highest peak and 3rd lowest valley in a single sampling length, averaged over 5 consecutive sampling lengths	$R_{3z} = \sum_{i=1}^{5} ({}_3P_i - {}_3V_i) / 5$	
Ten-point mean roughness (Fig 4)	R_z	Separation of the 3rd highest peak and 3rd lowest valley in a single sampling length	$R_z = P_3 - V_3$	
Maximum peak-to-valley height (Fig 6)	R_{max}	Separation of the highest and lowest peaks in a single sampling length: largest value of this separation in 5 consecutive sampling lengths		

Standards satisfied:	*Applications:*	*Drawbacks:*	*Similar or related parameters:*
UK BS1134, Germany DIN 4768/1, Japan JIS B0601, France NF E05-015, International ISOR468, etc	In almost universal use for general quality control. Easy to define and measure, good general description of height variations. Numerically close to R_q	Insensitive to wavelength, to small changes in profile geometry, and to occasional high peaks or deep valleys. Not an intrinsic property of the profile, increases as the square root of the sampling length[13]	Identical to arithmetic average aa and centre-line average cla
USA MIL - STD - 10 (1949)	As for R_a, but has extra theoretical significance as the standard deviation of the height distribution	As for R_a	Identical to the standard deviation σ of the profile height distribution. The variance σ^2 is the zeroth moment m_0 of the profile power spectrum[4]
None	Easy to define and measure, it describes the snape of the height distribution and is sensitive to occasional deep valleys or high peaks. A symmetrical height distribution, ie with as many peaks as valleys, has zero skewness. Profiles with peaks removed or deep scratches have negative skewness. Profiles with valleys filled in or high peaks have positive skewness. Has been used to characterize running-in[15–17] and to correlate drag coefficients of rough surfaces[18]	Large scatter due to random sampling[8]; skewness values of less than ± 1 probably not significant	
None	Has been used to characterize running-in[15,17] and to correlate drag coefficients of rough surface[18] A Gaussian height distribution has a kurtosis of 3. If $K<3$ distribution is said to be platykurtic and has relatively few high peaks and low valleys. If $K>3$ distribution is said to be leptokurtic and has relatively many high peaks and low valleys	Large scatter due to random sampling[8]; although independent of skewness in theory, a change in skewness due to running-in also changes the kurtosis[17]. Deviations from Gaussian (=3) of less than ± 2 probably not significant	
UK BS1134, International ISO R468	More sensitive to occasional high peaks or deep valleys than R_a. Useful for quality control if these are important	Large scatter due to random sampling, also dependence on sampling interval[8]; lengthy to compute, as entire array of peaks must be sorted in order	Average peak-to-valley height, qv
Germany DIN 4768/1	As for ten-point height	Scatter and dependence on sampling interval should be less serious than for ten-point height	Ten-point height, qv; mean apparent amplitude (maa) is similar but averaged over 13 consecutive 50mm sampling lengths[19]
None	As for ten-point height	As for ten-point height	Ten-point mean roughness, qv
Japan JIS B 0601	As for ten-point height	As for ten-point height	Average roughness depth, qv
Germany DIN 4768/1, ISO R468	Sensitive indicator of high peaks or deep scratches	Large scatter due to random sampling[8]	Average peak-to-valley height, qv

Texture descriptors

Parameter name:	*Symbol:*	*Definition in words:*	*Mathematical definition:*	*Digital implementation:*
High-spot count (Fig 7)	*HSC*	Number of excursions above profile mean line per unit length, measured over sampling length		Excursion counted if $z_i < 0$ and $z_{i+1} > 0$ (4 excursions in sketch)
Mean high-spot spacing (Fig 7)	S_m	Mean separation of excursions above profile mean line, measured over sampling length		Reciprocal of high-spot count
Mean slope (Fig 7)	None	Mean absolute profile slope over sampling length	$m = \frac{1}{L} \int^L \lvert\frac{dz}{dx}\rvert\, dx$	$m = \frac{1}{n-1} \sum_{i=1}^{n-1} \frac{z_{i+1}-z_i}{\ell}$
Average wavelength	λ_a		$\lambda_a = 2\pi R_a/m$	
Mean peak radius of curvature (Fig 7)	None	Mean reciprocal curvature of all peaks in sampling length; peak defined as local maximum	Peak curvature $C_p = \frac{d^2z}{dx^2}, z_{-x} < z_x > z_{+x}$	$C_{pi} = \frac{2z_i - z_{i-1} - z_{i+1}}{\ell^2}$, $z_{i-1} < z_i > z_{i+1}$ Mean peak radius of curvature $= \frac{1}{n-2} \sum_{i=1}^{n-2} \frac{1}{C_{pi}}$
Correlation length (Fig 8)	β^*	Distance over which an exponential autocorrelation function a decays to 10% of its initial value	$\beta^* = 2.3/a$ where $\rho(\tau) = \exp(-a\,\tau)$	
Density of extrema	D_e	Number of local maxima and minima (peaks and valleys of any height) per unit length of profile		
Bandwidth parameter	α		$\alpha = m_0 m_4 / m_2{}^2 = (D_e/D_0)^2$	
Topothesy	None	Decay constant of inverse-square profile power spectrum	$k = R_q{}^2 / \lambda_0$ where R_q is measured at cut-off λ_0	

All the foregoing discussion applies to surfaces which have Gaussian height distributions. Many important kinds of engineering surfaces are formed by two or more consecutive processes, where a finer finish is superimposed on an initial coarse finish. This will apply to any surface which has undergone running-in or wear. Such 'transitional' topographies[11] can often be represented as the superposition of two different Gaussian height distributions (Fig 3). The characterization of these topographies requires extra information (see below).

Finally it must not be overlooked that roughness parameters, being necessarily imperfect statistical representations of very complex geometrical structures, are more prone than many other physical measurements to scatter due to random sampling[8]. It is fruitless for theoreticians to argue or quality control engineers to prescribe differences of one or two percent when sampling error can amount routinely to 20%–50% or more about the mean of the quantity being measured.

Users' needs

The simplest kind of requirement is that of the user who runs, say, a

Standard satisfied:	Applications:	Drawbacks:	Similar or related parameters:
None	As its name implies, it describes the number of high regions in a length of profile, which is related (in a complicated way[20]) to the number of high spots in a given area of a bearing surface	Insensitive to short wavelengths	Identical to zero crossing density D_0[3] from which moments of the power spectrum can be found; reciprocal of mean high-spot spacing S_m
None	As for high-spot count	Insensitive to short wavelengths	Reciprocal of high-spot count
None	Friction[21], elastic contact[22], plastic contact[23], reflectance[24], fatigue crack initiation[25], hydrodynamic drag[18], spalling[26] and hydrodynamic lubrication[27] are sensitive to slope	Depends on sampling interval[3]	Second moment of power spectrum m_2 related by $\pi m^2 = 2m_2$[3]
None	Has been suggested for quality control[27]. Should be sensitive to certain kinds of wear or running-in where short wavelengths are removed	Numerical value depends on sampling interval	
None	Elastic contact[28]. Has been used to characterize wear[29,30] and lip seal performance[31]	Strongly dependent on sampling interval[13]	Related to mean summit (ie asperity) radius of curvature and to fourth moment m_4 of profile power spectrum[4]; mean valley radius of curvature is defined similarly
None	For profiles with an exponential autocorrelation function and a Gaussian height distribution the statistical geometry, eg mean slope and peak curvature etc, is completely characterized by the correlation length and R_q[2]. Has been used to characterize anisotropy[32] and wear[33]	Highly sensitive to long wavelengths[9]	Correlation distance. These terms are often used interchangeably and the decay distance is defined by different workers as 50%, 5% or $1/a$
None	Together with zero crossing density D_0 (high spot count) completely characterizes statistical surface topography[4]	Dependent on sampling interval	
None	A measure of the range of wavelengths present in a surface profile[4]; has been used to characterize hydrodynamic drag[34]	For certain spectra α is actually independent of bandwidth	
None	Characterizes completely the statistical topography of surfaces with this form of power spectrum independent of cut-off or sampling interval[7]		

jobbing machine shop working from drawings supplied from different national sources, and who simply wants to make sure that his output conforms to the appropriate specification. All he needs to know is that the parameters which he uses conform to the standards specified on the drawings. Although instrument manufacturers are surprisingly coy with this information, they presumably know themselves what they are selling, and he should be able to extract an appropriate assurance from them.

The next simplest is the case of the research worker who needs an instrument which will measure parameters which can be used as input to theories of rough surface interaction, in say tribology or contact mechanics. Here at least he knows or thinks he knows what parameters he needs; the difficulties are likely to be those of appropriate functional filtering, which is more an educational problem than an instrumental one. A classic example of this kind of misunderstanding is the comparison of roughness, measured at a standard 0.8mm cut-off, with lubricant film thickness in a bearing contact whose greatest horizontal dimension is a few microns. The resulting ludicrous values of so-called 'D-ratio' have inspired numbers of solemn theoretical papers in an attempt to explain them.

The most difficult case, and probably the most general one, is that of the engineer who has a quality control problem. All he knows is that his product will not work very well unless its roughness is 'right'. Specifying a range of values of R_a, say, does not lead to reliable results; some products within the tolerance band still fail, others outside perform satisfactorily. This indeed is why he is thinking of purchasing a multi-parameter system. But what extra parameters does he need and why?

A look at Table 1 (pages 98–101) may give him some help. Only a fraction of the vast total number of parameters proposed in the literature can be covered in a paper of this length, and the list selected comprises some of the most commonly encountered parameters and the most useful ones (not, unfortunately, the same thing). They are divided into three categories; height descriptors of a statistical nature, that is ones which give some average value of the behaviour of a profile in a plane normal to the surface; extreme-value height descriptors, that is ones which depend on isolated events; and texture descriptors, that is ones which describe the variation of the profile in a horizontal plane. No attempt has been made to treat descriptors which are functions rather than single parameters, eg bearing area curve, power spectrum, autocorrelation function etc, for which the reader is referred to the specialist literature.

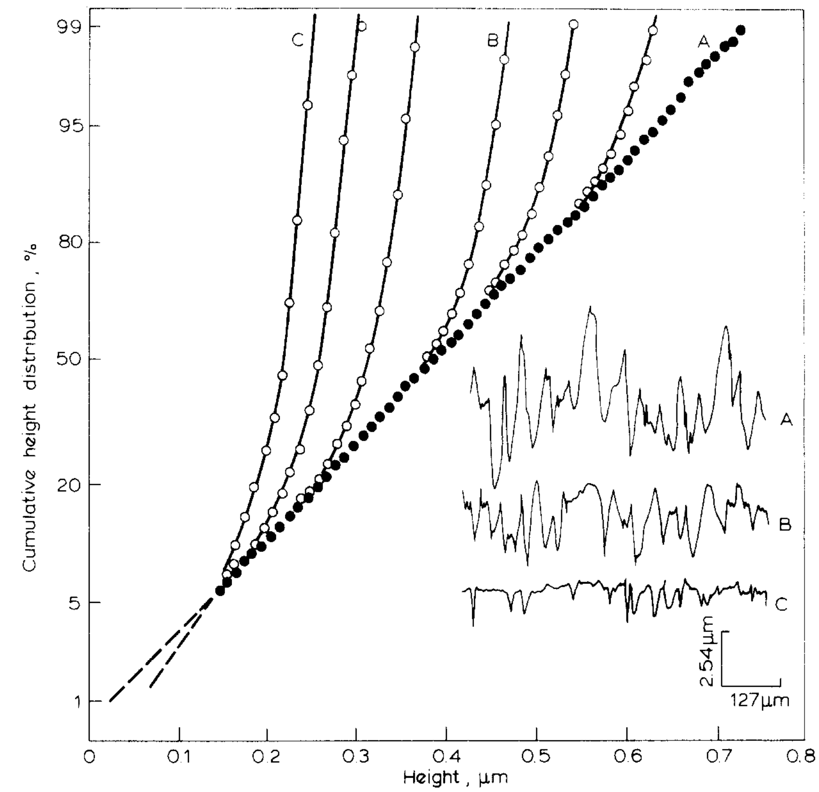

Fig 3 Transitional topography of a surface worn by lubricated sliding[11] plotted on a scale which shows a Gaussian distribution as a straight line

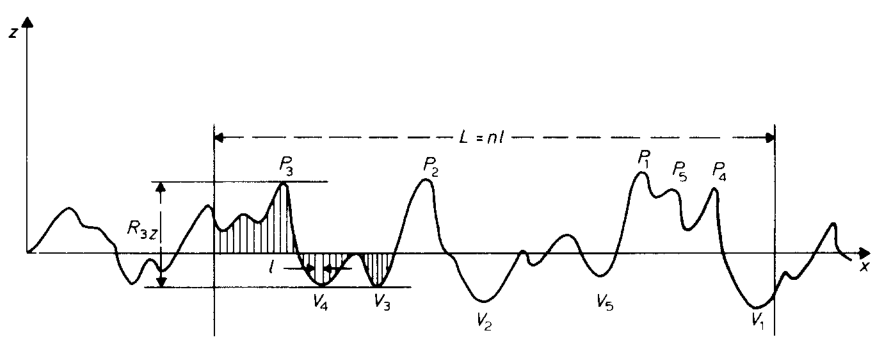

Fig 4 A single sampling length

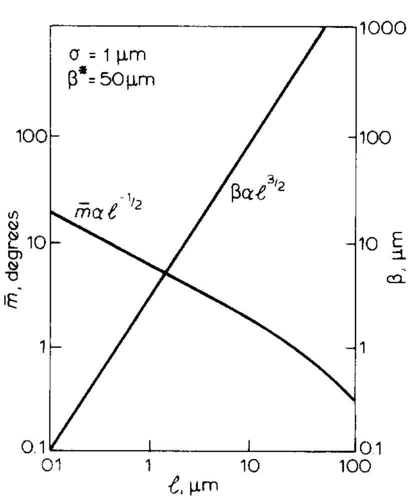

Fig 2 Theoretical variation of mean absolute slope m *and mean peak radius of curvature β with sampling interval ℓ for a profile of roughness 1 µm and correlation length 50 µm[13]*

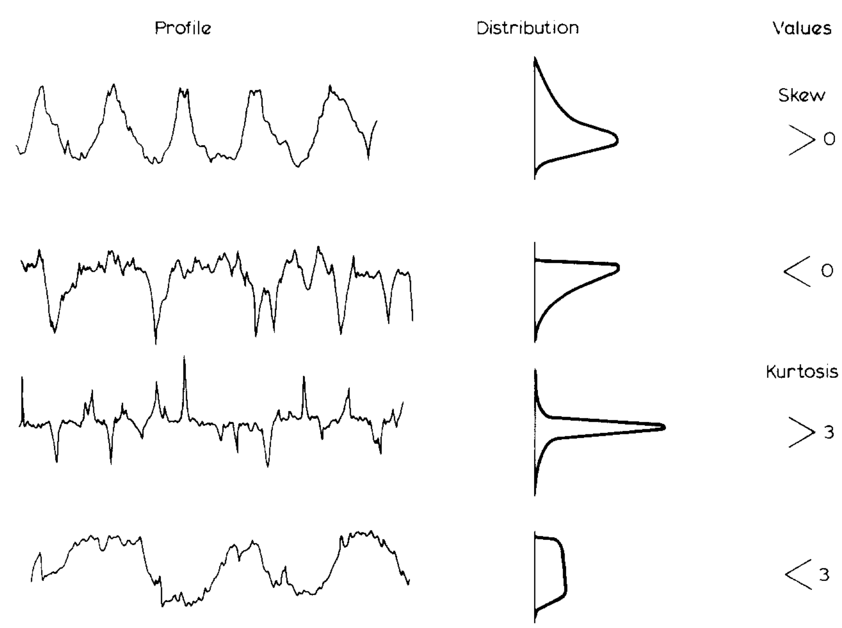

Fig 5 Profiles and their associated height distributions showing the effects of skewness and kurtosis[14]. Top to bottom: positively skewed; negatively skewed; leptokurtic; platykurtic

Discussion and conclusions

It is apparent that many of the parameters described are redundant or irrelevant or both. There seems no point in measuring both R_a and R_q, for instance, as their numerical difference in practice is usually smaller than the measuring error. Again, there seems little to choose among the extreme-value parameters to justify the hairsplitting involved in deciding between three different definitions of R_z. Looking at the texture parameters, the most popular descriptor, the correlation length, is the hardest to define, the most sensitive to filtering and the most tedious to compute.

In a previous discussion of running-in[12], it was concluded that for profiles with a Gaussian height distribution it would suffice to specify an average roughness and some measure of the texture. The high-spot count and density of extrema seem the most promising candidates for the latter; they are unambiguous, easy to measure, and together with R_q they determine the entire statistical geometry of isotropic surfaces, including slopes' and peaks' curvatures. If the surface has a lay then all these measurements are needed in two directions, along the lay and across it. In addition some measure of the symmetry of the height distribution is required to detect and quantify the presence of a transitional topography. The obvious candidate for this is the skewness; it is unambiguous, easy to measure and, unlike the extreme-value parameters, it is relatively insensitive to occasional deep scratches or other irrelevant surface events.

To a user starting with no preconceived ideas, then, it is recommended that he should start by establishing the range of surface wavelengths relevant to his particular application and then select appropriate high-pass and low-pass cut-offs ('functional filtering'[13]). If he has no easy way of initially establishing this range he may as well use the range programmed in by the manufacturer to begin with. Using the chosen cut-offs, he should measure R_a, D_o, D_e and skewness, enough times to get consistent results, and in more than one direction if appropriate. Armed with this information for each surface measured it should be possible with luck to see some pattern emerging of relationships between measurements and engineering function.

However, the ultimate arbiter must be the user. If he finds that in his experience the most effective parameter for his purpose is the difference between say the fifth highest peak and the seventh lowest valley within a millimetre, then this is the parameter which he should use, and he should harass the instrument manufacturer until it is provided. Engineering is primarily about solutions, not about explanations, and it is for the instrument manufacturer to respond to market pressure, not for the user to justify his preference.

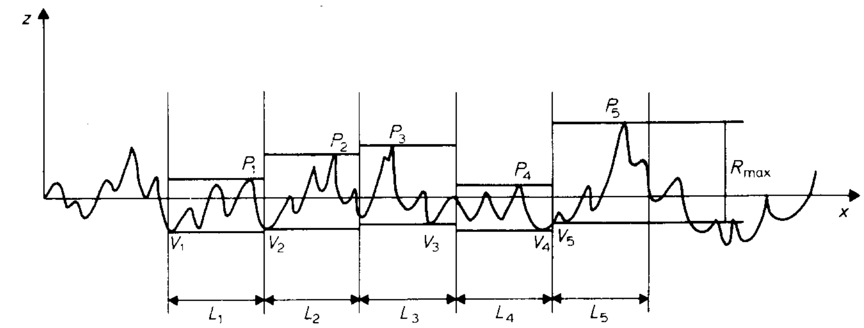

Fig 6 Five consecutive sampling lengths

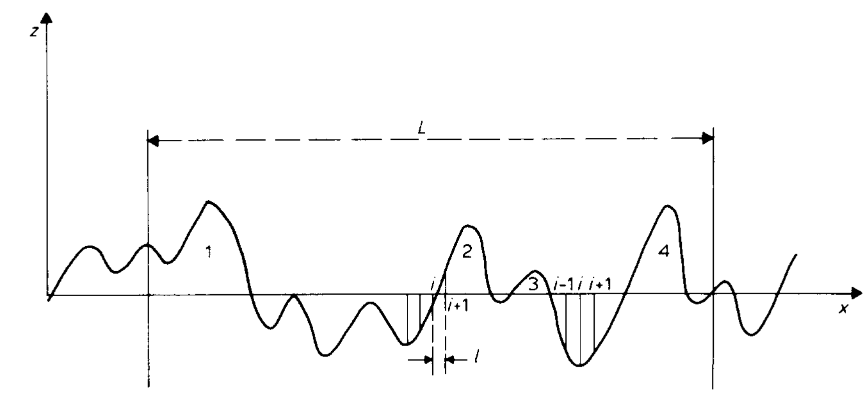

Fig 7 High-spot count and peak curvature

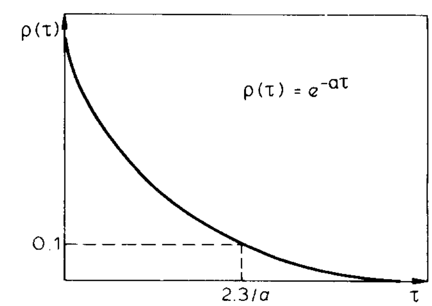

Fig 8 Exponentially decaying autocorrelation function and correlation length

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Book reviews

Optics in Metrology and Quality Assurance

SPIE Proceedings Vol 220

The seminar reported in these proceedings was planned to present a series of overview tutorial papers on optical technology as used in metrology and quality assurance and to complement these with in-depth papers on specific application areas, a total of 25 papers. It being impractical to comment on all these papers in a short review, only those which particularly caught the reviewer's attention will be discussed.

The first session, entitled 'Techniques Overview', was to have set the scene by reviewing applicable optical techniques. In practice, it took the form of a general session with papers describing specific systems which in no way encompassed the full range of optics in metrology. Amongst the more notable papers were one on the role of colour in industry with emphasis on the measurement of visually perceived colour and a second describing a new digital interferometer, DIAD. A further paper discussed the measurement of small dimensions (submicron) but the methods described were more relevant to a national standards laboratory than the more general situation to be found in production.

The 'Distance Surface and Profile Analysis' session covered a limited field of specific applications, ranging from the evaluation of windscreen optical distortion utilising a raster-scanned laser probe beam in conjunction with retroreflecting screen and holographic lenses, through the testing of aspheric surfaces by conventional interferometry and a companion paper on direct phase measurement in a spherical Fizeau interferometer, to the application of Fraunhofer diffraction methods in the measurement of percentage open-area of perforated sheet materials.

In the session entitled 'Circuit inspection' optics played a back seat to software-hardware dominated measurement systems. For example, a paper on the automated inspection of multilayer printed circuit boards using a novel 38 silicon cell detector array concentrated primarily on the logical decisions required of the software to detect line-breaks, line thinning, excess copper etc. The authors of two further papers clearly had a misconception as to the meaning of accuracy, confusing it with precision of repetition, and a total disregard of the necessity to use reference standards in the confirmation of absolute measurements of dimensions. Other papers discussed infra-red testing for circuit board defects and the use of a high resolution (10 000 TVL/M) vidicon to image an entire 50 mm by 50 mm substrate and compare it with a stored reference image.

Despite its title of 'Imaging and Image Processing' the fourth session included a major review paper on industrial robots and their uses. Starting with basic robotics and the requirements for controllers and manipulators the paper proceeded to describe simple robots, then medium technology and finally sophisticated industrial robots. Current applications in press loading, die casting and arc welding were discussed and the paper closed with a section on advanced robotics and future developments. The session did include some papers in line with its title, including one on the application of a variety of techniques to the non-destructive examination of micro-balloon targets, as used in a laser fusion program.

To summarize, these proceedings fail to present the promised comprehensive review of optics in metrology but nonetheless do contain a few interesting papers.

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Published, price $39, by SPIE, PO Box 10, Bellingham, Washington 98225, USA