Comparative study about the use of two and three-dimensional methods in surface finishing characterization

A. Sanz [1,*], A. A. Negre [2], R. Fernández [3], F. Calvo [4]

[1,2,3,4] *Department of Aerospace Materials and Production. ETSI Aeronáuticos. Universidad Politécnica de Madrid, Plaza Cardenal Cisneros 3, 28040 Madrid , Spain*

Abstract

The increasing number of works related to the surface texture characterization based on 3D information, makes convenient rethinking traditional methods based on two-dimensional measurements from profiles. This work compares results between measurements obtained using two and three-dimensional methods. It uses three kinds of data sources: reference surfaces, randomly generated surfaces and measured. Preliminary results are presented. These results must be completed trying to cover a wider number of possibilities according to the manufacturing process and the measurement instrumentation since results can vary quite significantly between them.

Keywords: Roughness; waviness; surface finishing; 3D measurement

---

1. Introduction

Surface finishing, which is understood as the set of microgeometrical properties of surfaces, is a topic of great importance in the field of processing in engineering and it is constantly under revision. The wide variety of parameters which are used in the characterization of surface finishing is a piece of evidence of its magnitude. On top of that, the most relevant standards such as ISO or ASME are in frequent revision.

The characterization of surface finishing is usually accomplished defining numerical parameters. The determination of the numerical parameters is influenced by several factors as shown in Figure 1. A first group covers the factors connected to the functional behaviors affected by the microgeometry of the part. Given the diversity of these behaviors there is no parameter which fits adequately these days. A second group includes several physical properties in which the measuring equipment is based on to obtain the microgeometrical values or magnitudes directly connected to the values. A third group embraces the manufacturing processes and treatments which determine the geometry of the surface. Finally, a fourth group, a bit more heterogeneous than the other three, is associated to the definition of boundary conditions and the handling of the information. Inside this group relevant aspects are included, such as determination of the measuring area or data filtering.

---

* Corresponding author. Tel.: +34-913-366-330; fax: 34-913-366-334.
E-mail address: a.slobera@upm.es

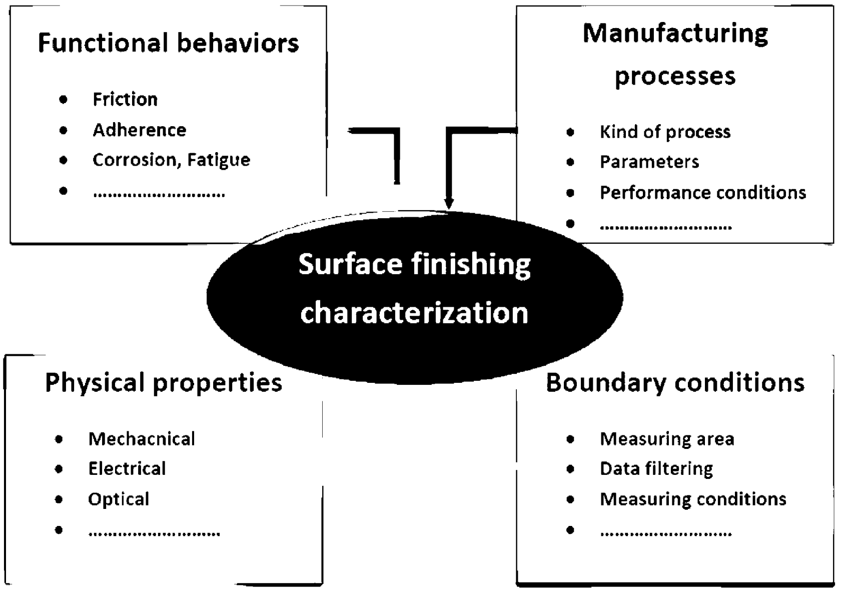

Figure 1. *Groups of factors which have influence on surface finishing characterization*

As indicated, the characterization of surface finishing is traditionally based on two-dimensional data contained in a profile. The profile is obtained by the intersection of a perpendicular plane to the surface and it is composed by a set of points $\{x_i, y_i\}$. In this set coordinate x stands for the measured length on the direction of the profile while coordinate z is the height at each point. The choice of the orientation of the profile, the number of points which defines it, the distance between these or the definition of reference lines to measure the height are part of the fourth group of afore-mentioned factors and its exhaustive explanation is not the purpose of this work. Information about this topic can be found in references and it is worth noting [1]. It may seem that elimination of a direction, the y-axis, is an important restriction when characterizing microgeometry. Even though it is, in fact, a limitation, the advantages of this way of working are, or at least have been so far, more than the setbacks. The basis of this fact is mainly due to two conditions: measuring instruments and the large amount of information to process.

With regard to the measuring instrumentation, although many surface finishing characterization methods exist, as shown in Figure 2, the thoroughly extended ones are the ones based on mechanical means and the use of a sensor in contact with the surface of the part. The reason for this spreading is its versatility, robustness and low cost compared to other kinds of measuring instrumentation. The latter are generally based on more fragile and expensive equipment with more restrictive requirements in the measuring environment and part typology.

The amount of information to process has been a limitation for a long time. The great advances in the data storage system changed it to a factor of less impact. It is an interesting fact that one of the first works in which the three-dimensional measuring technique [2] was applied used an array of 512x512 of 8 bit data which summed up to 256Kb. This amount of memory can be considered insignificant in these days, yet when the work was carried out it was a notable value. The matter presented here is whether the use of a considerably greater amount of information contributes to any additional benefit which supports its use.

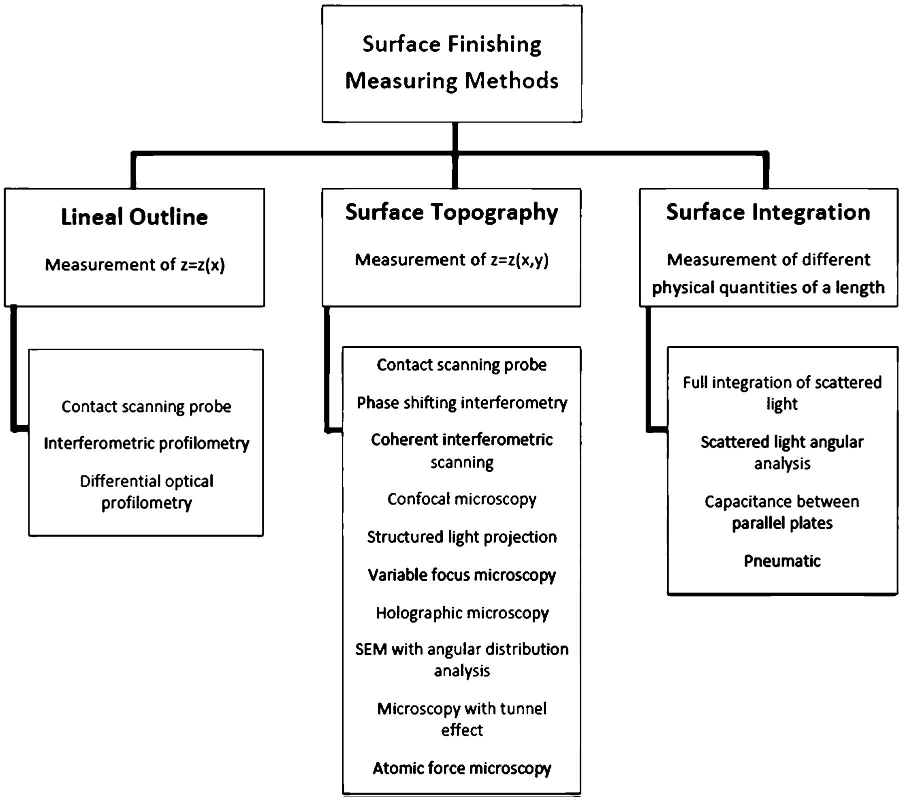

Figure 2. Surface finishing measuring methods according to [3]

Profiles obtained directly from the measuring instrument can be decomposed into a periodic sum of functions of different wavelength using Fourier series. The theoretically infinite range of wavelengths is filtered depending on the behaviors which want to be described. A filtering of the undesired wavelength is performed, obtaining several profiles: primary, roughness, waviness. The roughness profile is the most representative. It is denoted by the letter R. This profile encloses all the components whose wavelengths are more significant when describing the functional behaviors of the parts.

The R_a parameter is the most widely adopted among all the existing parameters in surface finishing characterization. The R_a parameter is an average value in height. Simplicity on evaluation along with good functional behavior leads users to resort to it increasingly frequent. Table 1 gathers percentages of the use of several parameters obtained from [4] and scientific search engines on the Internet. Data on the table reaffirm the higher adoption of R_a compared to other parameters. The exception which appears in the column of ISI WOK (1) is quite striking, yet at the same time contradictory with the other results. This could be due to the fact that the RMS concepts are applied in other contexts so usage in titles (bear in mind that this column is referred to the number of appearances in the titles of the works) is more common by researchers.

Table 1. Frequency of parameter usage

Parameters	Reference [4]	Academic Google	ISI WOK (1)	ISI WOK (2)
R_a	56.64%	70.64%	37.23%	59.61%
R_q (RMS)	17.70%	21.23%	56.38%	25.21%
R_z/R_t	19.47%	7.83%	6.38%	15.08%
R_{mr}	6.19%	0.29%	0.00%	0.09%

(1) In title only (2) In title or abstract

2. Three-dimensional surface finishing characterization

Even though the exposed arguments in the latter section are more favorable to use two-dimensional elements (profiles) in surface finishing characterization, there is an emergence of works on this topic. Particularly in the academic field there is a growing number of works which advocate the usage of three-dimensional measuring elements. The search of a higher precision and resolution in measures, reduction in costs of processing and storing systems and continuous progress in microscopy techniques are the reasons of the emergence of these works. ISO regulations in publishing phase and recently published endorse this tendency. The mentioned regulations are shown in Table 2. In spite of these facts, their use is still reduced in mass production.

Table 2. ISO regulations related to the three-dimensional characterization of surface finishing.

Published		**Under development**	
ISO 25178-601:2010	Geometrical product specifications (GPS) -- Surface texture: Areal -- Part 601: Nominal characteristics of contact (stylus) instruments	**ISO/DIS 25178-604**	Geometrical product specifications (GPS) -- Surface texture: Areal -- Part 604: Nominal characteristics of non-contact (coherence scanning interferometry) instruments
ISO 25178-6:2010	Geometrical product specifications (GPS) -- Surface texture: Areal -- Part 6: Classification of methods for measuring surface texture	**ISO/DIS 25178-605**	Geometrical product specifications (GPS) -- Surface texture: Areal -- Part 605: Nominal characteristics of non-contact (point autofocus probe) instruments
ISO 25178-602:2010	Geometrical product specifications (GPS) -- Surface texture: Areal -- Part 602: Nominal characteristics of non-contact (confocal chromatic probe) instruments	**ISO/DIS 25178-70**	Geometrical product specification (GPS) -- Surface texture: Areal -- Part 70: Physical measurement standards
ISO 25178-701:2010	Geometrical product specifications (GPS) -- Surface texture: Areal -- Part 701: Calibration and measurement standards for contact (stylus) instruments	**ISO/CD 25178-72**	Geometrical product specifications (GPS) -- Surface texture: Areal -- Part 72: XML file format x3p
ISO 25178-	Geometrical product specifications (GPS) -- Surface texture: Areal -- Part 2: Terms,	**ISO/DIS 25178-1**	Geometrical product specifications (GPS) -- Surface texture: Areal -- Part 1: Indication of

2:2012	definitions and surface texture parameters		surface texture
ISO 25178-3:2012	Geometrical product specifications (GPS) -- Surface texture: Areal -- Part 3: Specification operators	**ISO/DIS 25178-606**	Geometrical product specification (GPS) -- Surface texture: Areal -- Part 606: Nominal characteristics of non-contact (focus variation) instruments
ISO 25178-71:2012	Geometrical product specifications (GPS) -- Surface texture: Areal -- Part 71: Software measurement standards	**ISO/NP 25178-603**	Geometrical product specifications (GPS) -- Surface texture: Areal -- Part 603: Nominal characteristics of non-contact (phase-shifting interferometric microscopy) instruments

As it can be observed, development of the regulations is in a transition period. There are 7 regulations published and another 7 under development. One of the main innovations of these regulations is the definition of surface parameters, similar to the linear ones (obtained from profiles). As an example, the mathematical expressions of the parameters S_a and S_q are indicated. These two parameters are equivalent to the most frequently lineal ones, R_a and R_q.

$$S_a = \frac{1}{S}\iint_S |z(x,y)|\,dxdy\,;\,S_q = \sqrt{\frac{1}{S}\iint_S z(x,y)^2\,dxdy} \qquad (1)$$

Where S stands for the measuring surface and z is the height of the points (x, y) of the measured surface with respect to the mean plane. In the calculation of the three-dimensional parameters, the regulation proceeds in the same way for the rest of two-dimensional parameters. It is also worth indicating the fact that the three-dimensional parameters are calculated on the whole surface. In contrast to the parameters based on profiles, no distinction is made in specific measuring areas. In that case, the sampling length is used to limit the measuring area or the area where the parameters are evaluated. Additionally, the name of the three-dimensional parameter is the same regardless of the filtering for its determination. The latter does not happen in the parameters evaluated in the profiles whose name changes subject to the filtering.

3. Methodology and field of application of this comparative research

The execution of a complete comparative study among two-dimensional and three-dimensional methods exceeds the scope of this work. It would be necessary to compare the results obtained combining different measuring methods with several kinds of surfaces as well as distinct functional behaviors (different parameters).

In this range of possibilities, an option based on those considered the most common elements in surface finishing characterization has been chosen for the experimental part of this work:

- Contact probes utilization.
- Surface obtaining by machining process (face milling).
- Determination of the height parameters based on arithmetic mean and square root mean.

For the purpose of widening the scope of the results, work with surfaces obtained by simulation has been completed with the aim of establishing the valid conditions of the acquired results. Thus obtaining outcomes which could be extrapolated to other procedures and methods of measurement is possible in this way.

The accomplished methodology consists of determining the two-dimensional and three-dimensional parameters in several groups of surfaces. Specifically developed software has been used for this purpose. In order to validate the results retrieved by the software, they have been compared to the same results retrieved by the reference software in [5].

Surface generation is a key element in the methodology. Depending on the approach adopted mixed results can be obtained. There are many works related to surface generation which employ several methods depending on their functionality. The common factor of all of them is its random character. Nonetheless, their approach to randomness is different in each case. A widespread generating method is based on fractal surfaces. Greenwood's work [6] was a pioneer in this field and it has been followed by other researchers up to recently [7].

The majority of the developments based on this method are targeted to tribological applications where the "fractality" condition fits reasonably well to the expected behavior in the contact surface. The study of relevant functional behaviors such as friction [8], heat transfer [9] or electrical conductivity [10] between surfaces is often based on this model.

Another group of work is founded on the use of the statistical properties from the distribution of a microgeometrical characteristic of the profile. This characteristic is usually height of roughness. Among the last mentioned it is worth making a distinction among those based on Gaussian surfaces [11] and those which are founded on no Gaussian surfaces, depending whether the hypothesis of normality of the heights of the surface is admitted or not. A third group of works starts from a geometrical configuration established beforehand with regard to the process used in the surface manufacturing. From that configuration, it generates the surface microgeometry as in [13].

There are other alternatives like the ones used by Wu [14] based on surface generation by Fourier transform or Nemoto et al [15] based on a non-causal autoregression 2D model. In the present work, stochastic Gaussian generation combined with geometrical models based on the manufacturing process has been used. As it can be seen the casuistry is extremely wide, so it looks convenient to conduct an in-depth study which exceeds the scope of this work.

4. Results

A summary of the most significant results obtained with the previously described methodology is presented.


(a) (b)

Figure 3. *Milled test probe (a) and experimental set-up (b) for the data acquisition of S3 surfaces*

As indicated in the previous section, three groups of surfaces have been employed in this work. These surfaces are designated by S1, S2 and S3 and are defined by the following:

a) S1. *Reference surfaces:* selected from [5]. This has allowed optimizing the experimental method and comparing the results retrieved by the software.

b) S2. *Simulated surfaces:* generating pure Gaussian surfaces, that is, with values of height based on known normal distributions of known mean and variance and a model combined of known geometry and random perturbations.

c) S3. *Experimental surfaces*: working with aluminum alloy 7075 test probes produced by face milling as shown in Figure 3(a). Straight shank end mills of 10 mm diameter with a Ti-Al-N covering have been used. The test probes have been machined with various feed rates in order to obtain different surface finishing grade. Three dimensional data have been retrieved connecting a mechanic rugosimeter to a table of coordinates which allows the movement in the xy plane to obtain various profiles as shown in Figure 3(b).

Figure 4 shows a three-dimensional representation of exemplar surfaces from each of the considered groups. In the surfaces from groups S1 and S2 the periodicity in the values are perceived presenting few difficulties. Those periodic components also appear in surfaces from group S3. This time they are a consequence of the machining process. However, visualization is not as clear as in the surfaces from the other two groups. In the results, a surface from each group has been selected since the values obtained in various surface studies do not generate significant variations inside each group.

Table 3 shows the selected surfaces as well as the chosen S_a and S_q obtained in each surface, expressed in micrometers.

Table 3. Information of the representative surfaces of each group S1, S2 and S3

	S1	**S2**	**S3**
Label	SG2-3 [reference 5]	Sinusoidal basis with Gaussian perturbation	3 flute end mill, feed 31 mm/min, depth of cut 0.5 mm
S_a	0.7979	0.5678	0.9214
S_q	1.0000	0.7053	1.1863

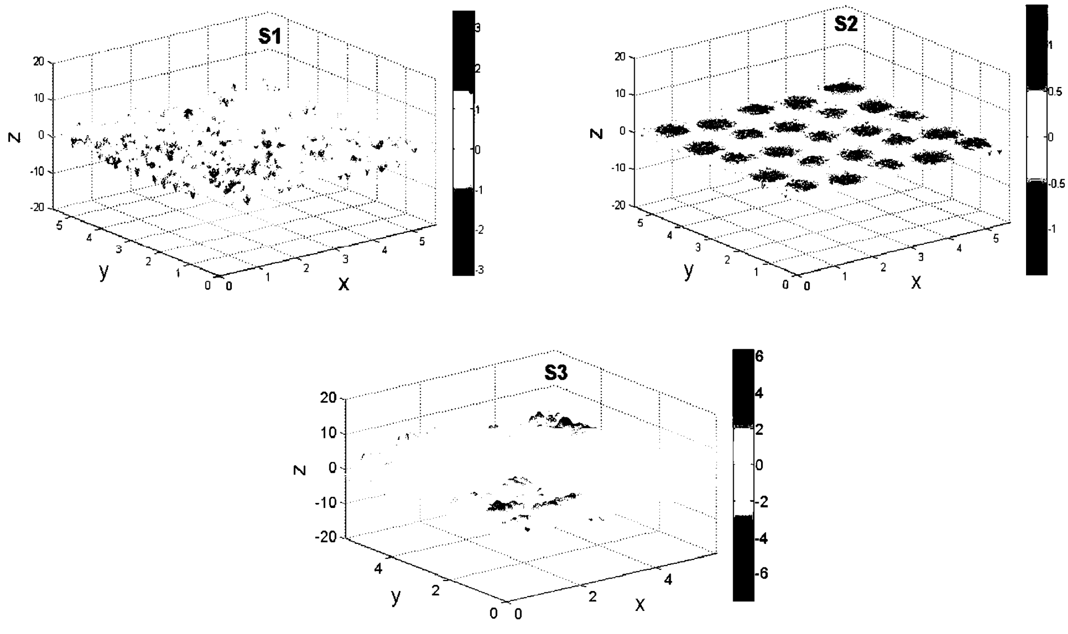

Figure 4. Three-dimensional representation of the measured surfaces

Table 4. Values of Ra and Rq calculated for the surfaces in each group S1, S2 and S3

Alpha	Ra_S1	Rq_S1	Ra_S2	Rq_S2	Ra_S3	Rq_S3	alpha	Ra_S1	Rq_S1	Ra_S2	Rq_S2	Ra_S3	Rq_S3
0	0.7716	0.9473	0.6447	0.7669	0.8266	1.0034	**92**	0.7923	1.0483	0.6474	0.7936	0.7706	0.9376
4	0.7391	0.9037	0.6997	0.8256	0.8004	0.9928	**96**	0.8017	0.9775	0.6577	0.7832	0.8838	1.1880
8	0.7676	0.9648	0.5611	0.6854	0.8176	1.0251	**100**	0.8008	1.0096	0.5226	0.6499	0.8854	1.1406
12	0.7962	1.0177	0.4995	0.6182	0.7969	1.0089	**104**	0.8539	1.0189	0.4682	0.5910	0.8591	1.0753
16	0.7656	0.9714	0.4844	0.6029	0.7599	0.9640	**108**	0.8684	1.0494	0.4340	0.5629	0.9895	1.2885
20	0.6528	0.8642	0.4972	0.6266	0.7793	1.0123	**112**	0.7679	0.9477	0.4714	0.6053	0.9231	1.2271
24	0.7019	0.8482	0.5194	0.6602	0.7789	1.0105	**116**	0.7901	1.0118	0.5361	0.6699	0.8650	1.1382
28	0.5885	0.7482	0.5166	0.6425	0.8132	1.0470	**120**	0.8365	1.0199	0.5385	0.6767	0.8392	1.0600
32	0.6187	0.7744	0.5105	0.6359	0.8965	1.1299	**124**	0.9325	1.1183	0.4595	0.5888	0.8418	1.0583
36	0.7835	0.9727	0.4270	0.5130	0.9648	1.2394	**128**	0.8983	1.1013	0.4453	0.5536	0.8595	1.1011
40	0.7227	0.8523	0.4199	0.5251	0.9641	1.2277	**132**	0.7697	0.9699	0.4437	0.5509	0.8599	1.0857
44	0.6066	0.7581	0.4499	0.5447	0.8752	1.0974	**136**	0.7787	0.9766	0.4460	0.5440	0.8099	0.9844
48	0.6783	0.8219	0.4126	0.5172	0.9110	1.1413	**140**	0.8070	1.0382	0.4146	0.5216	0.8859	1.0942
52	0.5616	0.6700	0.4270	0.5235	0.8944	1.1837	**144**	0.8353	1.0192	0.4393	0.5419	0.8884	1.0937
56	0.8029	0.9602	0.4642	0.5807	0.8947	1.1622	**148**	0.7231	0.9204	0.5182	0.6409	0.7917	1.0043
60	0.7231	0.9209	0.5570	0.6763	0.9461	1.1976	**152**	0.8022	0.9841	0.5492	0.6757	0.7424	0.9366
64	0.7466	0.9158	0.5823	0.7210	0.8694	1.1467	**156**	0.8943	1.0853	0.5058	0.6462	0.7455	0.9369
68	0.6246	0.7746	0.5202	0.6535	0.9167	1.1697	**160**	0.9072	1.0974	0.4753	0.6224	0.7176	0.8927
72	0.6513	0.7976	0.4622	0.5941	0.9339	1.1976	**164**	0.8313	1.0563	0.4882	0.6189	0.7065	0.8813
76	0.6370	0.7895	0.4932	0.6093	1.0768	1.3670	**168**	0.9099	1.1399	0.5053	0.6318	0.7246	0.9120
80	0.6383	0.7776	0.5531	0.6818	0.9048	1.2205	**172**	0.8662	1.1017	0.5856	0.7236	0.7855	0.9839
84	0.6583	0.8197	0.6295	0.7514	0.9447	1.2014	**176**	0.7616	0.9379	0.6409	0.7721	0.8619	1.0812
88	0.8071	1.0373	0.6631	0.8060	0.8685	1.0886	**180**	0.7716	0.9473	0.6447	0.7669	0.8266	1.0034

Table 4 shows the values of the R_a y R_q values in each surface using an angular parameter (alpha) which represents the inclination of each profile with respect to x-axis. In these calculations, no sampling length has been used and it has been applied the expression to the whole measuring length. The latter makes possible to compare the obtained results, since the three-dimensional parameters are calculated in the whole surface, not in certain areas of the surface.

It can be observed how the obtained values for the two-dimensional parameters oscillate around their three-dimensional counterparts. Contingent upon the considered surfaces, orientations with maximum values of the two-dimensional parameters appear. In particular, it happens for the alpha values of 124°, 4° and 76° in S1, S2 y S3 respectively.

5. Conclusions

The following conclusions have to be taken in mind in the scope of measuring and boundary conditions previously mentioned. Even though their approach aims at a possible generalization to other procedures, parameters and methods, such generalization demands a greater experimental set of results before being accepted.

Inside a same surface, no significant variations exist in the parameter comparison if R_a is compared to S_a or R_q with S_q.

The calculation of the three-dimensional parameters obtained as mean values (cases of R_a and R_q), soothes down the results and could mask the heterogeneous nature of the surface of the part.

The act of determining values of two-dimensional or tridimensional parameters does not result in a significant variation in the parameters based on average height values.

To sum it up, bearing in mind the cost of the equipment, the measuring conditions required and the obtained results, the usage of tridimensional methods does not seem justified. Their usage could make sense only in out of the ordinary conditions and very definite functional behaviors.

References

[1] T.R. Thomas, Rough Surfaces, World Scientific Publishing Company, 2nd Edition (1999) ISBN: 978-1-86094-100-9.

[2] E. Clayton-Teague, F. E. Scire, S. M. Baker, and S. W. Jensen Three-Dimensional Stylus Profilometry, Wear, 83 (1982) 1-12.

[3] UNE-EN ISO 25178-6:2010, Especificación geométrica de productos (GPS). Calidad superficial: Áreas. Parte 6: Clasificación de métodos para medir la calidad superficial.

[4] T. Li Softgauges for surface texture, PhD thesis(2011), University of Huddersfield

[5] National Institute of Standards and Technology. Mechanical Metrology Division. Reference Software for 3D Surface Analysis (2013) http://physics.nist.gov/VSC/jsp/index.jsp

[6] J. A. Greenwood and J. B. P. Williamson, Contact of Nominally Flat Surfaces, Proceedings of the Royal Society of London. Series A, Mathematical and Physical Sciences, Vol 295, 1442 (1966) 300-319.

[7] P. Sahoo and N. Ghosh, Finite Element Contact Analysis of Fractal Surfaces, Journal of Physics D: Applied Physics, Vol. 40 (2007), pp. 4245-4252.

[8] V. L. Popov, A. É. Filippov, Force of friction between fractal rough surface and elastomer, Technical Physics Letters , vol 36, num 6 (2010) 525-527.

[9] J.Gao, X. Fu, Fractal Model for the Effective Thermal Conductivity of Goose Down Assembly, Advanced Science Letters, vol 10, num 1 (2012) 666-668.

[10] N. A. Torkhov, V. G. Bozhkov, Fractal character of the distribution of surface potential irregularities in epitaxial n-GaAs, Semiconductors, vol 43, num 5(2009) 551-556.

[11] F. Robbe-Valloire, Statistical analysis of asperities on a rough surface, Wear, Vol 249, num 5–6 (2001) 401-408.

[12] A. Tian, X. Liu, D. G. Chetwynd, Z. Cai, Stylus contact on short wavelength random surfaces. A simulation study, Measurement Science and Technology ,vol 18 (2007) 1694–1702.

[13] A. Antoniadis, C. Savakis, N. Bilalis, A. Balouktsis, Prediction of Surface Topomorphy and Roughness in Ball-End Milling, Int J of Advanced Manufacturing Technology, vol 21, num 12 (2003) 965-971.

[14] J.J. Wu, Simulation of rough surfaces with FFT, Tribology International, Vol 33, Num 1 (2000) 47-58.

[15] K. Nemoto, K. Yanagi, M. Aketagawa, I. Yoshida, M. Uchidate, T. Miyaguchi, H. Maruyama, Development of a roughness measurement standard with irregular surface topography for improving 3D surface texture measurement, Meas Sci Tech, Vol 20 Num 8 (2009) 1-7.