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Developments in 3D surface metrology

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Abstract

Over the past eight years the subject of 3D surface metrology has developed from something of a novelty to a position where it has now become a crucial tool in the characterisation of engineering surfaces across a broad range of applications. It is widely accepted that the nature of the topography of a surface has a significant influence on the efficiency and functional performance of the surface. The functions that have been identified in various studies include wear, friction, lubrication, corrosion, fatigue, coating, paintability, etc. It is also increasingly being recognised that in order to fully study and control surface manufacture to enhance the above applications, studies need to be carried out from a 3-D perspective. Until recently however, the vast majority of research, industrial applications and national and international roughness standards were based on 2-D measurement techniques. It is now recognised that the characteristics of surfaces cannot be completely interpreted in some cases without 3-D information and many models established for understanding surface performance based on 2-D profiles have been unsuccessful. A number of key research groups have been working in this area in an effort to produce definitive 3D surface roughness standards. This paper reviews the most recent work in the field of 3D surface characterisation undertaken by the authors as part of a European multi partner project and outlines the development towards a 3D surface roughness standard.

1.0 Introduction

The assessment of surfaces using two dimensional surface profiles has been employed since the early nineteen thirties. In those early days of the development of new measurement techniques, engineers had come to the conclusion that they needed to understand more about surfaces to be able to judge how they interact.

In the 1930's transducer technology was limited to mainly mechanical devices which often involved intricate pivots, linkages and springs. The resulting 2D trace produced on a smoked screen was a representation of the differentially magnified surface, formed as a circular function, from which some simple estimations of amplitude and hence roughness could be made.

As the subject progressed further, combined analogue/mechanical devices were developed. As a consequence of mechanical technology and simple analogue valve driven electronics, the early instruments were only capable of measuring and displaying profile information with numerical data obtained by averaging the signal obtained from the movement of the mechanical stylus. The resulting average roughness parameter eventually became an accepted measure of a surface. The assumption was that the trace data was taken from a part of the surface from which topographical features were representative of the surface as a whole. This parameter, sometimes in partnership with an extreme value parameter, peak to valley height, became embodied in standards developed in a number of countries and are known as the average roughness Ra, and peak to valley height Rt. Unfortunately the value of the average roughness and peak to valley roughness had a very limited value in relating the surface to its functional effectiveness. Their primary use was in process monitoring and control.

1.1 Development of Surface Parameters

The early parameters were useful, as a means of communication between design, manufacture and its control and between a supplier and a customer of components and products. These parameters were and are still widely used as a bench mark for manufacture and surface tolerance specification on engineering drawings. A serious and significant feature of the limitation of these early parameters was that they had no relevance to the application of the surfaces to their functional performance and functional requirements. It can be shown that a range of surface generation processes can yield surface roughness values (Ra) of the same or similar value despite clear differences in the true 3D surface topography and when clearly the differing surfaces have differing functional properties.

The parameters' (Ra and Rt) limitations were such that even by the nineteen forties, engineers and designers were already looking for better ways to describe a surface. The introduction and continual improvement of computers allowed engineers to develop in an unstructured way numerous numerical parameters until eventually, by the 1980's over one hundred primary descriptors had been developed and were described in numerous national standards. Many of these parameters were poorly defined and of very limited use This explosion in parameters, was aptly defined as the "parameter rash" by Whitehouse[1].

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It is now recognised that the characteristics of surfaces cannot be completely interpreted, in the majority of cases, without 3-D information and that many models established for understanding surface performance based on 2D profiles had limited success [2,3,4]. The discrepancy between 2-D surface models and experimental evidence led many to begin to take the 3-D approach more seriously.

The **3-D approach** has a number of clear advantages over **2-D practice** -

- *The 3-D approach comes closer to describing a "real" surface and the parameters derived posses a greater functional significance*
- *The 3-D technique allows areal parameters to be derived for the first time, e.g., texture "strength" and direction, material and void volumes, etc..*
- *Since the 3-D technique takes data from an area rather than a trace, the parameters have a greater statistical significance and less variation[5].*
- *3-D measurements are visually more effective as a characterisation tool.*

Research into 3D surface topography was conducted by a small number of research groups in both the stylus/optical community and this work showed the scope of the technique. In early 1989 the E.C. funded a BCR project aimed at developing an integrated approach to topography characterisation [5]. The results of this project were discussed at length in several EC workshops and conferences[6,7] and the consensus of the panel of international experts was that it formed a strong basis for further work which could lead to standardisation. In 1998 a second E.C. funded project was instigated this time with a far larger industrial input.[8] The aim of this project is to provide a practical basis for the previous, largely theoretical, study with the hope of producing a draft standard for 3D surface measurement and characterisation.
In spite of the inherent advantages, *no 3-D topography standard currently exists*, though ISO and ANSI/ASME have begun preliminary consideration of a standard. Industry is faced with the situation where currently 3-D measurement is being carried out using haphazard modifications of existing 2-D techniques. To develop a standard, significant work, based on the foundation laid by the previous EC project[6] needs to be carried out.

2.0 3D Surface Roughness Parameters

To avoid the situation in 3D surface measurement of the "parameter rash" it is widely recognised that the number of surface numerical descriptors (parameters) should be kept to a minimum or at least a primary set or suite of parameters should be established. The results of the initial and present sponsored E.C. projects has produced a basic suite of parameters for the characterisation of surface roughness in 3D, Table 1.

Table 1 Primary set of 3D surface roughness parameters

Amplitude Parameters	
Sq	Root-mean square deviation of the surface (μm)
Sz	Ten point height of the surface (μm)
Ssk	Skewness of the surface
Sku	Kurtosis of the surface
Spatial Parameters	
Sds	Density of summits of the surface (mm^{-2})
Str	Texture aspect ratio of the surface
Sal	Fastest decay autocorrelation length (mm)
Std	Texture Direction of the surface (deg)
Hybrid Parameters	
$S\Delta q$	Root-mean square slope of the surface(μm/μm)
Ssc	Arithmetic mean summit curvature (μm^{-1})
Sdr	Developed surface area ratio (%)
Functional Parameters Characterising bearing and Oil Retention Properties	
Sbi	Surface Bearing index
Sci	Core Oil Retention Index
Svi	Valley Oil Retention Index
Sm	Material volume (μm^3/mm^2)
Sc	Core Valley Volume (μm^3/mm^2)
Sv	Deep valley volume (μm^3/mm^2)

The primary parameter set is split into four groupings of parameters: amplitude parameters, spatial parameters, hybrid parameters, and functional parameters.

The amplitude parameters are closely based upon their 2D equivalents and essentially quantify surface heights Sq and Sz and the surface height amplitude distributions Ssk and Sku. It should be noted that a 3D equivalent of the Ra parameter has not been included but has been replaced by Sq based upon the more statistically relevant Rq[6], figure 1.

The spatial parameters are designed to asses 3D aspects of the surface texture and lay, they assess the peak density, texture strength and dominant texture direction. These parameters are particularly useful in distinguishing between highly textured and random surface structures. For example a surface with a well defined lay tends to have high values of texture aspect ratio, a short fastest autocorrelation length and a well defined texture direction. figure 2. These parameters are highly sensitive to sample spacing during data collection.

The hybrid parameters are parameters based upon both amplitude and spatial information They define numerically, hybrid topography properties such as the slope of the surface, $S\Delta q$, the curvature of high spots, Ssc and the interfacial area, Sdr. The parameters having particular relevance to the contact properties both electrical and thermal, sealing properties, wear and optical reflectance properties of a surface [9]. These parameters are again highly dependant on the data sample spacing.

The functional parameters attempt to assess the functional topographical features of the surface through analysing material volumes, Sbi, and void volumes Sci, Svi via dimensionless indices or through direct volume calculations. The rationale behind the parameters is to split the surface into three height zones, the peak zone, the core zone and the valley zones and then to make volume calculations based on the three zones. For example, an automotive bearing surface which needs a good load bearing capability and good lubrication retention will have a high material volume, Sm, and a high valley volume, Sv, figure 1, whereas a seal type surface where sealing properties need continuous surface ridges, will have a low material volume and a large core volume, Sc.

2.1 Novel Areal Assessment Techniques

Further development of areal parameters is progressing on two fronts. Improving the definition and hence robustness of the parameters defined in the original integrated suite of surface descriptors and also the development of new parameters which provide more comprehensive, tribology related descriptors which yield more useful information on such important aspects as lubricant reservoirs, and valley connectabilty. In the area of contact mechanics and tribology the shape of the contacting asperities are also important, not only in their "as prepared condition", but also as they will appear, deformed, under some form of loading. Topographical fundamentals such as features defined as saddle points, ridges, valleys, peaks and pits are critical to tribological interaction and need analytical techniques which define their nature.

The terms used above are not new, many have been well used in other fields where topography has been recognised as significant for many years. These alternative fields include cartography, which has specific uses in map preparation, architecture and in military logistics. Hence some of these well used techniques, derived from these fields are currently being investigated with the intention of employing the more generally useful concepts in the areas of tribology and contact mechanics and moving away from solely statistically based parameters, to a position where the surface is constructed as a single function rather than discrete points. These new analytical techniques consider the surface as a continuous function and split the surface into maximum and minimum slope zones terminating at saddle points, peaks or pits and bounded by valleys and ridges. Mathematical procedures have been developed which allow the significant topographical events to be combined and the insignificant events to be "pruned" leaving

only functional important features. The process can be described as 3D motif combination, figure 3.
As a consequence of these current developments it is believed that the future first issue of the three dimension surface characterisation standard may include some of these derivatives

3.0 Filtering Techniques for 3D Surfaces

A vitally important consideration for 3D characterisation must be the appropriate separation of surface components in terms of roughness, waviness and form as well as multi-scalar topographical features which underpin the value of the information conveyed by the many parameters.

Filtering is a natural way to insulate specific bands of information from the surface by breaking down the signal in the frequency domain. The great advantage of filtering is that it does not assume the general shape of the surface as any particular waveform. It takes the waveform as received from the measuring instrument and decomposes it, unlike least square polynomial curve fitting which can distort the residual signal if the order of the polynomial is poorly specified in relation to the original shape of the surface.

For 3D surface characterisation, Gaussian and zonal filters can be used as means of extracting the roughness and waviness[6]. Similar to the linear phase filter of 2D characterisation methods, both the rough surface and wavey surface can be obtained from a single filtering procedure without any phase distortion. The Gaussian filter is ideally suited for smoothing the surface features. The zonal filter has good frequency selectivity and is therefore suggested for use in situations which require strict frequency selectivity. The use of the Fast Fourier Transforms is strongly recommended to implement these filtering procedures due to the fact that FFT is easy to perform with high computational efficiency.

The above filtering techniques are all strongly based on an assumption that the micro-geography of the surface is composed of similar sinusoidal waveforms with different wavelength. In this case, surface filter procedure is simply the breaking down of a surface signal from which the form has been removed, into a series of harmonic contents, then reconstructing roughness and waviness respectively by using convolutions or inverse FFT. However, a real surface consists of different waveforms, which not only include sinusoids with defined frequencies, but also some multi-scalar peaks, pits and scratches with very little, or even no prior frequencies. Therefore, using the above filtering process, some significant topographical features of a surface will be average out, so that the output signal may include some incorrect information if different areas of a manufactured surface are checked. This is especially likely when the surface is produced by a sequence of manufacturing processes such as highly polished precision surfaces. Moreover, when the surface metrology extends to nano-surface characterisation, it is extremely difficult to say that the nano-surface obeys Gaussian Distribution rules. At the present time there is considerable effort being devoted to improving the understanding and methods of filtering to allow for effective dominant feature separation.

Future research into filtering techniques will be focused on fields, such as the multi-scalar functional surfaces, nano-surface analysis and robust filtering techniques. An anticipated application of wavelet analysis has emerged in three-dimensional surface metrology assessment. Wavelet analysis can be used to decompose a surface signal into the scale-space, without an assessment of frequency content of the original signal. In this case, the surface topography can be interrogated via a flexible transmission bank according to intended functional information which is required to be drawn from it. The roughness, waviness and form information involved in surface topography are separated and recovered respectively. The multi-scalar functionally relevant topographical features are identified and captured. The main difference between wavelet analysis and classical Fourier analysis is that Fourier analysis is a breakdown of a signal into a series of harmonic content, then this space-based information is transferred into frequency-based information. The limitation of Fourier analysis is that it can only identify frequency events over space without any information about local position. Wavelet analysis can overcome this problem. In wavelet analysis, the space-based information is then transferred into scale-based information, which provides not only the frequency events of the original signal but also keeps their location properties completely identified. Another useful property is that there is no distortion of the data boundary. As a result, specific topographical features can be identified with very little or no prior frequency information. Due to this ability, wavelet analysis will become a very powerful tool in surface texture analysis in the future. It is possible that wavelet analysis will become a general surface filtering method and it will be used in primary roughness separation through to topography pattern recognition. [10], Figure 4 shows the topography of a polished replacement hip joint surface, large deep scratches and pits which are functionally significant need to be identified. Figure 4b shows how the wavelet filter has removed the form deviation and the high frequency roughness components

Robust filtering is the evaluation of the roughness of multi process surfaces such as plateau honed cylinder bores and is critical to the implementation of 3D surface analysis techniques. These surfaces result from a combination of rough machining process and final precision machining designed to process only the outer layers of the surface. The final roughness obtained is not subject to normal random error assumptions and is significantly skewed by the influence of outliers in the data resulting from overlaying machining processes. Robust filters are being developed which suppress the influence of the outliers. The filters weight the data processed giving a higher weighting to the data considered to be of a higher precision and a lower weighting to the outlier data. In this way data from processes such as plateau honing can be successfully filtered [8], figure 5.

4.0 Contents of the Proposed Standard

The contents of the proposed new standard therefore should contain all the elements which are essential to the user and the instrument manufacturer. As a consequence the standard will include the following features;-

1. Parameters and their complete definitions
2. Indication of their functional usefulness in the different fields.
3. Examples of visualisation techniques and their manipulation.
4. Procedures for instrument and software verification.
5. Filtering in its widest sense.
6. The relationship between 3D surface parameters and 2D parameters.
7. A well defined data file format.

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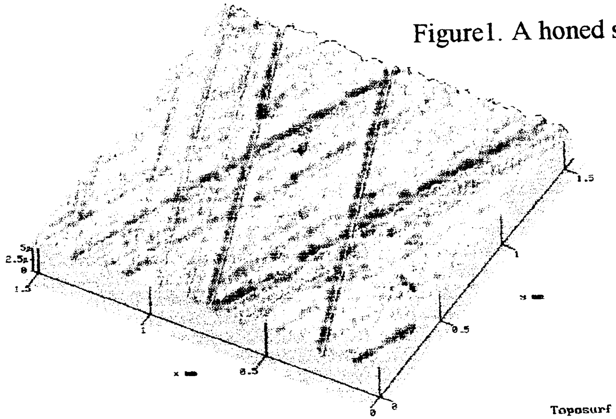

Figure1. A honed surface

Sq 0.84μm; Sz 6.09μm; Ssk -0.69; Sku 3.84; Sds 5.22x10^2 mm^{-2}; Str 0.085; Sal 0.024mm; Std 22°; SΔq 0.088; Ssc 9.07x10^{-3} mm^{-1}; Sdr 0.38%; Sbi 0.754; Sci 1.17; Svi 0.184; Sm 3.86x10^{4}μm^3/mm^2 ; Sc 7.80x10^{5}μm^3/mm^2; Sv 1.55x10^{5}μm^3/mm^2

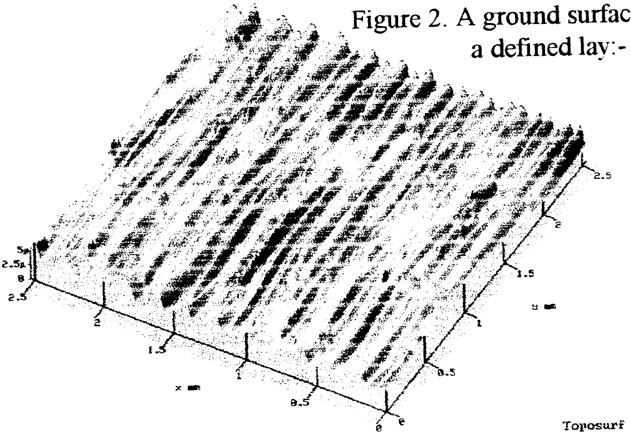

Figure 2. A ground surface with a defined lay:-

Sq 0.75μm; Sz 4.7μm; Ssk 0.22; Sku 2.61; Sds 2.53x10^{2}mm^{-2}; Str 0.065; Sal 0.036mm; Std 0°; SΔq 0.047; Ssc 3.58x10^{-3} mm^{-1}; Sdr 0.11%; Sbi 0.601; Sci 1.59; Svi 0.10; Sm 3.78x10^{4}μm^3/mm^2; Sc 9.47x10^{5}μm^3/mm^2; Sv 7.69x10^{4}μm^3/mm^2

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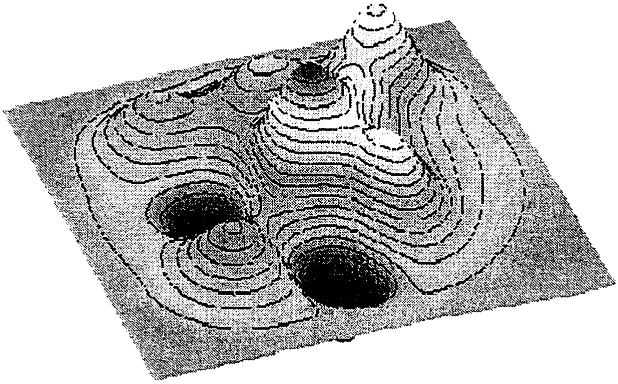

Figure 3 Simulated 3D surface showing peaks, pits, saddle points and slope zones combined into a continuos surface

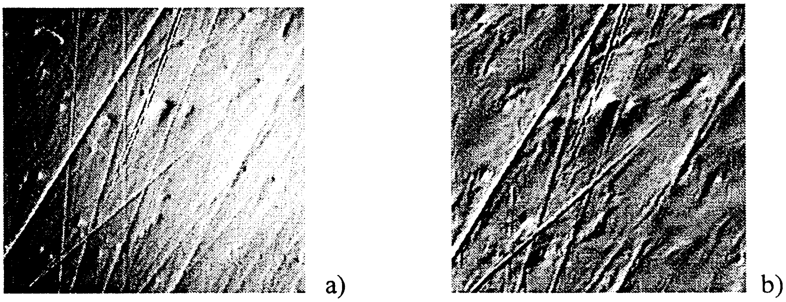

Figure 4a Surface topography of a spherical polished replacement hip joint. 4b Same surface with form error and high frequency roughness removed using wavelet filtering, leaving deep scratches and pits for further analysis.

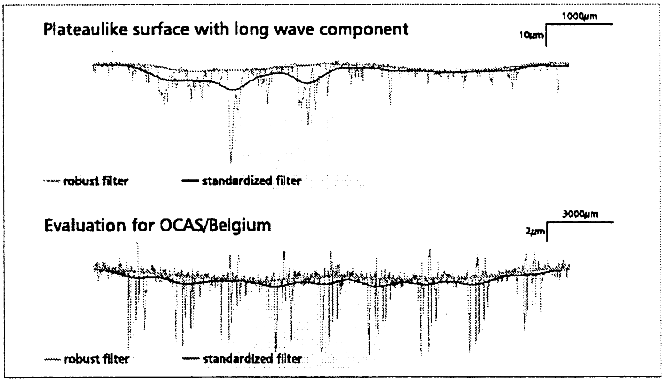

Figure 5 2D representation of "robust" filtering