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# INFLUENCE OF MEASUREMENTS ON 3D ROUGHNESS PARAMETERS

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**ABSTRACT**

*This paper presents the influence of the number of measurements in evaluating the surface quality with the help of 3D profilometry with contact. The measurements were done on a coated surface as resulted from an original laboratory technology elaborated by one of the authors. The results were useful for improving the coating technology. The surface investigation was done with the help of a 3D profilometer, for squared areas of 500 μm and here there are analyzed the average of the 25 measurements for amplitude, spatial and functional parameters. There were studied the influence of parameters' values extracted from these measurements on the average value of each analyzed parameter and the extreme values in order to give some recommendation for the surface quality assessment of these types of surfaces. Also there were compared the results of all measurements with two restricted number of measurements on the same investigated area.*

**Keywords:** 3D roughness parameter, measuring method, surface quality

## 1. INTRODUCTION

Modern measuring equipments for the surface topography evolved and are now capable of reaching a higher accuracy, but in the same time, a smaller scale supposes a smaller area of investigation [14, 15]

Several measurements in different zones on a sample may produce results within a large range due to the variations of the surface texture across the sample surface. Consequently, the results of any single measurement and even of several ones may not be representative of the overall surface quality [1, 9, 10]. A solution to this problem of how close are the measured values to the actual value characterizing the entire surface is to take multiple measurements in different areas of the surface and to apply a procedure of surface investigation depending on the surface type, its dimensions, the involved materials and the engineer experience. For the manufactured surfaces even international standards recommend the number of measurements and tolerances of ±16% around the value recommended or desired after the manufacturing process.

How many measurements does one have to perform to be within this tolerance? Further, how big a tolerance can one accept, especially for non-conventional manufacturing process, like this used for coating a hard steel? [1, 7, 8, 11]

The expectation of a 3D measurement is that only one measurement (or at least a small number) should be sufficient for analysing of a part surface, mainly due to the time needed per measurement. The large number of data points in one 3D measurement was hoped to give a statistically stable basis for the analysis of a surface [1, 6].

This study presents an analysis of the topography of a coated with the help of 3D parameters and it evaluates the modification of the average values depending on the number of measurements.

## 2. SAMPLES, EQUIPMENT AND METHODOLOGY FOR TOPOGRAPHY ASSESSMENT

The parameters taken into account in this study are presented in the Annex at the end of the paper, for their denominations.

Commercially available 316L stainless steel specimens having the composition Fe+Cr: 18.00; Ni: 12.00; Mo: 2.50; Mn: 1.70; P: 0.04; C: 0.02; S: 0.01; Si: 0.15 (wt. %) were used as the substrate in the present study. The electrochemical process of deposition was performed in a small three-electrode cell on plate specimens. The process was carried out potentiostatically with a potentiostat/galvanostat connected to a computer.

The coating technology was established by physisist Alina Cantaragiu and it is the subject of a research PhD [2], as a possible solution for increasing durability of knee replacement prothesys.

The samples were discs of 10 mm in diameter. Prior to making electrical contacts, the plate was mechanically polished using 600 and 1200 grit emery paper, organically degreased with acetone, etched in a 1:1 $HCl:H_2O$ solution for 60 seconds, chemical degreased with ethylic alcohol for few seconds and rinsed with distilled water. Then, the samples were activated by cathodisation at -1.1 V vs. SCE in a 0.1 M NaOH solution for 2 minutes and finally rinsed with doubly-distilled water. The deposition was performed at room temperature (23-25ºC) at -1.43 V potential vs. Ag/AgCl electrode. The electrochemically coating process with $TiO_2$, was done for 90 minutes (Fig. 1) The deposited layer was then, heated in air at 400ºC for 1 h in air to obtain crystalline $TiO_2$ film.

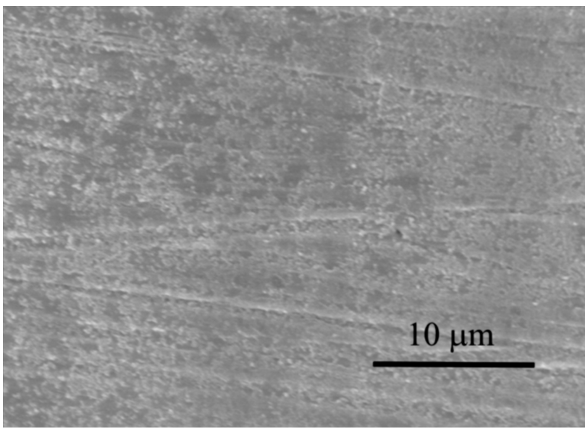



Fig. 1. A SEM image of the coated surface

The coated sample was investigated without any other process of surface finishing.

The profilometer PRO500 3D (with stylus) was used to measure the surface topography assisted by a dedicated soft [13].

The choice of area size is important since the selected area should be large enough to characterize a representative part of the surface or, at least, to generate stable parameter values. The vertical range was set at 500 μm, as the authors have less information about this coating technology and the scan speed was selected as 35 μm/s. All records have been done with 200 points on each line. The pitch between the lines was set at 5 μm.

Both the sampling interval and the measuring area have a strong influence on the measuring time and must therefore be optimised [6]. Here there was investigated a square area formed by 5 x 5 micro-areas, each one of 500 μm x 500 μm, in the central zone of the metallic area (Fig. 2).

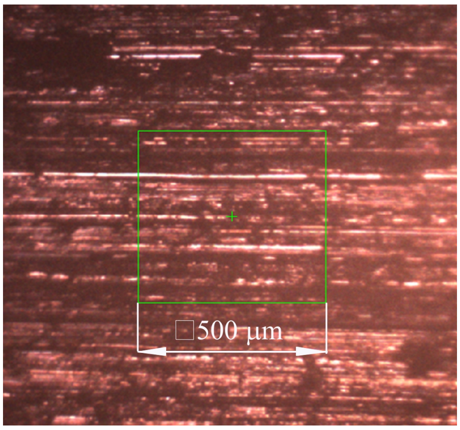



Fig. 2. One the squared area of investigation

The 3D parameters were calculated for raw profiles because they offer the possibility of pointing out extreme values and this was one of this paper's aims: to detect extreme values of the analyzed parameters and the raw profiles help „building" a virtual image closer to the actual one [1, 13, 14]. The equivalent contact force of the stylus was set for hard metallic surfaces, at 63 mg.

For a 2D study there are recommendations even in ISO standards [5, 7, 11, 12], but for 3 D measurements references are still few and the number of investigated areas will be established by the equipment range of measure, the experience and skills of the investigator and the type of surfaces to be investigated. Specialists talk about an actual measuring strategy [3-8, 10-12]. A statistical method is able to analyze the variation trend of the selected parameters, with the aim of anticipating an out-of-tolerance result.

Here there were investigated 25 square areas for a coated parts, these areas being positioned one to each other (Fig. 3), roughly meaning there was investigated a zone of ~ 2,500 μm x 2,500 μm.

| | | | | |
|---|---|---|---|---|
| **1** | **2** | **3** | **4** | **5** |
| **6** | **7** | **8** | **9** | **10** |
| **11** | **12** | **13** | **14** | **15** |
| **16** | **17** | **18** | **19** | **20** |
| **21** | **22** | **23** | **24** | **25** |

Fig. 3. The order of the measurements

After each new measurement, the mean and the standard deviation are calculated for each of the subgroups (1-2, 1-3,…, 1-25).

## 3. RESULTS AND DISCUSSION

The dispersions in 2D profile measurements on a single surface are well known and reluctantly accepted. Therefore, the common practice is to measure a number of profiles and to use the mean value when grading the quality of the surface. There are also standards that deal with these matters such as the 16% rule described in ISO 4288 [12].

The symbols are explained only for one of the analyzed parameter, *Sa*, but the symbol meaning is the same for all parameters of interest presented in this paper. The parameter is noted without index for the average value of all 25 measurements, else there is a subscript “av x” that signifies the average value of the parameter for x measurements. The following notations will be used in this study. They will be explained for the parameter Sa.

$Sa$ or $Sa_{av\,n}$ – the average value of the parameter *Sa* for the maximum number of measurements (here, 25)

$$Sa_{av\,n} = \frac{1}{n}\sum_{i=1}^{n} Sa_i \tag{1}$$

where $n$ is the number of measurements ($n=1, 2,\ldots, 25$), $Sa_i$ – the value of the parameter for the measurement $i$;

$Sa_{max}$ – the maximum value of the parameter *Sa* for all the measurement done on the same sample;

$Sa_{min}$ – the minimum value of the parameter *Sa* for all the measurement done on the surface part;

$\Delta Sa$ – the difference between the extreme values of the same parameter is calculated as:

$$\Delta Sa = Sa_{max} - Sa_{min} \tag{2}$$

$Sa^{s}_{av\,n}(\%)$ – the upper deviation of the parameter from the average value $Sa_{av\,n}$ to the maximum value of all measurements, as percentage:

$$Sa^{s}_{av\,n}(\%) = \frac{Sa_{max\,n} - Sa_{av\,n}}{Sa_{av\,n}} 100 \quad [\%] \tag{3}$$

$Sa^{i}_{av\,n}(\%)$ – the lower deviation of the parameter below the average value $Sa_{av\,n}$, calculates as:

$$Sa^{i}_{av\,n}(\%) = \frac{Sa_{min\,n} - Sa_{av\,n}}{Sa_{av\,n}} 100 \quad [\%] \tag{4}$$

Figure 4 presents the values obtained for all 25 measurements for the amplitude parameters taken into account for this study and in the right side of the plot there are given the average values for set of measurements. One may notice that the average for parameters *Sa* and *Sq* reach values close to the average obtained with all measurements after 5...6 measurements and they evolved in a narrow range as compared to the other amplitude parameters, especially *Sku* and *Sy*. This could be a characteristic of the coating technology, that is to have very high isolated peaks and narrow height distribution as *Sku* is greater than 3. *S10z* has a „translated evolution” as compared to *Sy* and thus it is of less interest when assessing the surface quality. Figure 5 presents several virtual images of the investigated areas for some extreme values of the amplitude parameters.

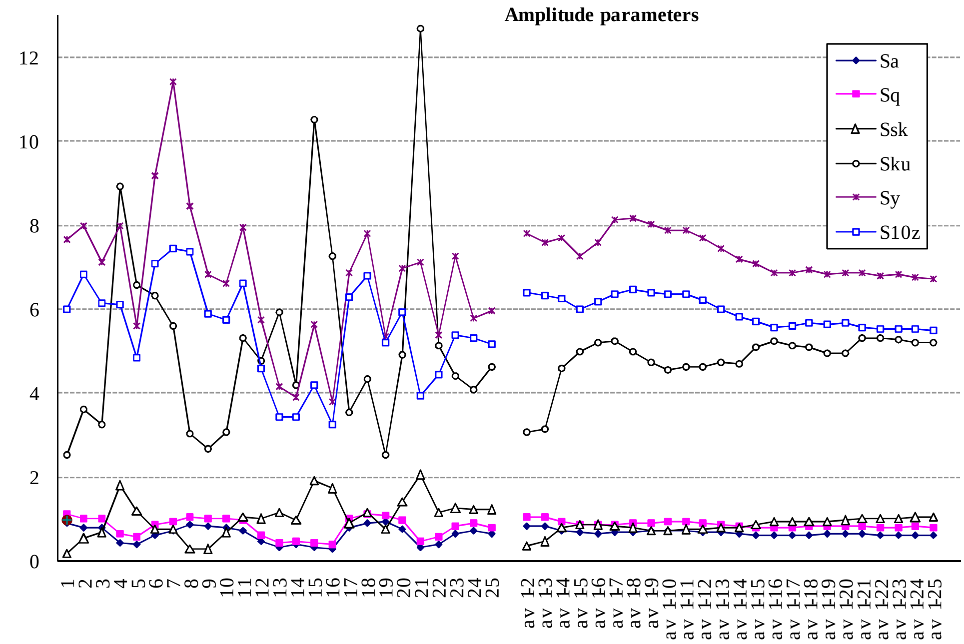
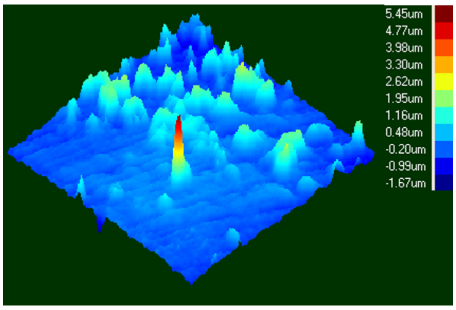
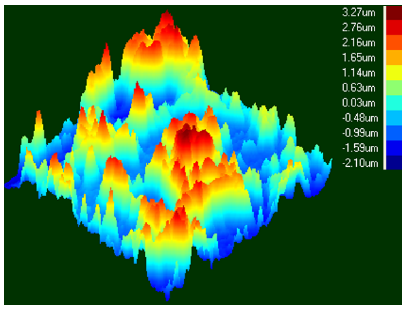


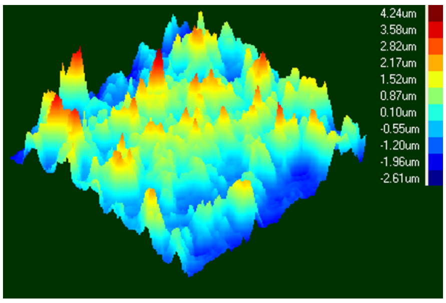

Fig. 4. The values of several amplitude parameters and their average values depending on the set of measurements



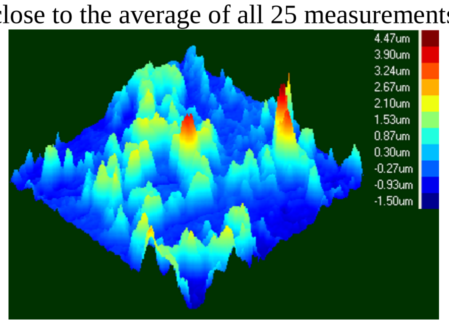

21th measurement: the maximum value for *Sku*




19th measurement: the area with *Sa*, *Sq* and *Ssk* close to the average of all 25 measurements




9th measurement: the minimum value for *Ssk* and *Sku*




25th measurement: the values for the amplitude parameters are closer to the average ones

Fig. 5. Some virtual images of the investigated micro-areas

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As for the hybrid parameters presented in Fig. 6, one may notice a „following" tendency for *Sdq* and *Sdq6*. All three parameters here presented reach an average close to the average for all measurements after 4...5 measurements. The investigator could analyze only one of the two parameters *Sdq* or *Sdq6*. *Sdr* has the same pattern as the other two parameters, but in spite of its large range of variation, the average value close to the value characterising the square of 2,500 μm x2,500 μm is reached after 4...5 measurements.

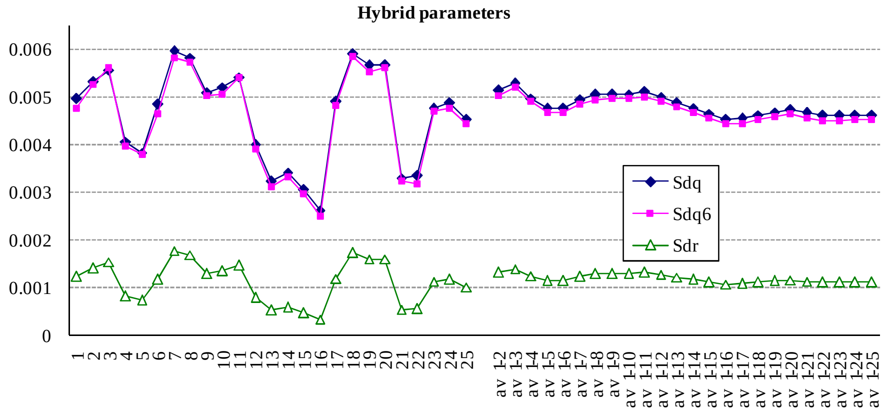



Fig. 6. The hybrid parameters

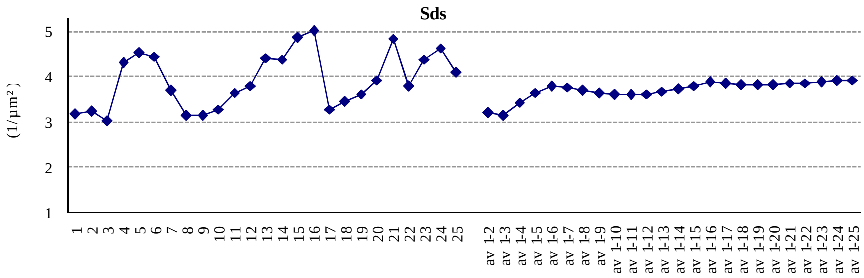



Fig. 7. The density of summits for the investigated micro-areas

Analyzing Fig. 6, one may notice that all three hybrid parameters has a "following" tendency, underlining that one could be enough for evaluating slope gradient of investigated area and the average close to the value obtained for the 25 measurements is reach after 4...5 measurements. *Sds* oscillates near 4 and except the first 3 measurements that gave lower value, the other calculated averages are in a narrow range (Fig. 7).

The functional parameters are of great interest in tribology as they could give information about the bearing capacity of the surface, the lubricant retention in the valley zone and the wear tendency of the upper part of the topography [1, 3, 8]. Figure 8 presents the values of the 25 measurements and the average calculated for sets of measurements. *Sbi* and *Svi* are quite insensitive to the measured area, meaning the material is uniformly distributed in these zones of the topography, as comparing one zone to the other and even *Sci* do not have a large variation after calculating its average from 4...5 measurements.

The other three functional parameters are spread in larger intervals, meaning they have to be investigated in order to assess the surface quality, especially for tribological applications. Therefore, they were presented again in Fig. 9 as a sum, *(Spk+Sk+Svk)*, for each micro-area and also in the right side of the plots there is the sum of the average value for each parameters – this could characterize a hypothetical equivalent topography of the actual one. This sum obtained as the sum of the average value for each parameter *Spk*, *Sk* and *Svk* is similar (as total value and individual values of the parameters) to those obtained for the micro-areas 5, 12, 22. Evaluating these parameters, the authors concluded that the laboratory coating technology could be improved in order to have more uniform distribution of these parameters. An imaginary topography characterized by the sum of maximum and minimum values of those parameters are also given in Fig. 9. For tribological applications, *Spk* should be lower and with narrower range of variations, meaning the technology generates high isolated "slim" peaks that will be worn very quickly. An imaginary surface having the minimum values for these three parameters is also given in Fig. 9, this results being very similar to the measurement 16, and close to the measurements 13, 14 and 15. Also, the core of the topography is not uniform distributed in the investigated area of 2,500 µm x 2,500 µm. Taking into account the finishing of the steel support, as presented in [2], it is possible that the spread of functional parameters *Spk*, *Sk* and *Svk* could be restricted by an improvement of the surface quality before applying the coating as the process tends to uniformly cover the substrate.

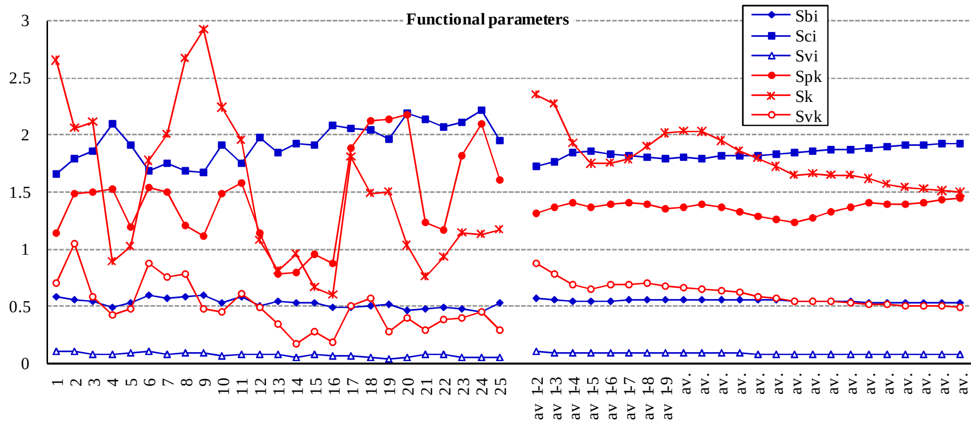



Fig. 8. The functional parameters

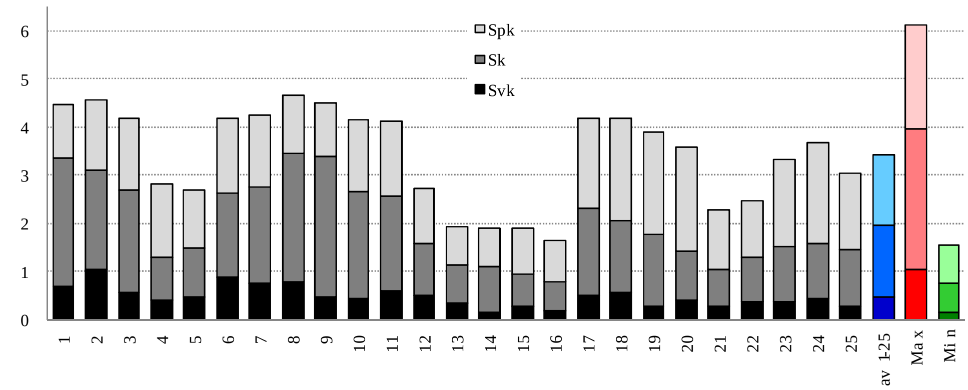
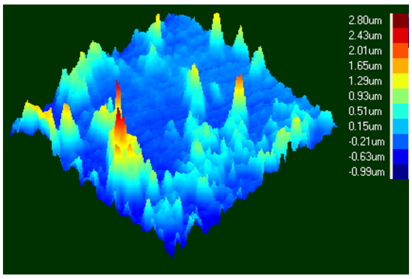
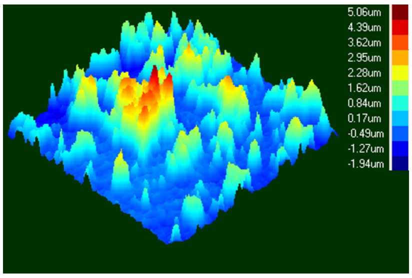


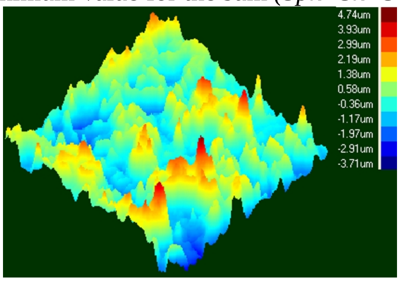

Fig. 9 The sum of the functional parameters *(Spk+Sk+Svk)*



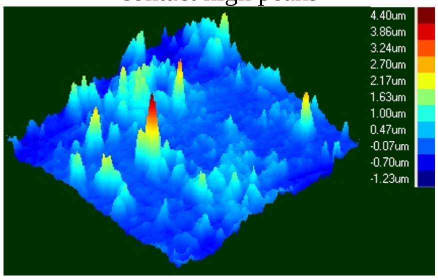
16th measurement: the micro-zone with the minimum value for the sum *(Spk+Sk+Svk)*



20th measurement: localized group of contact high peaks



8th measurement: the greatest value for the sum *(Spk+Sk+Svk)*



15th measurement: low values for the functional parameters, close to the imaginary topography characterized by their minimum values

Fig. 10. The virtual images for particular aspects of the functional parameters

In Table 1 there were done the following calculations for comparing the averages of each set of measurements. The explanations are given only for the parameter *Sa*.

$$\Delta Sa_{av(i,k,...)} = \frac{Sa_{av(i,k,...)} - Sa_{av(1-25)}}{Sa_{av(1-25)}} 100 \quad [\%] \tag{5}$$

where $\Delta Sa_{av(i,k,...)}$ is the relative difference (as a percentage) between the average obtained with all 25 measurements, $S_{av(1-25)}$, and the average of the selected set of measurements *i*, *k*, ..., $Sa_{av(i,k,...)}$. The position and the number of the measurement is according to Fig. 3.

Analyzing the values in Table 1, one may notice that for this type of surface, there are two groups of parameters taking into account their sensitivity to the measurement number:

- with a larger deviation from the average of the surface investigation (25 measurements): *Sku*, *Std*, *Sdr*,
- with narrow deviation from the same average value:
    - *Ssk* is very close to the imposed threshold, but
    - *Sa*, *Sq* and *S10z,* frequently used for surface quality assessment have a variation of around 10%,
    - *Sbi*, *Sci* and *Spi* are less sensitive to the number and location of the measurements.

The functional parameters *Spk* and *Svk* have a deviation from the average obtained from all 25 measurements, around 10%, but *Sk* is less, meaning that the core of the topography is more stable in high, this helping the idea that load could be supported similarly all over the surface.

Table 1. The comparison among three sets of measurements

| Para-meter, S | $av_{(1-25)}$ | The measurement set *(3,11,15,20)* | | The measurement set *(1,5,21, 25)* | |
|---|---|---|---|---|---|
| | | $S_{av(3,11,15,20)}$ | $\Delta S_{av(3,11,15,20)}$ [%] | $S_{av(1,4,21,25)}$ | $\Delta S_{av(1,5,21,25)}$ [%] |
| *Sa* | **0.6427** | 0.6407 | 0.32 | 0.5746 | 10.60 |
| *Sq* | **0.8248** | 0.8259 | -0.13 | 0.7473 | 9.40 |
| *Ssk* | **1.0563** | 1.2310 | -16.54 | 1.1745 | -11.19 |
| *Sku* | **5.2015** | 5.8820 | -13.08 | 6.6027 | -26.94 |
| *Sy* | **6.7474** | 7.0037 | -3.80 | 6.5883 | 2.36 |
| *S10z* | **5.5073** | 5.5918 | -1.53 | 4.9978 | 9.25 |
| *Sds* | **3.9284** | 3.9850 | -1.44 | 4.1625 | -5.96 |
| *Sdq* | **0.0046** | 0.0047 | -1.85 | 0.0042 | 9.98 |
| *Sdq6* | **0.0045** | 0.0047 | -3.24 | 0.0041 | 10.25 |
| *Sdr* | **0.0011** | 0.0012 | -3.71 | 0.0009 | 20.55 |
| *Sbi* | **0.5246** | 0.5329 | -1.59 | 0.5276 | -0.56 |
| *Sci* | **1.9261** | 1.9021 | 1.25 | 1.9116 | 0.76 |
| *Svi* | **0.0732** | 0.0699 | 4.41 | 0.0799 | -9.22 |
| *Spk* | **1.4392** | 1.4605 | -1.48 | 1.2874 | 10.55 |
| *Sk* | **1.4922** | 1.4639 | 1.90 | 1.3972 | 6.36 |
| *Svk* | **0.4875** | 0.4656 | 4.50 | 0.4382 | 10.11 |
| *Std* | **58.1655** | 70.1338 | -20.58 | 53.2688 | 8.42 |
| Stdi | **0.8598** | 0.8818 | -2.55 | 0.8580 | 0.22 |

Sampling the investigated surface at equal intervals could hide extreme values of the parameters. For instance, *Ssk* and *Sku* are smaller with 10% to 26% than the values recorded for all the investigated surface 2,500 μm x 2,500 μm, but *Sy* varies only with around ±4%.

The threshold of 16% was selected with reference to ISO 4288:2002 [12], but based on the engineer's experience and the nature of the investigated surfaces, this could be modified for a better evaluation of surface quality.

The number of measurements needed for calculating a stable mean value depends on which parameter is needed. It was found that it is often necessary to perform at least 5 measurements to obtain a stable mean value for many roughness parameters, while others needed a larger number. The reason for this is that there is often one or a few measurements that diverge from the expected normally distributed result.

It can be argued that this dispersion depends on the manufacturing process being unstable, resulting in a surface that is not equal at different places on a part. The point made here is that the investigated surfaces are typical engineering surfaces and the dispersions presented here will be closer the real one when measuring 3D surface roughness [1].

But this paper is dealing with quality assessment for coated surfaces with the help of top technologies and it is important to have a survey of the influence of the coating technology on the generated surfaces.

Analyzing Figures 6-9 and Table 1, the 3D parameters could be grouped in two categories:

– **more robust**: *Sq* and *Sa* are good examples of amplitude parameters with smaller dispersions and it is relatively less sensitive to sampling number of measurements;

– **less robust:** *Sku* is very sensitive to sampling number of measurements and has a large dispersion, meaning that the laboratory technology for surface finishing has to be improved in order to eliminate very high sharp and rare peaks; *Ssk* presents also a large dispersion (see Table 1, its deviations being limited by -16.54% and -11.19% of the average value of the parameter); it is worthy to point out that the average values for the sets of 4 measurements gave values always lower than the average of all measurements for *Ssk* and *Sku*, but relevant for an evaluation of surface quality.

calculating a stable mean value depends to a large extent on which parameter is needed. It was found that it is often necessary to perform at least 5 measurements to obtain a stable mean value for many roughness parameters while others needed a larger number. The reason for this is that there is often one or a few measurements that diverge from the expected normally distributed result.

It can always be argued that this dispersion depends on the manufacturing process being unstable, resulting in a surface that is not equal at different places on a part, especially for research and laboratory studies.

Therefore, all analyzed parameters do not obey that kind of rule (similar to the 16% recommended in [12, 13]) and further laboratory work is necessary for reducing their deviation range.

The number of measurements needed for the calculation of a stable mean value depends to a large extent on which parameter is needed. It was found that it is often necessary to perform at least 5 measurements to obtain a stable mean value for many roughness parameters while others needed a larger number. The reason for this is that there is often one or a few measurements that diverge from the expected normally distributed result.

## Conclusions

There were compared the amplitude parameters, spatial parameters and six functional ones for this type of surfaces in order to illustrate the statistical assessment of the surface quality by these parameters. The overall results showed that it was clear that a single 3D surface measurement is not normally sufficient to statistically quantify a surface, but the number of measurements required is usually below that required by 2D techniques. The required number is small, but none the less, this may be still too time-consuming in a production system.

For this coating technology a number of 4...5 measurements of 500 μm x 500 μm micro-areas, distanced by several millimeters could be able to give o good assessment of the surface quality.

The coated surfaces (as resulted from the applied technology) could not obey the rule of ±16% for spreading range around the average values, the authors pointed out higher values around the average one for this type of surfaces.

Analyzing the scattering of the amplitude parameters’ values it was concluded that the finishing of the surface on which the coating is deposited should be improved in order to reduce rare and randomly distributed high peaks.

Thus, the following conclusion could be given. It could be necessary to apply a technology (mechanical process as honing or polishing) after they are deposited, in order to have a better quality of this type of coatings.

## Annex. The 3D investigated parameters

**Amplitude parameters**

**The roughness average**, *Sa*, defined as

$$Sa = \frac{1}{MN}\sum_{k=0}^{M-1}\sum_{l=0}^{N-1}\left|z(x_k, y_l)\right| \quad \text{(A.1)}$$

**The root mean square**, *Sq*,

$$Sq = \sqrt{\frac{1}{MN}\sum_{k=0}^{M-1}\sum_{l=0}^{N-1}\left[z(x_k, y_l)\right]^2} \quad \text{(A.2)}$$

**The surface skewness**, *Ssk*,

$$Ssk = \frac{1}{M \cdot N \cdot S_q^3}\sum_{k=0}^{M-1}\sum_{l=0}^{N-1}\left[z(x_k, y_l)\right]^3 \quad \text{(A.3)}$$

**The surface kurtosis**, *Sku*,

$$Sku = \frac{1}{M \cdot N \cdot S_q^4}\sum_{k=0}^{M-1}\sum_{l=0}^{N-1}\left[z(x_k, y_l)\right]^4 \quad \text{(A.4)}$$

**The peak-peak height defined as the height difference between the highest point and the lowest one**

$$Sy = z_{max} - z_{min} \quad \text{(A.5)}$$

**Functional parameters**

**The surface bearing index**, *Sbi*,

$$Sbi = \frac{Sq}{Z_{0.05}} \quad \text{(A.8)}$$

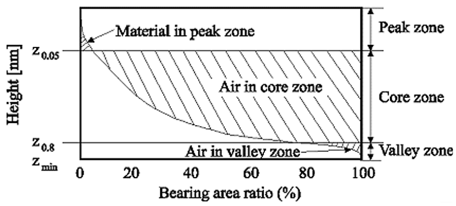



Fig. A.1. Bearing curve illustrating the calculation of *Sbi*, *Sci* and *Svi*

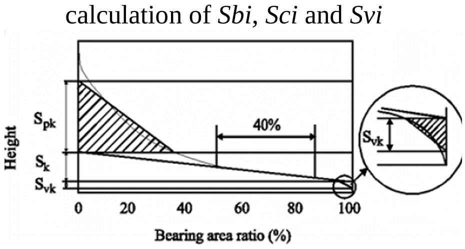



Fig. A.2. Bearing curve illustrating the calculation of *Spk*, *Sk* and *Svk*

where $Z_{0.05}$ is the distance from the top of the surface to the height at 5% bearing area.

**The core fluid retention index**, *Sci*,

$$Sci = \frac{1}{Sq}\frac{V_v(h_{0.05}) - V_v(h_{0.80})}{(M-1)(N-1)\delta x \cdot \delta y} \quad \text{(A.9)}$$

where $V_v(Z_x)$, is the void volume over the bearing area ratio curve and under the horizontal line at $h_x$, here $x$ being equal to 0.05 and 0.80, respectively.

**The valley fluid retention index**, *Svi*,

$$Svi = \frac{1}{Sq}\frac{V_v(h_{0.80})}{(M-1)(N-1)\delta x \cdot \delta y} \quad \text{(A.10)}$$

**The reduced summit height**, *Spk*, **the core roughness depth**, *Sk*, and **the reduced valley depth**, *Svk*, are given in Figure A.2, according to [13].

**Hybrid parameters**

**The root mean square slope**, *Sdq*, is the RMS value of the surface slope with the sampling area, defined as:

$$Sdq = \sqrt{\frac{1}{(M+1)(N+1)}\sum_{k=0}^{M-1}\sum_{l=0}^{N-1}\left(\frac{z(x_k, y_l) - z(x_{k-1}, y_l)}{\delta x}\right)^2 + \left(\frac{z(x_k, y_l) - z(x_k, y_{l-1})}{\delta y}\right)^2} \quad \text{(A.11)}$$

**The area root mean square slope**, *Sdq6*, is similar to *Sdq*, but includes more neighboring points in the calculation of the slope for each point.

**The surface area ratio**, *Sdr*, is the difference between the interfacial area relative to the area of the projected flat plane ($x$, $z$):

$$Sdr = \frac{\sum_{k=0}^{M-2}\sum_{l=0}^{N-2} A_{kl} - (M-1)(N-1)\delta x \cdot \delta y}{(M-1)(N-1)\delta x \cdot \delta y} 100\,[\%] \qquad (A.7)$$

**Spatial parameters**

**The density of summits**, *Sds*, is the number of local peaks per unit of area. The texture direction, *Std*, is the angle of the dominating texture of the investigated area. The texture direction index, *Stdi*, is a measure of how dominant the dominating direction is [13].

For all relationships presented in the Annex, *M* are the number of lines and *N* the number of points on each lines, δx and δy are the distance between 2 points along the x and y axe, respectively.

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