Progress of surface texture standardisation

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Abstract

In this paper, important concepts in the new ISO surface texture standardisation system, so called scale-limited surfaces and feature-based attributes are discussed. Scale-limited surfaces provide a flexible way of identifying the various different scales of surface texture required to be specified for manufacture. The feature-based technique solves problems in multi-functional surface analysis including structured surface assessment. We present industrial applications with new areal parameters in ISO 25178 including: Field parameters – defined from all the points on a scale limited surface and Feature analysis – defined from a subset of features on a scale limited surface.

1 Introduction

The surfaces of manufactured components are being optimised for function and production cost because of the demands for higher performance at lower cost. Many of these surfaces are being deliberately textured with geometrical patterns to achieve this aim. The characterisation of profiles is inadequate to control the manufacture of these patterns and areal characterisation is required. As a consequence of manufacturing changes, the International Organization for Standardization (ISO) has now issued the ISO 25178 series of standards [1] that move the primary definition of surface texture from profile to area based definitions.

1.1 New Concepts

Traditional profile parameters provide a simple approach to controling the manufacturing-process for machined surfaces: they monitor changes in the surface texture: once a manufacturing process has been established that produces workpieces that function well, it is assumed that all that is necessary to maintain acceptable production is to control the manufacturing process by monitoring changes in the surface texture. The disadvantages are that profile surface parameters are not capable of diagnosing product functional performance directly, and so can not control structured surfaces.

The areal method attempts to characterize the fundamental topographical features of the surface, including assessment of texture shape and direction, estimation of feature attributes, and differentiation between connected and isolated features. Areal surface characterization was not simply an extension from profile to the areal case [2], but was a genuine attempt to characterize areal features.

1.2 Unified Co-ordinate System

Surface irregularities have traditionally been divided into three groups loosely based on lateral scale: (1) roughness (primary texture), generated by the material removal mechanism such as tool marks, (2) waviness, produced by imperfect operation of a machine tool, and (3) errors of form, generated by errors of a machine tool, distortions such as gravity effects, thermal effects, etc. To ensure consistency the measured profile was specified to be orthogonal to the lay (the direction of the predominant pattern of the surface irregularities). This direction is not necessarily related to the datum system of the workpiece, as is the case for errors of form, such as straightness etc. [3]. and consequently profile texture applies to a different co-ordinate system than the datum system.

In the new standard on areal surface texture, the primary definition of surface texture is changed from one being based on profiles to one based on areal surface and there are no requirements for the co-ordinate system to be related to the lay. Therefore a unified co-ordinate system has been established for both surface texture and form measurement. This system is known as GPS geometric product specification.

1.3 Scale-limited Surface

An important change in the ISO standardisation system is to embody a new concept called a *scale-limited surface* defined in ISO 25178-Part 2 [4]. This provides a flexible way of identifying the various different scales of surface texture now required to be specified for manufacture.

An areal surface characterization does not now require three different parameter groups (P,W & R) as in ISO 4287:1997 [5]. For example, in areal characterisation, Sq, the root mean square parameter, is only defined on a scale-limited surface rather than the Primary Pq, Waviness Wq and roughness Rq profiles as in the profile system. A scale-limited surface depends on which filters or operator are used to define it. An SF surface is obtained in Figure 1b, using an S-Filter and an F-Operator (Figure 1a), in combination, and an SL surface is obtained using an S-Filter and an L-filter. Both SF and SL surfaces are scale-limited surfaces. An SF surface is equivalent to a primary surface, and an SL surface equivalent to a roughness surface.

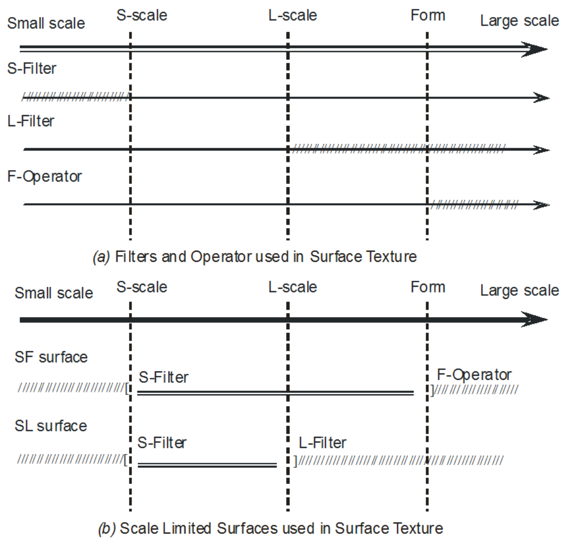
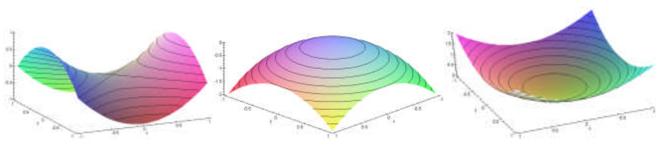


Figure 1 Filters (S-Filter or L-Filter), Operator (F-Operator) and Scale-limited surfaces (SF surface or SL surface).

1.4 Feature-based Surface Attributes

Another critical change in surface texture is feature-based characterisation for multi-functional surface analysis including structured surface assessment. This technique was originally proposed in 1997 [6]. Here a surface is decomposed into basic point elements: peaks, pits, saddle points (as shown in Figure 2a) and line elements: course lines and ridge lines (as shown in Figure 2b) by using Maxwell's method. In this way, any surface can be decomposed into elements and then reconstructed using significant elements with ranked orders, for functional assessment.



(a) Critical points (Peak, pit and saddle point).

(b) Critical lines (course line and ridge line).

Figure 2 Basic elements of a surface

2 Numerical Parameters

ISO 25178-Part 2 has two classes of areal parameters: Field parameters – defined from all the points on a scale limited surface and Feature parameters – defined from a subset of predefined topological features on a scale limited surface.

2.1 Field Parameters

The field parameter set consists of the S-parameters, which describe both amplitude and spatial information, and the V-parameters which give fundamental volumetric information based on the areal material ratio curve.

2.1.1 S-parameter set

The S-parameter set contains 12 parameters divided into four basic types: height, spacing, hybrid and miscellaneous. The height parameters depend on the amplitude deviation to describe amplitude related properties of a surface. They mirror the profile amplitude parameters. The spacing parameters refer to the spatial properties of surfaces. ***Sal*** and ***Str*** parameters are designed to assess areal aspects of surface texture, including texture strength and the uniformity of the texture in all directions. They are particularly useful in distinguishing between highly textured and random surface structures, as well as monitoring machine tool vibration and chatter. The hybrid parameters ***Sdq*** and ***Sdr*** are based on both amplitude and spatial information. They numerically describe hybrid topography properties, such as the slope of the surface and the interfacial area. Hybrid parameters have particular relevance to contact properties, both electrical and thermal, sealing properties, as well as wear and optical reflectance properties of a surface. There is one miscellaneous parameter *Std*, which is designed to provide information on the texture direction, such as the lay direction of the surface texture.

Given a cloud of points of a measured surface $z(x, y)$ within a definition area ***A***, the 12 S-parameters are listed in Table 1.

Table 1 The 12 S-parameter set [4]

S-parameter set(12)	Height	*Sq*	Root mean square height	$Sq = \sqrt{\frac{1}{A}\iint_A z^2(x, y)dxdy}$
		Ssk	Skewness	$Ssk = \frac{1}{Sq^3}\left[\frac{1}{A}\iint_A z^3(x, y)dxdy\right]$
		Sku	Kurtosis	$Sku = \frac{1}{Sq^4}\left[\frac{1}{A}\iint_A z^4(x, y)dxdy\right]$
		Sa	Arithmetical mean height	$Sa = \frac{1}{A}\iint_A \lvert z(x, y)\rvert dxdy$

		Sp	Maximum peak height	Largest peak height value
		Sv	Maximum pit height	Smallest pit height value
		Sz	Maximum surface height	Sum of Sp and Sv
	Spatial	*Sal*	Auto-correlation length	$Sal = \min_{tx,ty \in R} \sqrt{tx^2 + ty^2}$ where $R = \{(tx,ty) : f_{ACF}(tx,ty) \le s\}$
	Spatial	*Str*	Texture aspect ratio	$Str = \dfrac{\min_{tx,ty \in R} \sqrt{tx^2 + ty^2}}{\max_{tx,ty \in Q} \sqrt{tx^2 + ty^2}}$ where $R = \{(tx,ty) : ACF(tx,ty) \le s\}$, $Q = \{(tx,ty) : ACF(tx,ty) \ge s \,\&\, {**}\}$
	Hybrid	*Sdq*	Root mean square gradient	$Sdq = \sqrt{\frac{1}{A}\iint_A \left[\left(\frac{\partial z(x,y)}{\partial x}\right)^2 + \left(\frac{\partial z(x,y)}{\partial y}\right)^2\right] dxdy}$
	Hybrid	*Sdr*	Developed interfacial area ratio	$Sdr = \frac{1}{A}\left[\iint_A \left(\sqrt{\left[1 + \left(\frac{\partial z(x,y)}{\partial x}\right)^2 + \left(\frac{\partial z(x,y)}{\partial y}\right)^2\right]} - 1\right) dxdy\right]$
	Miscellaneous	*Std*	Texture direction	The angle of the absolute maximum value of the angular power spectrum, with respect to a specified direction.

Note: ***s*** *is predefined value, which has 0 < s < 1 and default 0.2;* f_{ACF} *is the areal auto-correlation function of* $z(x,y)$*; ** is the property that the* f_{ACF} *> s on the straight line connecting the point* (tx,ty) *to the origin.*

2.1.2 V-parameter set

The V-parameter set [4] in Table 2 is designed to assess the functional topographical features of the surface by analysing the material volume and void volume of a scale-limited surface. The rationale behind the parameters is to split the material ratio curve of a surface into three height zones, the peak, the core and the valley zones, and then to make volume calculations based upon those zones. The peak zone corresponds to initial running-in wear, the core zone to wear throughout the lifetime of the component, and the valley zone to lubricant retention under heavy wear conditions.

Table 2 The 13 V-parameter set [4]

V-Parameter (13)	Areal parameters	*Sk*	Core distance	Distance between the highest and lowest level of the core surface.
V-Parameter (13)	Areal parameters	*Spk*	Reduced peak height	Average height of the protruding peaks above the core surface.
V-Parameter (13)	Areal parameters	*Svk*	Reduced valley height	Average height of the protruding dales below the core surface.

	Smr1	Peak material ratio	(Peaks) ratio of the area of the material at the intersection line which separates the protruding hills from the core surface to the evaluation area.
	Smr2	Valley material ratio	(Dales) ratio of the area of the material at the intersection line which separates the protruding dales from the core surface to the evaluation area.
	Spq	Plateau root mean square deviation	Slope of a linear regression performed through the plateau region
	Svq	Dale root mean square deviation	Slope of a linear regression performed through the dale region
	Smq	Relative material ratio	(Plateau-to-dale) areal material ratio at the plateau-to-dale intersection.
Void volume	*Vvv*	Dale void volume	$Vvv = Vv(p)$, with default $p = 80\%$.
	Vvc	Core void volume	$Vvc = Vv(p) - Vv(q)$, with default $p = 10\%,\ q = 80\%$.
al volum	*Vmp*	Peak material volume	$Vmp = Vm(p)$, with default $p = 10\%$.
	Vmc	Core material volume	$Vmc = Vm(q) - Vm(p)$, with default $p = 10\%,\ q = 80\%$.
Oth er	*Sxp*	Peak extreme height	$Sxp = Smc(p) - Smc(q)$ with $p = 97.5\%,\ q = 50\%$.

Note: *the involved functions Vv and Vm describe the volume of the voids and materials per unit area which are derived from the inverse areal material function Smc:*

$$Vm(p) = \frac{K}{100\%}\int_0^p Smc(q) - Smc(p)dq \text{ , and } Vv(p) = \frac{K}{100\%}\int_p^{100\%}\left[Smc(p) - Smc(q)\right]dq$$

where ***K*** is a constant to convert to millilitres per metres squared.

2.1.3 Applications

During the last decade, these parameters and functions have been used in surface measurement instruments and the automotive, aerospace, biomedical and high-tech industries.

A typical biomedical example is the artificial matt finished femoral stems which are widely used in clinical hip replacement. This kind of stem has a "matt" bead blasted surface which provides a "mechanical locking" with the bone cement. A total of 75 artificial stems were tested with different wear degrees, grouped into 5 sequential sets and their surface textures measured (see Figure 3). The height, spatial, hybrid and bearing-based parameters are examined. A group of field parameters have been found significant for the discrimination of the wear grades (see Table 3), e.g. ***Sq***, ***Sdq*** and ***Vmp***. A more detailed study can be found in [2].

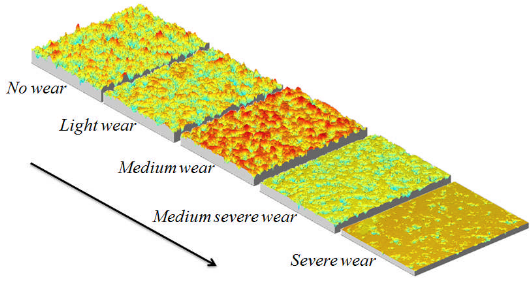


Figure 3 Progression of wear on matt finish femoral stems

Table 3 Useful parameters for describing wear of femoral stems

Amplitude				Spatial				Hybrid			Bearing-based		
Sq	Sz	Ssk	Sku	Sds	Str	Sal	Std	Sdq	Ssc	Sdr	Vmp	Vvc	Vvv
•	•	•	Δ	Δ	o	Δ	o	•	Δ	•	•	•	•

- Significant discrimination; Δ Some discrimination; o Little or no discrimination

The areal autocorrelation function (AACF) [4] has also been a very useful tool to demonstrate efficient diagnostics for stochastic surfaces. For example, in milling, chatter has been known as an important influential factor to the surface quality. Figure 4 presents three typical facially milled surfaces under different machining conditions. An automated identification process can be realised using the AACF. More examples of investigations of field parameters assessment of stochastic surfaces can be found through the reference [7] regarding polishing, turning, grinding, general engineering and bio-medical applications.

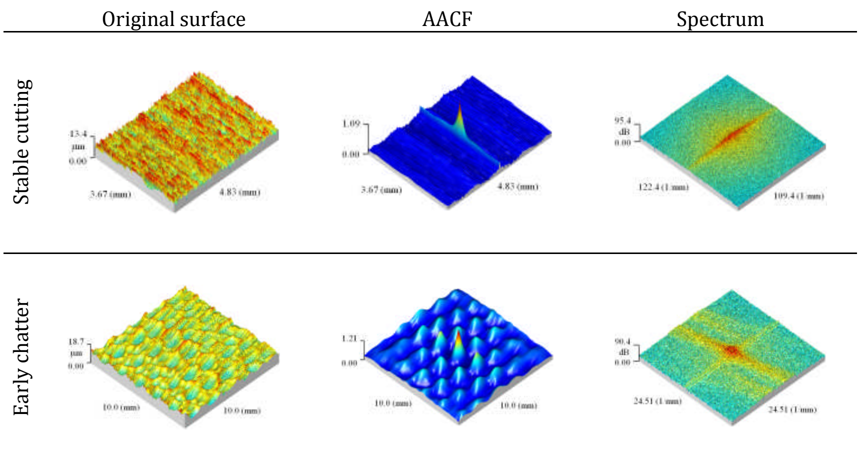


Figure 4 Milled surfaces (under different cutting conditions) and comparison of their AACF results and spectrum

2.1.4 Software measurement standards for field parameters

Reference software, developed by the National Physical Laboratory, is now available for the evaluation of a subset of areal surface texture parameters [8], which highlights the definitions of the parameters and provide the tools to implement parameters to keep an unbroken documented chain with ISO 25178 standards to ensure the traceability of surface measurements. Industry and commercially software packages can be assessed using this reference software.

2.2 Feature characterisation

In feature based characterisation, a surface is seen as a composition of geometric features. By applying statistics to a subset of the predefined topographic features, feature parameters can be produced.

2.2.1 Five steps to a feature parameter

Feature characterisation does not have specific feature parameters defined but has instead a toolbox of pattern recognition techniques that can be used to characterise specified features on a scale limited surface. The feature characterization process is in five steps (see Table 4):

Table 4 Five steps to a feature parameter [4]

<table>
<tr><td colspan="4">Step 1: Types of scale limited features</td></tr>
<tr><td>Class of limited feature</td><td colspan="2">Type of scale limited feature</td><td>Designated symbol</td></tr>
<tr><td rowspan="2">Areal</td><td colspan="2">Hill</td><td>H</td></tr>
<tr><td colspan="2">Dale</td><td>D</td></tr>
<tr><td rowspan="2">Line</td><td colspan="2">Course line</td><td>C</td></tr>
<tr><td colspan="2">Ridge line</td><td>R</td></tr>
<tr><td rowspan="3">Point</td><td colspan="2">Peak</td><td>P</td></tr>
<tr><td colspan="2">Pit</td><td>V</td></tr>
<tr><td colspan="2">Saddle point</td><td>S</td></tr>
<tr><td colspan="4">Step 2: Criterial of size for segmentation</td></tr>
<tr><td>Criteria of size</td><td colspan="2">Designated symbol</td><td>Threshold</td></tr>
<tr><td>Local peak/pit height (Wolf Pruning)</td><td colspan="2">Wolfprune</td><td>% of Sz</td></tr>
<tr><td>Volume of Hill/Dale (at height of connected saddle on change tree)</td><td colspan="2">VolS</td><td>Specified volume</td></tr>
<tr><td>Area of Hill/Dale</td><td colspan="2">Area</td><td>% of definition area</td></tr>
<tr><td>Circumference of Hill/Dale</td><td colspan="2">Circ</td><td>Specified length</td></tr>
<tr><td colspan="4">Step 3: Methods of determining significant features</td></tr>
<tr><td>Class of feature</td><td>Method of determining significant features</td><td>Designated symbol</td><td>Parameter units</td></tr>
<tr><td rowspan="2">Areal</td><td>Areal feature is significant if not connected to the edge at a given height</td><td>Closed</td><td>Height is given as a material ratio</td></tr>
<tr><td>Areal feature is significant if it is connected to the edge at a given height</td><td>Open</td><td>Height is given as a material ratio</td></tr>
</table>

Point	A peak is significant if it has one of the top N Wolf peak heights	Top	N is an integer
	A pit is significant if it has one of the top N Wolf pit heights	Bot	N is an integer
Areal, line, point	Use all the features	All	-

Step 4: *Selection of feature attributes*

Feature class	Feature attributes	Designated symbol
Areal	Local peak/pit height	Lpvh
	Volume of areal feature (at height of connected saddle on change tree)	VolS
	Volume of areal feature (at height of connected to edge)	VolE
	Area of areal feature	AreaE
	Circumference of areal feature	Cleng
Line	Length of line	Leng
Point	Local peak/pit height	Lpvh
	Local curvature at critical point	Curvature
Areal, line, point	Attribute takes value of one	Count

Step 5: *Attribute statistics*

Attribute statistic	Designated symbol	Threshold
Arithmetic mean of attribute values	Mean	-
Maximum attribute value	Max	-
Minimum attribute value	Min	-
RMB attribute value	RMS	-
Percentage above a specified value	Perc	Value of threshold in units of attribute
Histogram	Hist	-
Sum of attribute values	Sum	-
Sum of all the attribute values divided by the definition area	Density	-

Step 1: *Type of texture feature*. The three main types of texture features are areal features (hills & dales), line features (course and ridge lines) and point features (peaks, pits & saddle points). It is important to select the appropriate type of texture feature for the function of the surface under inspection.
Step 2: *Segmentation*. Segmentation is used to determine the scale limited features. The segmentation process consists of first finding all of the hills and dales on the scale limited surface. This usually results in over-segmentation of the surface and so the “smaller” segments are pruned out to leave a suitable segmentation of the scale limited surface.
Step 3: *Determining significant features*. "Function" does not interact with all features in the same way; different features interact differently. Segmentation is also used to determine those features that are functionally significant to those that are not. It is this set of significant features that is used for characterisation.
Step 4: *Selection of feature attribute*. Once a set of significant features have been determined it is necessary to determine suitable feature attributes for characterisation. Most attributes are a measure of size of the feature e.g. length, area or volume of the individual features.

Step 5: *Attribute statistics*. Calculation of a suitable statistic of the attributes, a feature parameter, or alternatively a histogram of attribute values, is the final part of feature characterisation.

2.2.2 Feature parameters

To record the feature characterization it is necessary to indicate the particular tools used in each of the five steps. This can be achieved by using the following convention: Start with the letters ***FC*** to indicate that this is a feature characterisation; For each stage, in turn use the designated symbol from the appropriate table to indicate the tool required; Some stage tools require further values for completeness. Use the symbol ";" to delimit between each stage and the symbol ":" to delimit within a stage. If a tool is not specified in this standard then a reference to the tool definition can be used instead. With this convention, nine suggested feature parameters as listed in Table 5.

Table 5 Nine feature parameters defined in ISO 25178-2

Feature parameters (9)	*Spd*	Density of peaks	*Spd = FC;H;Wolfprune:X%;All;Count;Density.*
	Spc	Arithmetic mean peak curvature	*Spc = FC;P;Wolfprune:X%;All;Curvature;Mean.*
	S10z	Ten point height of surface	*S10z = S5p + S5v.*
	S5p	Five point peak height	*S5p = FC;H;Wolfprune:X%;Top:5;Lpvh;Mean.*
	S5v	Five point pit height	*S5v = FC;D;Wolfprune:X%;Bot:5;Lpvh;Mean.*
	Sda(c)	Average area of dales	*Sda(c) = FC;D;Wolfprune:X%;Open:c/Closed:c;Area;Mean.*
	Sdv(c)	Average area of hills	*Sha(c) = FC;H;Wolfprune:X%;Open:c/Closed:c;Area;Mean.*
	Sdv(c)	Average volume of dales	*Sdv(c) = FC;D;Wolfprune:X%;Open:c/Closed:c;VolE;Mean.*
	Shv(c)	Average volume of hills	*Shv(c) = FC;H;Wolfprune:X%;Open:c/Closed:c;VolE;Mean.*

Note 1: *for these parameters if not otherwise indicated the default value of 'Wolfprune: X%' is Wolfprune:5%.*
Note 2: *for the last four parameters if not otherwise indicated the default value of 'Open:c' is Open:c.*

2.2.3 Applications

Fig. 5a is a grinding wheel surface. Grits on a grinding wheel are geometrically undefined in both location and shape. In order to ascertain the qualitative measurement of cutting edges, a feature based method has been used. In Figure 5a 409 peaks were detected. Hill recognition with Wolf pruning at 5% (i.e. 5% of the peak-to-valley of the data) also produces a count compatible with manual counting for all grain sizes. Figure 5b shows the result with 60 peaks. Wolf pruning has the added advantage that the significant peak in each segment is given allowing further analysis.

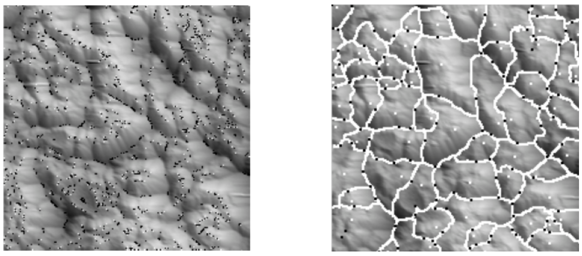


Figure 5 Grit extract from a grinding wheel surface. (a) Initial topography data; (b) Hill segmentation after Wolf pruning

The titanium surfaces fabricate by polishing, sandblasting, followed by acid etching. Figure 6 is a sample surfaces with the micrometre scale measured by an atomic force microscope (AFM). The segmentation illustration of the AFM image is shown in Figure 6. The ***Spd*** and ***Sdv*** parameters reflect the basic geometric information of the micro-features.

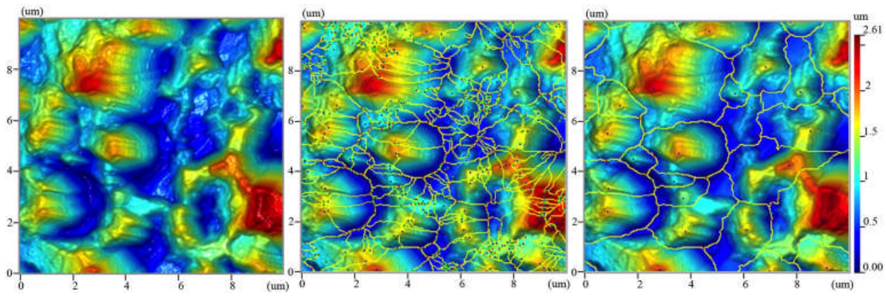
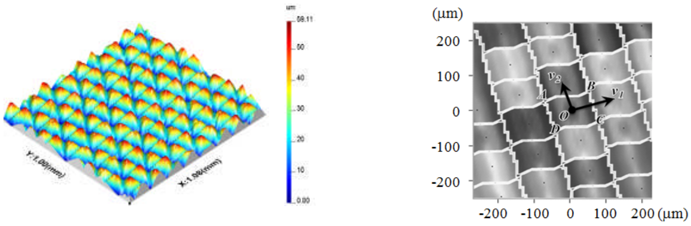


Figure 6 (a) 2D view of sample S3. (b) Hill segmentation before Wolf pruning. (c) Hill segmentation with 5 % Sz Wolf pruning.

The power spectrum and autocorrelation function of a tessellated (predetermined or structured) surface are periodic; the AACF of a structured surface can be used to create a symmetric translation surface. Combining AACF together with segmentation a novel way can be generated to solve this type of surface assessment. By using the segment around the origin, the average basic cell, called unit tile, of the structured surface can be found. From the relationship of the unit tile with other segments it is easy to determine two independent planar translational vectors. Figure 7b shows that a unit tile (a quadrilateral consisting of two adjacent triangular pyramids at the origin) from a 3M abrasive surface (Figure 7a). The relationship can be established between the unit tile and its eight neighbors by two translation vectors. A unit tile can be mapped by the two translational vectors onto adjacent congruent structures.



(a) A commercial abrasive surface *(b) The pattern model*

Figure 7 The pattern model of a commercial abrasive surface derived from combined Auto-correlation and segmentation.

3 Conclusion

In the past ten years there have been tremendous changes in the generation, use and control of surfaces. These changes have been due to the need to optimise performance, miniaturize and generally to add value to manufacture of parts. These include the comprehensive expansion of surface parameters and surface characterization of traditional processes as well as structured surfaces. The advances have been primarily in areal considerations, which are now incorporated into the standards. Numerical methodologies have been at the forefront of the developments in areas such as 'operational parameters'.

4 Acknowledgements

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