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Evolution of 3D Surface Parameters: A Comprehensive Survey

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ABSTRACT
Precision surface finishes are used in a wide variety of applications. From bearing races and rolling elements to parallel slide ways, the topography of these surfaces is critical to the performance of the products. With the advent of diamond turning and other abrasive precision finishing such as magneto-rheological finishing process, nanometric surface finish can be realized. The ultra precision surfaces also find applications in optics and/or bio-medical implant surfaces. The 2D roughness parameter defined in standards are inadequate for characterising surfaces therefore analysis of 3D roughness parameter is necessary for broad analysis of surface conditions.

Keywords: roughness, topography, amplitude, parameter.

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I. INTRODUCTION

The interaction between two surfaces is an important area of study in industrial applications. A lot of research has been done on the surface topography as it helps in understanding the interaction between the surfaces. The two-dimensional (2D) parameters defined in standards are inadequate for characterizing surfaces because real surfaces interact in 3 dimensions. It can be seen in case of two surfaces in contact 3-D amplitude and spatial parameters are important. Also, texture has important role in hemodynamics (dynamics of blood flow in and around a cardiovascular implant. The project aims to characterize select engineered precision finished surfaces and/or textured surfaces to improve functional response.

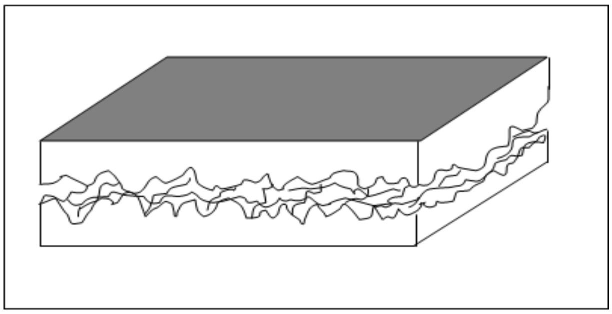


Figure 1.1 The surface interaction in contact of two surfaces.

Therefore a set of 3D parameters are required to describe the properties of surface in effective way. Also the functional properties cannot be obtained by using 2D parameters. Various 3D parameters have been defined based on different properties like amplitude properties and spatial properties required for describing the surface [1]. These parameters have been successful in analyzing various problems in industrial and research field.

II. 3-D SURFACE PARAMETERS

2.1 3-D Surface parameters.

Until recently only 2-D roughness parameters [1-2] were in use which do not provide the complete picture, especially concerning the lay characteristics of the surface. Hence, there has been a push within both industry and academia for transition to 3-D parameters. This need arises partially due to the realization that surfaces interact in three dimensions instead of two [3]. The primary parameter set proposed by Stout et al. [7] involves

14 parameters, which characterize the major aspects of topographic features. There are four parameters for describing the amplitude and height distribution properties, four parameters for describing spatial properties, three parameters for describing hybrid (i.e. both amplitude and spatial) properties and three parameters for some functional properties. Table 2.1 shows the 14 3-D parameters proposed by Stout et al [7].

Table 2.1 - Set of 14 3-D parameters given by Stout et al. [4]

Amplitude Parameters	**Spatial Parameters**	**Hybrid Parameters**	**Functional Parameters**
RMS Deviation S_q	Density of Summits S_{ds}	RMS Slope $S\Delta q$	Surface Bearing Index S_{bi}
Ten point Height S_z	Texture Aspect Ratio, S_{tr}	Mean Summit Curvature S_{sc}	Core Fluid Retention Index S_{ci}
Skewness S_{sk}	Texture Direction S_{td}	Developed Area Ratio S_{dr}	Valley Fluid Retention Index S_{vi}
Kurtosis S_{ku}	Fastest Decay Autocorrelation Length S_{al}		

2.2 AACF and APSD Analyses

The autocorrelation function for surface profiles is based on the idea that profile readings can be treated as random signals. This type of analysis has found extensive use in random signal processing in communication. The autocorrelation function for surface profiles is based on the idea that profile readings can be treated as random signals. This type of analysis has found extensive use in random signal processing in communication. The idea of computing various random process functions for machined surfaces was first proposed by Dong et al. [7] used AACF and APSD for characterization of 3-D spatial parameters. They also studied characteristics of AACF and APSD for a variety of engineered surfaces. The following section provides a detailed description of AACF and APSD which form the basis of 3-D spatial surface characterization.

2.2.1 AACF

The areal autocorrelation function describes the general dependence of data at one position on the data at another position. As discussed earlier, the autocorrelation function has been effectively used for random signal processing. It provides information about time data in case of communication signal and spatial data in case of 2-D surface analysis. For 3-D surface analysis the areal ACF or AACF is given as follows:

$$R(\tau_x, \tau_y) = E[\eta(x, y)\eta(x + \tau_x, y + \tau_y)]$$
$$= \lim_{l_x, l_y \to \infty} \frac{1}{4 l_x l_y} \int_{-l_y}^{l_y} \int_{-l_x}^{l_x} \eta(x, y)\eta(x + \tau_x, y + \tau_y)\, dx\, dy \qquad (2.1)$$

A non-biased discrete estimation of the AACF is given by Eq. (2.2).

$$R(\tau_i, \tau_j) = \frac{1}{(M - i)(N - j)} \sum_{l=1}^{N-j} \sum_{k=1}^{M-i} \eta(x_k, y_l)\eta(x_{k+i}, y_{l+j}) \qquad (2.2)$$

where,

$i = 0,1 ...., m < M ; j = 0,1 ...., n < N$

$\tau_i = i\Delta x; \tau_j = j\Delta y$

$\eta(x, y)$ is the residual surface [5] after a plane is fit to remove the form (longer wavelength and undulations) from the surface data; m and n are the autocorrelation lengths in the x and y directions, respectively. As i, j approach M and N, respectively, fewer data points are available for computation of AACF and the statistical confidence decreases considerably. Therefore, maximum coordinates in the x and y axes are restricted to $\tau_m = \Delta xM/2$ and $\tau_n = \Delta yN/2$. Figure 2.1 shows the normalized AACF plots for the surfaces given by Singh et al. [5] for ground (GD), honed (HN), hard turned (HT) and isotropic finished (IF) surfaces used in bearing industry.

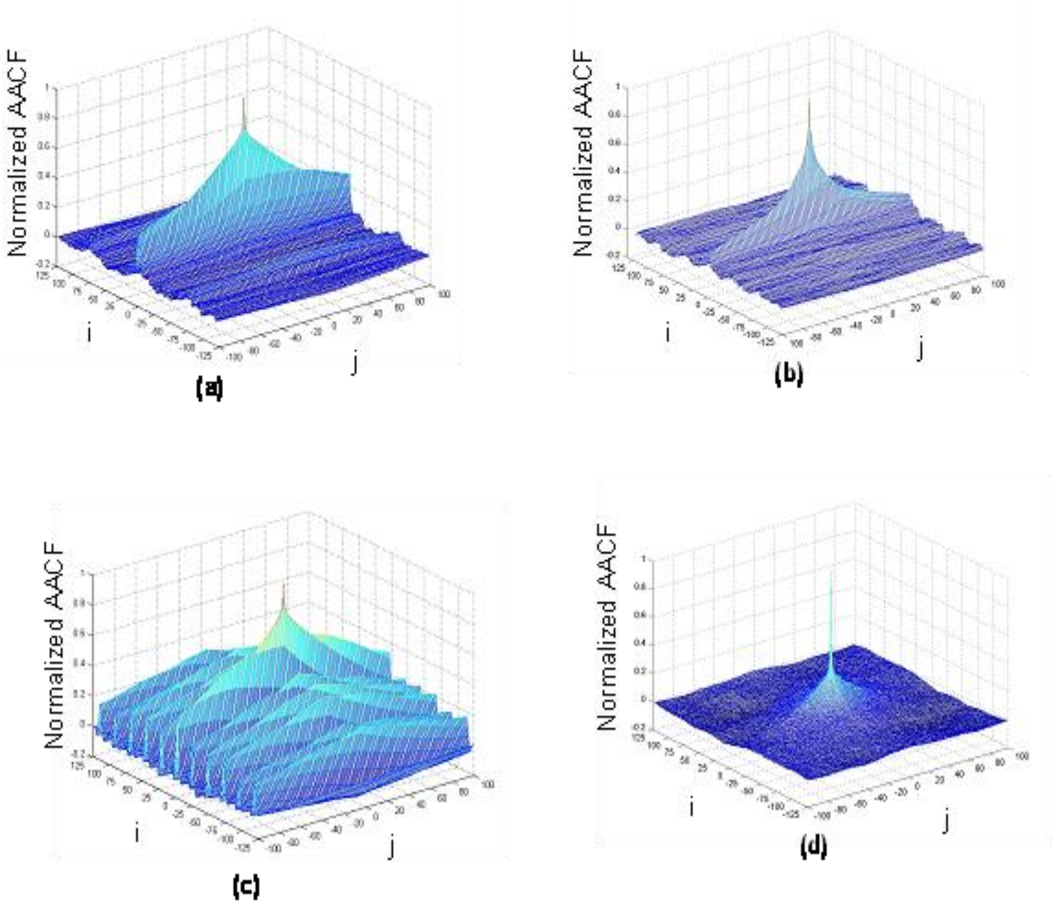


Figure 2.1. Normalized AACF plots for the: (a) GD, (b) HN, (c) HT and (d) IF surfaces[5].

The AACF is an effective tool to visualize the correlation in different directions. It is evident from Figure 2.1 (a) that for the GD surface, which exhibits a strong directional property, the decay of the auto correlation function is very slow along the lay and very rapid across the lay. For HT surface (Figure 2.1(c)) a distinct periodicity can be observed. For the IF surface, there is no correlation in any particular direction and hence the decay is uniform in all directions as shown in Figure 2.1(d). Thus, it can be inferred that distinctive properties can be identified from the AACF. Consequently, AACF analysis is used to compute 3-D texture parameters, namely texture aspect ratio (S_{tr}) and fastest decay (S_{al}).

2.2.2 APSD

Spectral analysis is a powerful tool to condense the time/space domain information into the frequency domain. Once frequency domain data is available we can accentuate the information for individual frequency or wavelength contribution. Power spectral analysis can help in distinguishing between the roughness and waviness because of distinct differences in the wavelengths. Dong et al. [8] discussed the Hermitian symmetry for 2-D spectral analysis and algorithm to compute the APSD and extract texture parameters. For the residual surface η(x,y) (given by Dong et al. [9]), its continuous and discrete Fourier transforms are given by Eqs.(2,3) and (2.4), respectively.

$$F(\varpi_x, \varpi_y) = \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} \eta(x, y) e^{-j2\pi(\varpi_x x + \varpi_y y)} dx\, dy \qquad (2.3)$$

$$F(\varpi_p, \varpi_q) = \sum_{l=1}^{N-1} \sum_{k=1}^{M-1} \eta(x_{k+1}, y_{l+1}) e^{-j2\pi(\frac{p}{M}k + \frac{q}{N}l)} \qquad (2.4)$$

where ϖ_p and ϖ_q are angular frequencies in two directions as defined below:

$$p = 0,1 \ldots., M - 1; q = 0,1 \ldots., N - 1;$$

$$\varpi_p = \frac{p}{\Delta x M}, \varpi_q = \frac{q}{\Delta y N}$$

The areal PSD can be implemented by:

$$G(\varpi_p, \varpi_q) = F(\varpi_p, \varpi_q) F^*(\varpi_p, \varpi_q) \tag{2.5}$$

where '*' denotes complex conjugate. Manipulations need to be carried out to get the center coordinates to be at the origin. Figure 2.2 shows the APSD plots for the various surfaces [5].

For anisotropic surfaces, most of the power is located in the direction perpendicular to the lay. This is observed in the GD surface (Figure 2.2 (a)) and to some extent in the HN surface (Figure 2.2 (b)). The HT (Figure 2.2 (c)) surface has power concentrated at the specific frequency of periodicity perpendicular to the lay. The IF surface (Figure 2.2 (d)) is a random surface and hence the power is concentrated at the origin. The APSD is required to compute the texture direction S_{td} parameter.

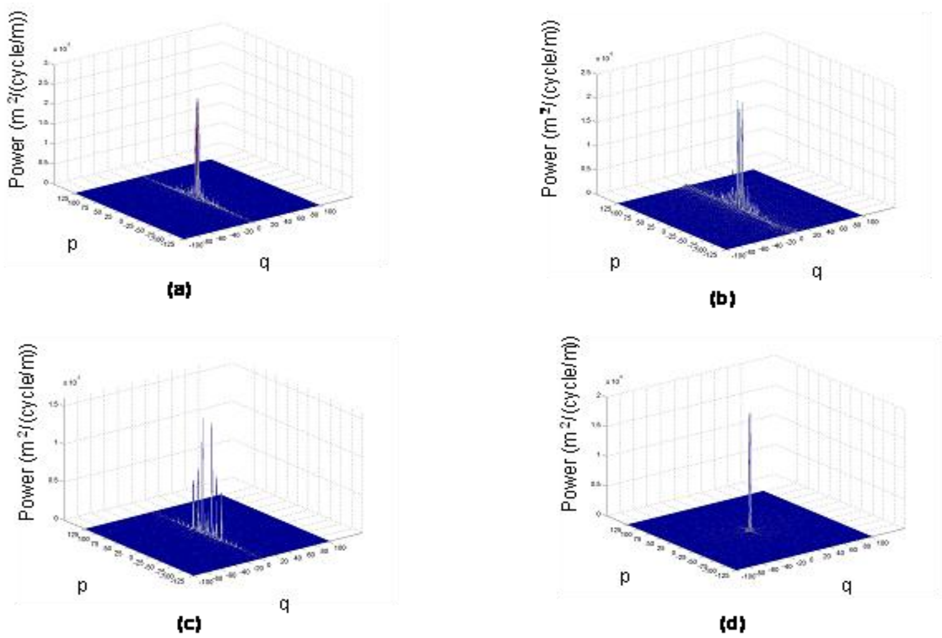


Figure 2.2. APSD plots for the: (a) GD, (b) HN, (c) HT and (d) IF surfaces [5].

2.3 Computation of 3-D Parameters

As discussed previously, there exist a set of 3-D parameters that describe the spatial and amplitude features of a given surface. These parameters provide a more realistic estimate of the 3-D surface features in comparison to their 2-D counterparts. Some of these 3-D parameters were computed for the four surfaces of interest here. These parameters are discussed in detail by Dong et al. [3-4].

2.3.1 3-D Amplitude Parameters

Amplitude parameters are important parameters for surface topography. Many 2-D parameters [1-2] have been defined in national and international standards. The two 3-D amplitude parameters that were computed for the surfaces studied here are: 3-D root mean square roughness (S_q) and surface skewness (S_{sk}).

Root Mean Square Deviation of Surface Topography (S_q)

This is a statistical amplitude parameter defined as the root mean square value of the surface asperity departures from the reference datum within the sampling domain. This is assumed to provide a conservative estimate of the average asperity height measured from the datum. The S_q parameter, in continuous and discrete forms, is given as follows:

$$S_q = \sqrt{\frac{1}{l_x l_y} \int_0^{l_y} \int_0^{l_x} \eta^2(x, y)\, dx\, dy} = \sqrt{\frac{1}{MN} \sum_{j=1}^{N} \sum_{i=1}^{M} \eta^2(x_i, y_j)} \tag{2.6}$$

where, l_x and l_y are the side lengths of the sampling area. This parameter is of significant tribological importance as it plays a key role in determining the frictional response of a surface as will be seen later in the report.

Skewness of topography height distribution (S_{sk})

The skewness is the measure of asymmetry of surface deviations about the mean plane. It is given defined as follows:

$$S_q = \frac{1}{S_q^3} \int_{-\infty}^{\infty}\int_{-\infty}^{\infty} \eta^3(x, y)\, p(\eta)\, dxd\ y = \frac{1}{MNS_q^3} \sum_{j=1}^{N} \sum_{i=1}^{M} \eta^3(x_i, y_j) \qquad (2.7)$$

It can be used effectively to describe certain aspects of the shape of the topographic height distribution. From a functional point of view, it can indicate presence of spikes. Large negative skewness may be found in surfaces that have pits and troughs. S_{sk} is unstable if used for indicating functional properties of the surface because the effect of a small number pits or spikes can have a significant effect on the computation of skewness.

2.3.2 3-D Spatial Parameters

Spatial parameters are important because 2-D parameters cannot capture directionality and the degree of anisotropy. Both deterministic and random surfaces can possess isotropic or anisotropic character. The greatest difficulty with the spatial parameters is that they are usually difficult to describe by parameters owing to the random and multi-wavelength components of the surface. The four important spatial 3-D parameters evaluated here are: S_{al}, S_{tr}, S_{td} and $S_{ds.}$

Fastest Decay Autocorrelation Length (S_{al})

This parameter describes the nature of the AACF. It is the shortest distance from the origin in which the normalized AACF decays to a value of 0.2. Whitehouse and Archard [10] modeled the autocorrelation decay for a random surface with Gaussian distribution to be exponential. The fastest autocorrelation decay to a value 0.1 was used. Since actual surfaces do not display exponential decay, Dong et al. [4] used a decay value of the normalized AACF of 0.2. Mathematically, S_{al} is given as follows:

$$S_{al} = \min(\sqrt{\tau_x^2 + \tau_y^2}),\ \overline{R}(\tau_x, \tau_y) \leq 0.2 \qquad (2.8)$$

This is an important parameter as it identifies the direction in which the correlation is less. It decays very rapidly across the lay direction for a surface exhibiting strong lay characteristics as illustrated in Figure 2.1 (a). Also, the decay rate of the AACF is governed by the significant frequency components. A large value of S_{al} indicates that the surface is dominated by low frequency components whereas a small value indicates otherwise. Turned surfaces have larger values and ground and honed surfaces have smaller values of S_{al}.

Density of Summits (S_{ds})

Density of summits is the number of summits contained in a unit of sampling area. It is computed as follows:

$$S_{ds} = \frac{Number\quad of\quad Summits}{(M-1)(N-1)\Delta x \Delta y} \qquad (2.9)$$

This parameter is a function of summit definition. A summit is a central point of an area above the mean plane which has highest value among all data points of the area. The definition of sampling area is ambiguous; there are many definitions that exist such as the nearest eight neighbors [11], a contour area or a window. Thomas [11] showed that the S_{ds} (based on 8 nearest neighbors) increases rapidly as the sampling frequency increases. This necessitates an ideal definition of area over which a summit is defined. Dong et al. [4] suggested a sampling area based on S_{al} and S_{ds} computed from this definition is not very sensitive to sampling frequency. Sampling area is a square (Δx=Δy) whose half length is equal to the S_{al}. Although more summits can be found using any other definition, they are considered correlated hence only one summit is recognized. In this study S_{ds} is computed based on S_{al}. The abrasive processes such as the ground and honed surfaces have very high frequency components, meaning that the lay is very closely spaced and therefore summits occur more often. Consequently, the S_{ds} value is higher for those processes. It is a very good estimate of the average number of asperities per unit area and is found to influence the frictional response of the surfaces under mixed lubrication.

Texture Aspect Ratio (S_{tr})

The texture aspect ratio is used to identify the texture pattern, i.e. long-crestedness or isotropy. Texture aspect ratio can serve as the measure of isotropy. The definition of texture aspect ratio is as follows:

$$S_{tr} = \frac{\text{The distance that the normalised AACF has the fastest decay to 0.2 in any possible direction}}{\text{The distance that the normalised AACF has the slowest decay to 0.2 in any possible direction}}$$
(2.10)

A large value of this parameter indicates strong isotropy ($S_{tr} > 0.5$) while a small value ($S_{tr} < 0.3$) indicates strong anisotropy. In the study done by Singh et al. [5-6], IF surface has a value of 0.67. The GD surface, which is strongly anisotropic, exhibits a very low value of 0.08.

Texture Direction (S_{td})

Texture direction is used to indicate the pronounced direction of lay. This is extracted from the APSD. Since the coordinate system is arbitrary, the coordinate system [4] is defined as shown in Figure 2.3. The formula for computation of S_{td} is given by:

$$\begin{aligned} S_{td} &= -\beta, \ \beta \le \pi/2 \\ &= \pi - \beta, \ \pi/2 < \beta \le \pi \end{aligned} \qquad (2.11)$$

where β= value of θ at which G_a (θ) is maximum.

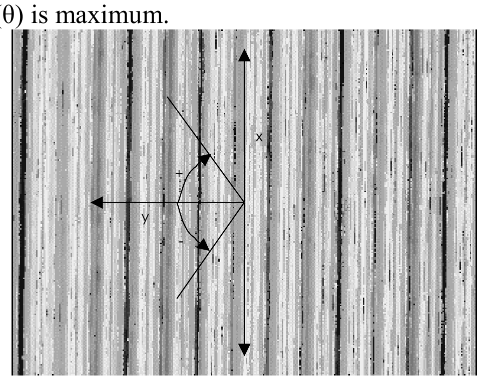
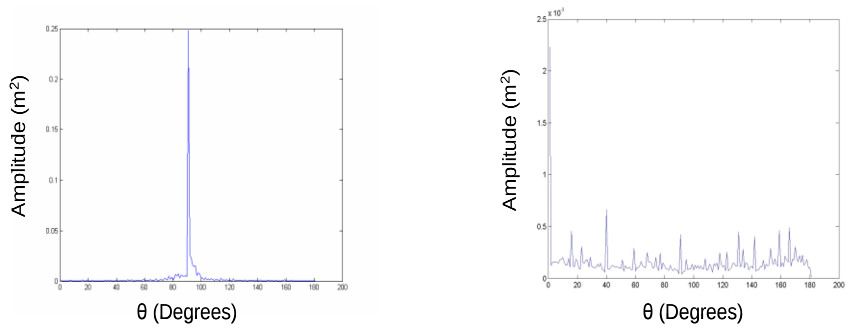


Figure 2.3. Definition of texture direction.

G_a (θ) is the angular spectrum it is derived from APSD by integrating the spectral energy radially between 0 and 179 degrees.

$$\left.\begin{aligned} G_a(\theta) &= \int_0^{R(\theta)} G(\theta, r)\,dr \\ R(\theta) &= \frac{1}{2}[(\Delta x \cos\theta)^2 + (\Delta y \sin\theta)^2]^{-1/2} \\ 0 &\le \theta \le 179 \end{aligned}\right\} \qquad (2.12)$$

First G(θ,r) was extracted from the APSD for all the surface orientations and then sorted in ascending order. Numerical integration was carried out by the trapezoidal rule and the maximum value computed.



(a) (b)

Figure 2.4. Typical angular spectrum plot for texture orientation (a) lay perpendicular to Y-axis and (b) isotropic surface

The texture direction is given by the angle corresponding to the maximum amplitude in the angular spectrum plot. Since all surfaces except the IF surface have lay perpendicular to the Y axis, the maximum amplitude occurs at an angle of 90^0 as illustrated in Figure 2.4(a). The IF surface has no preferred direction of lay and consequently there is no peak in the angular spectrum plot as shown in Figure 2.4 (b) [5].

2.3.3 Hybrid Parameter

RMS Slope($S_{\Delta q}$)

The root mean square slope of the surface within the sampling area is computed as follows:

$$\rho_{ij} = \left[\left(\frac{\eta(x_i, y_j) - \eta(x_{i-1}, y_j)}{\Delta x} \right)^2 + \left(\frac{\eta(x_i, y_j) - \eta(x_{i-1}, y_j)}{\Delta x} \right)^2 \right]^{1/2} \qquad (2.13)$$

$$s_{\Delta q} = \left(\frac{\sum_{j=2}^{N} \sum_{i=2}^{M} \rho_{ij}^2}{(M-1)(N-1)} \right)^{0.5} \qquad (2.14)$$

Arithmetic mean summit curvature of the surface (S_{sc})

III. CONCLUSION

[1] Experience shows advantages of certain finishes in certain roles.
[2] 2D roughness measurement(stylus) often correlated with functionality.
[3] Surfaces contact in three dimensions.
[4] 3D texture parameters affect functionality.
[5] AACF describes the general dependence of data at one position on the data another position used for fastest decay autocorrelation length and density of summits.
[6] To calculate the spatial parameters, the AACF, APSD and Angular spectra for each surface must be analysed.

REFERENCES

[1]. ANSI, Surface Texture: Surface Roughness, Waviness and Lay, American Standard ANSI 8.46.1, 1985

[2]. ISO, Surface Roughness - Terminology - Part 1: Surface its Parameters, International Standard IS0 428711, 1984.

[3]. W.P. Dong, P.J. Sullivan and K.J. Stout, Comprehensive study of parameters for characterizing three-dimensional surface topography - III: Parameters for characterizing amplitude and some functional properties, **Wear**, 178 (1994) 29-43.

[4]. W.P. Dong, P.J. Sullivan and K.J. Stout, Comprehensive study of parameters for characterizing three-dimensional surface topography - IV: Parameters for characterizing spatial and hybrid properties, **Wear,** 178 (1994) 45-60.

[5]. R. Singh, S. N. Melkote, and F. Hashimoto, Frictional Response of Precision Finished Surfaces in Pure Sliding, **Wear,** 258 (2005) 1500-1509.

[6]. R. Singh, R. C. Kalil, S. N. Melkote, and F. Hashimoto, Correlation of 3-D Precision Machined Surface Topography with Frictional Response, **Proceedings of IMECE 04: 2004 ASME International Mechanical Engineering Congress and Exposition**, IMECE2004-59534, Anaheim, California, USA, MED, v 15, 2004, 871-879.

[7]. W.P. Dong, E. Mainsah, K.J. Stout and P.J. Sullivan, Three-dimensional surface topography - Review of present and future trends, in K.J. Stout (ed.), **Three-dimensional Surface Topography: Measurement, Interpretation and Applications, A Survey and Bibliography**, Penton, 1994, pp. 65-85.

[8]. W.P. Dong and K.J. Stout, Two-dimensional fast Fourier transform and power spectrum for surface roughness in three dimensions, **Proc. I. Mech. E.,** Vol. 209, pp. 381-391, 1995.

[9]. W.P. Dong, E. Mainsah, K.J. Stout, Reference planes for the assessment of surface roughness in three dimensions, **Int. J. Mach. Tools Manufact.** Vol. 35, No.2, pp. 263-271, 1995.

[10]. D.J. Whitehouse and J.F. Archard, The properties of random surfaces of significance in their contact, **Proc. R. Sot. London,Ser. A,** 316 (1970) 97-121.

[11]. T. R. Thomas, **Rough Surfaces**, Imperial College Press, 1999.