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AN ANALYSIS OF SLOPE OF SURFACE TOPOGRAPHY

The fundamental aim of this paper is to assess various methods of surface topography slope calculations. Computer generated and measured 2-D profiles and 3-D surface topographies of random and asymmetric ordinate distributions were analysed. The paper examines the use of various differential formulae for the calculation of surface slope. The effect of measurement errors on random profile slope was analysed. Dependence among slope and other parameters, relation between average and rms slope as the measure of profile asymmetry were studied. Variation of profile slope was examined. Prediction of surface slope after 2 processes was performed. The errors of obtaining surface slope based on profile slopes in orthogonal directions were analysed based on computer generated and real surface topographies. The deviation between profile slopes in two orthogonal direction as the measure of anisotropy of honed cylinder surfaces was examined.

Keywords: surface topography, slope, measurement errors

1. INTRODUCTION

Height parameters are very useful for prediction of the sustainability of the surfaces under hydrodynamic lubrication, where the oil film thickness should be sufficient to completely separate the surfaces. In boundary lubricated or dry friction regimes they are not simply related to tribological functions. A criterion of asperity deformation is the so-called plasticity index. Its first method of calculation was developed by Greenwood and Wiliamson [1], and then by Whitehouse and Archard [2]. There are approaches based on profile slope [3, 4, 5]. From topographical properties of the surface, slope is the most substantial [6].

However, the average slope is not an intrinsic property of the surface, so it is necessary to consider slopes in various scales. On paper [7] some scales of slopes were analysed. The slopes of asperities were measured and used to predict the boundary-lubricated friction and wear coefficient of cam-rocket assembly.

In publication [8] based on application of fractal geometry theory, a quantitative assessment method of rms slope of 3D surface topography was recommended, by means of the concept of surface spectral moments. The same authors in Reference [9] evaluated the anisotropy of surface by the variances of the profile slope (2nd profile spectral moments). This variance cannot express only the amplitude distribution, but also shows its frequency behaviour.

Second profile spectral moment can be obtained [10]:

$$m_2 = \int_0^\infty \omega^2 G(\omega) d\omega = \pi^2 m_0 d_z{}^2 = 2(R_0 - R_1)/(\Delta x)^2 \,, \tag{1}$$

where: $G(\omega)$ is profile spectral density, m_0 - 0th profile spectral moment, Δx - sampling interval, R_0, R_1 - values of autocovariance function of first and second points.

But the average profile slope of profile of normal ordinate distribution is [11]:

$$\Delta a = \left(\frac{2m_2}{\pi}\right)^{0.5}. \tag{2}$$

Nayak [11] developed the following equation for 3D slope:

$$S_{\Delta a} = \left(\frac{\pi m_2}{2}\right)^2 = \frac{\pi}{2}\Delta a. \tag{3}$$

Average slope Δa or root-mean square (rms, Δq) slope are commonly used. Chetwynd examined the use of the three-, five- and seven-point Lagrangial differential formulae in the context of surface texture analysis [12]. The error in measuring rms slope by them relative to the theoretical values for sinewaves, full-wave rectified sinewaves and Gaussian random signals has been shown to reduce as the number of points in formulae increases.

In works [13, 14] a conformal surface model was proposed. It is based on the joint of segments of increasing profile slope. It can be used for example to evaluate anisotropy or profile asymmetry. This method can be extended into three dimensions.

Some instruments operate essentially as slope- measuring devices. Interferometric profiling instruments based on Nomarski microscope are the example. The surface slope is calculated at each point and the profile is calculated by integrating the slope data [15]. In the geometrical optics regime the angular distribution of the scattered light is related to surface slope distribution [15, 16]. The author of book [17] found a strong correlation between surface rms slope and the ellipsometry parameter. He also elaborated a glossmeter, for which the signal is correlated with the surface rms slope.

Most conventional surface measuring instruments have a limited slope capability. The stylus cannot accurately measure a profile over slopes grater than 90° minus the flank angle. Flank angles of 45° and 30° are commonly available. The slope limitation is a problem for measurements of surfaces with steep cracks or holes, such as those on ceramics or cast materials [18]. With the analysis of stylus flank angle and through the analysis of local slopes, a determination of the presence of re-entrant features (folds, micro-burst etc) can be made [19]. There are problems using optical focus methods during analysis of surfaces of great slopes [20]. When steep slopes are encountered on a specimen surface, the scanning focus spot loses focus and rapidly searches for focus, what leads to rogue spikes and sharp pits being falsely registered [21, 22]. For interferometric instruments, rapid slope changes trouble most systems, this is due to insufficient returned light resulting from angled reflection and because of fringe ambiguities [22]. White light vertical scanning interferometer can induce artifacts close to sharp, steep slopes on the surface [23]. A high slope capability of the SEM and low slope capability of optical profilers were found [24]. Recently many new techniques have been developed through several EU projects so slope limitation wouldn't be a serious problem in the near future.

2. THE AIM AND SCOPE OF THE INVESTIGATIONS

The fundamental aim of this paper is to assess various methods of slope calculation in 2D and 3D systems. The additional aim is to analyse slope properties of random surfaces.

The scope of the investigations contains:

- the analysis of profiles of known slope,
- study of measurement error effects on profile slope,
- the analysis of slope parameter relations to other parameters for random profiles,

- the analysis of real profile slope symmetry,
- the study of profile slope repeatability,
- relation of average and rms slope as measure of asymmetry of random surface ordinate distribution,
- the analysis of methods of slope distribution presentation,
- prediction of slope of random surfaces after two processes,
- prediction of 3-D surface slope based on 2-D profile slopes in orthogonal directions,
- the analysis of slope relation in orthogonal directions as the measure of honed cylinders anisotropy.

3. METHODS

Real and computer generated random profiles were analysed. Profiles of random ordinate distribution and special shape of aucocorrelation function and triangular profiles were computer generated. The method of simulating profiles after two processes is based on a probability method of their characterisation [25] (see Fig. 1). The modelled profile was created by superposition of 2 profiles: PP (plateau) and PV (valleys). Each profile was characterised by 2 parameters, height standard deviation (called *Rpq* for plateau profile and *Rvq* for valley profile) and horizontal. The distance between mean lines of two profiles is called DIS.

For each point "i" of two profiles: PP (plateau) and PV (valleys), if PP(i) < PV(i) then resulted profile PR(i) = PP(i), in other case PV(i).

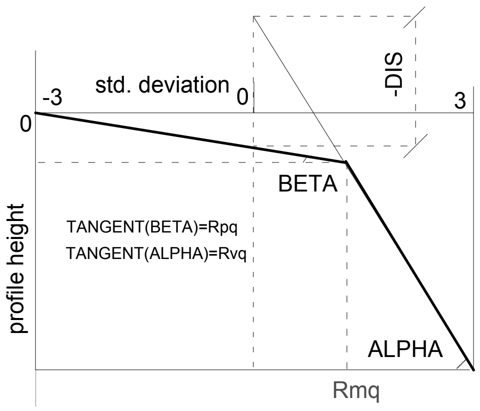


Fig. 1. Method of description of profile after two processes.

The analysis of 3D computer-generated surfaces was done. Iso- and anisotropic surfaces of exponential shape of auto correlation function were generated. The results of measurement of some surfaces were analysed (after turning, vapour blasting, shot peening, grinding, barrel finishing, honing, polishing and others, as well as of engine parts -pistons, pins, cylinders, small pistons from Diesel fuel pumps and others after engine operating).

3.1. The analysis of profiles of known slope

In order to obtain a profile rms or average slope, three formulae can be used. Equations based on 2, 3 and 7 neighbouring points were selected. The following formulae are used for calculating local slope, respectively:

$$\frac{dz_i}{dx} = \frac{z_i - z_{i-1}}{\Delta x} \quad , \tag{4}$$

$$\frac{dz_i}{dx} = \frac{z_{i+1} - z_{i-1}}{2\Delta x} \quad , \tag{5}$$

$$\frac{dz_i}{dx} = \frac{z_{i+3} - 9z_{i+2} + 45z_{i+1} - 45z_{i-1} + 9z_{i-2} - z_{i-3}}{60\Delta x} \quad , \tag{6}$$

where z_i - ordinates of profile points.

Chetwynd [12] found out that the method based on 7 points is better than the method based on 3 points. The method based on 2 points is used by old software of roughness measuring equipment builders, and approximately in ISO 4287 - 1984 standard. What is the difference between the slope calculated according to Eqs. (4) and (5)? Both are two-point slope (however Eq. (5) will be called three-point slope), the only difference is that one (Eq. (4) is at sampling interval Δx, the other at sampling interval $2\Delta x$.

Most comparatively new programs are based on the 7-point Lagrangian differential formula (Eq. (6)) as specified in ISO 4287-1996. In this version only the rms slope exists. 7-point equation was used in order to minimise the effect of high-frequency noise.

In order to find what equation is correct it is necessary to compute the slope when its correct value is known. It is believed that the 2-point formula should be better than the 7-point formula and one can obtain the worst results using a 3-point equation (when sampling interval was Δx).

Profiles consisting of straight lines of known slope and random profiles were used.

In the first case (straight lines) it was found that when the distance between lines (measured as the number of digital points) was big, the error obtained using the 7-point formula was a smaller than the error obtained using the 2-point equation. During sampling interval increase the change of average slope based on 2-point equation was smaller in comparison to 7-point equation. In this case the decrease of average slope were bigger than that of rms slope.

Computer generated random profiles of normal ordinate distribution were analysed. The autocovariance function of this profile type is described by the following equation:

$$R(\tau) = \sigma^2 e^{-k\tau^2} \,. \tag{7}$$

The rms slope should be similar to [12]:

$$\Delta q = \frac{\sigma}{\Delta x}\sqrt{\left|2\ln(\rho_1)\right|} \quad , \tag{8}$$

where: σ - standard deviation of profile height, τ - spatial distance, k - the constant, ρ_1 - the correlation coefficient of second point, Δx - sampling interval.

It was found that Δq values obtained by Eq. (8) were the most similar to rms slopes received using 2 point-formula, then 7 and 3-point formula.

Rms slope was also computed based on autoccorrelation function [10], see Eq. (1) for profiles of normal ordinate distribution and exponential shape of autocorrelation function. Rms slope based on the 2-point equation was very similar to this value.

From the considerations presented above one can conclude that the method based on 2 points gave usually a better value than the method based on 7 points.

3.2. Effects of errors of surface measurement using stylus instruments on a slope

Various effects on real and computer-generated profile slope were digitally simulated (the influence of sampling interval, quantisation errors, digital filtration, use of single skid, flat and rounded tip, high-frequency noise, singular scratch) using software developed by the author. Modelling the effect of rounded skid was based on the procedure described in Reference [26]. The effect of high frequency noise was simulated by addition of random or sinusoidal profile of small wavelength to the original profile.

The slope of random surfaces depends on the short-wavelength limit. We measure only finite difference approximation to slope of, tending to infinity as the sampling interval is reduced to zero. Increase of sampling interval, size of the stylus tip (flat or rounded), and short-wavelength cut-off cause a decrease of the slope.

During a sampling interval increase, the change of average and rms slope calculated using the same method was similar. Changes of slope values determined by 2-point and 7-point methods were similar for simulated surfaces, in the case of real random surfaces the 7-point method caused slightly greater changes.

The transmission bands were introduced into standards. After applying the short wavelength cut-off phase correct filter λ_s a primary profile is obtained. The main difference between the sampling interval and the short cut -off change was that during low-pass filtration the height parameters had a tendency to decrease. When only a long-wave high-pass Gaussian filter was used, the change of slope was small.

The effect of the rounded radius of stylus tip was similar to short wavelength low-pass filtering. In these cases the decrease of slope of random profiles of normal ordinate distribution obtained by the 2-point method was the biggest, 7-point smaller and 3-point – the smallest, the decrease of the average and rms slope was similar. In the case of flat stylus tip the change of average slope was bigger than that of rms slope. The smallest changes were obtained when the 3-point formula was used, the 7-point equation caused bigger, 2-point – the biggest changes. The effect of mechanical filtration on other surface parameter changes is described in References [27, 28].

Changes of parameters caused by a sampling interval increase, short wavelength low-pass filtration and size of stylus tip depend on the correlation between the neighbouring ordinates, when it was smaller – the change was greater. The effect of a circular tip is also proportional to the profile height.

Figure 2 presents a change of the average slope (calculated according to the 7-point formula) caused by a sampling interval increase. Simulated profiles of random ordinate distribution and exponential shape of autocorrelation function of various correlation lengths were analysed.

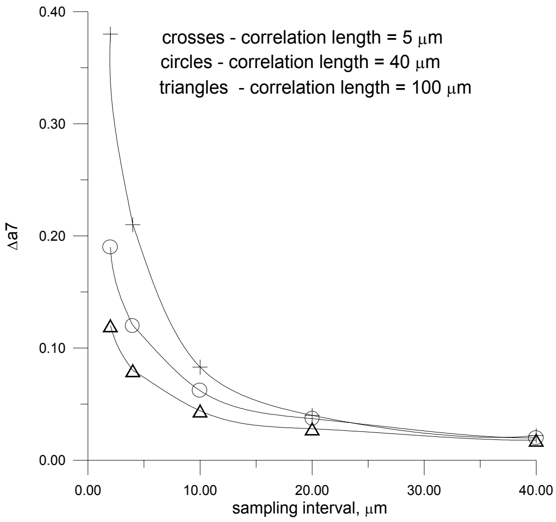


Fig. 2. Sampling interval effect of average slope changes of modelled random profiles.

The effect of the singular skid mechanical filtration on slope values is small. It was found that the difference of slopes of measured and levelled profiles was also small. The biggest differences were found when the average slope was calculated according to the 2-point formula, but they were always smaller than 1% (only 2-point and 7-point were analysed).

The slower the stylus moves, the finer details can be resolved. At the other end of the scale, the stylus flight is possible - it is the possibility for the stylus to lose contact with the surface because of a rapid impulse, such as a rising surface step. The parameters that affect this phenomenon are stylus speed, stylus force on the surface, damping constant in the vertical direction, and surface characteristics - the amplitude and spatial wavelength on the surface (surface slope). In the majority of results, profile height, slope, peak density and curvature decreased, horizontal profile parameters increased. The decrease was biggest at greatest measuring speed. For example, an increase of traversing speed from 0.5 to 3 mm/s caused a decrease of slope to about 30% (see [29]).

Surface slope didn't change substantially when the number of height levels was not smaller than 100. Usually a decrease of the number of digital levels caused a decrease of deviation $\Delta a/\Delta q$, particularly if correlation between neighbouring points is big (the errors were small when the correlation between measuring points was smaller than 0.9). The effect is smaller when the 7-point Lagrangian differential formula was used (instead of 2-point method). Details are given in Reference [30].

The described character of 2-D profile slope distortion (caused by mechanical filtration, high-pass digital filtration, stylus flight, quantization and sampling) was confirmed in the 3-D surface topography case.

In real measurement, high-frequency noise can greatly affect the stability of slope estimation. Noise can be caused by instability of the mechanics with any influences from the environment or by internal electrical noise. Most of the most important high-frequency noise is the result of vibration.

Slope and peak radius of curvature are considerably affected by noise. The effect of noise on slope increase was the smallest at high signal-to-noise ratio. The influence of noise on slope was bigger for bigger differences between the frequency of noise and of the original signal. The tendency of slope increase depends on the character of noise. Random noise caused bigger changes of rms than average slope, changes of slope calculated by the 2-point formula were bigger than when the 7-point formula was used. Sinusoidal noise caused opposite tendencies (bigger changes or rms. slope, smaller changes caused by 2-point equation). However, average differences were smaller than 10%. The influence of noise on slope was bigger for higher frequencies of noise. This effect was smaller for smaller spacing parameters of the original signal.

Outliers (i.e. strong spike-like components) may represent anomalous behaviour, e.g. random measurement errors. The increase of the average profile slope, caused by individual peak or valley existence on the profile of random ordinate distribution, was smaller than that of an rms slope. The change of average slope calculated by the 3-point formula by an imposed triangular scratch was the biggest, with 7-point – smaller, with 2-point – the smallest. As was possible to predict, changes of parameters were bigger when the ratio of the scratch height and amplitude standard deviation of random structure was bigger. The change of slope was bigger when the width of the scratch was smaller and the horizontal parameters of the random part were bigger. Figure 3 presents two profiles with triangular scratches. Change of slope after introducing the scratch shown in the upper graph was bigger. The isotropic surfaces with two scratches were analysed. It was confirmed that the presence of the scratches affects mainly the rms than the average slope of 3-D surface topography.

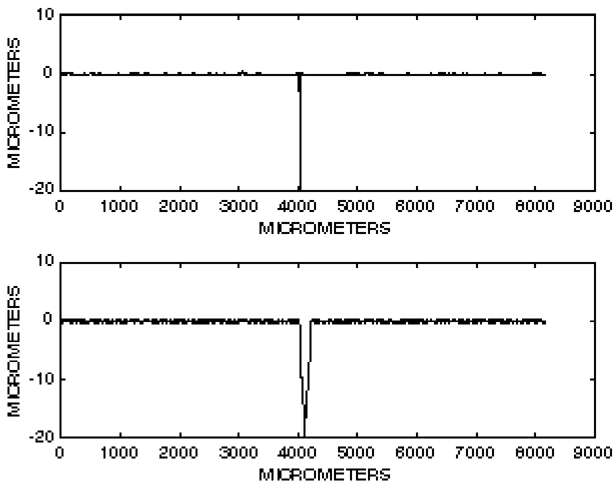


Fig. 3. Fine profile of Rq parameter 0.1 μm with superimposed scratches of width 40 μm (upper graph) and 200 μm (lower graph). The correlation length of the upper profile was 100 μm, of lower profile 10 μm.

One can see that not always the 7-point formula caused smaller measurement errors than the 2-point equation.

3.3. Slope relations to other parameters of random surfaces

In calculations an unfiltered profile was analysed without using a short wavelength filter. The slope depends on height and horizontal surface features. It is proportional to height and inversely proportional to spacing parameters. During analysis of generated profiles of normal ordinate distribution and exponential shape of autocorrelation function it was found that profile slope is proportional to inversion of *Sm* when the profile height is the same. Figure 4 presents the effect of surface height on the average profile slope angle (in other Figures tangent of slope was given) calculated according to 7-point Lagrangian differential formula. It also presents a similar effect of the horizontal parameter *Sm*. The biggest slope exists when the horizontal parameter is the smallest and the amplitude parameter is the biggest.

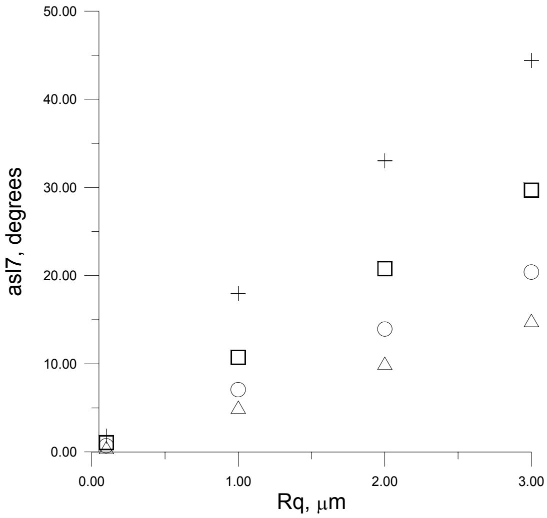


Fig. 4. The effect of amplitude and spacing on average slope angle values for computer generated random profiles (crosses - *Sm* = 11 μm, squares - *Sm* = 23 μm, circles - *Sm* =37.4 μm, triangles - *Sm* = 57 μm).

The slope parameters of modelled profiles of random ordinate distribution were also correlated with the curvature of peaks (the linear coefficient of correlation "r" was about 0.99). It was also found that the rms slopes were about 1.25 of the average slope. But the values of slope calculated according to 3-point formula were about 0.7 (0.71 - 0.75) of slope values calculated according to the 7-point Lagrangian differential equation, but the last results (7-point formula) were about 0.85 - 0.9 of slope values calculated using the 2-point method.

After analysis of simulated profiles after 2 processes, a very strong dependence between profile slope and peak curvature (the correlation coefficient was bigger than 0.93) was found, similarly to the modelled profiles after one process. The slope divided by standard deviation of height was inversely correlated with *Sm* and correlation length (distance, in which the autocorrelation function decays to 0.1 value); the linear coefficients of correlation were about -0.65.

In two cases described above the profile slope was correlated with height parameters. About 30 measured random profiles of different ordinate distribution after various processes were analysed. The dependencies between slope and peak curvature ("r" was about 0.9), and height parameters (for example with *Rq* 0.85), but not spacing parameters were found. Profile slope divided by *Rq* was inversely correlated with *Sm* ("r" was about -0.8), with correlation length (about -0.75) and positively with peak density (0.6 - 0.65).

25 random surface topographies were additionally studied. Parameter $S\Delta q$ was correlated with *Sq* ("r" = 0.7), developed surface area ratio *Sdr* (0.93) and average summit curvature *SSc* (0.94). The dependence between $S\Delta q$ and *Sdr* can be easily explained. For comparatively small slope values $Sdr \approx S\Delta q^2/2$. Surface slope divided by *Sq* was inversely correlated with fastest decay of autocorrelation function *Sal* ("r" was about -0.75) and positively with density of summits *Ssc* (about 0.55).

The connection between slope and surface amplitude is obvious; the rougher surfaces have steeper slopes.

After study of random real profiles it was confirmed that slope values based on the 3-point equation are the smallest. Average and rms slopes obtained using the 2-point formula were similar or bigger (mainly if the sampling interval was bigger than stylus tip size) than the value based on the 7-point equation. The difference was usually greater for greater sampling intervals.

3.4.The analysis of slope distribution symmetry of real profiles

The new standard ISO 4287-1996 does not define precisely the exact form of the root mean square slope $P\Delta q$, $R\Delta q$, $W\Delta q$ of the assessed profile calculation.

Usually the following method of rms slope is used [22]:

$$\Delta q = \sqrt{\frac{1}{l}\int_0^l \left(\frac{dZ}{dx}\right)^2 dx} \ . \tag{9}$$

However the following equation for rms slope (as slope standard deviation) of the profile is sometimes used [31]:

$$\Delta q = \sqrt{\frac{1}{l}\int_0^l \left(\frac{dZ}{dx} - \overline{\frac{dZ}{dx}}\right)^2 dx} \ , \tag{10}$$

where:

$$\overline{\frac{dZ}{dx}} = \int_1^l \frac{dZ}{dx} dx \ , \tag{11}$$

l is the sampling length.

Usually the average slope is obtained by calculating the mean absolute slope (the mean of the moduli of the slopes). This is given by [22]:

$$\Delta a = \frac{1}{l}\int_0^l \left|\frac{dZ}{dx}\right| dx \ . \tag{12}$$

But similarly to Eq. (10) a different formula is possible:

$$\Delta a = \frac{1}{l}\int_0^l \left|\frac{dZ}{dx} - \overline{\frac{dZ}{dx}}\right| dx \ . \tag{13}$$

The results obtained by Eqs. (9) and (10), as well as (12) and (13) are the same only for symmetrical profile slope distributions.

These equations were used for real profiles of various shapes of the ordinate distribution. Rms and average slopes were calculated by 2 and 7-point formulae. It was found that rms slopes were very similar independently of subtracting the mean slope (not absolute value) during calculation.

The average slopes obtained using the 7-point formula using two possible methods were almost the same. However for some profiles the Eq. (13) gave smaller slope values than Eq. (12), when the 2-point formula was used, but differences were small. So the mean local profile slope was very small.

Figure 5 presents the distribution of slope of honed cylinder profiles. Gathering segments of increasing profile local slope did it. It is a modification of the method presented in Reference [13].

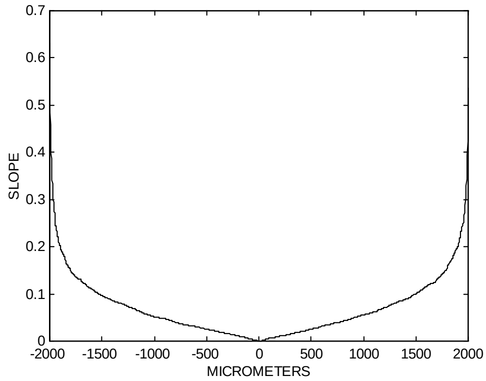


Fig. 5. Slope distribution of honed cylinder profile.

3.5. The analysis of profile slope variation

The slope is seriously affected by high-frequency noise. It could affect its variation. Therefore for 3-dimensional random machined surface topographies the repeatability of average slope and rms slopes of the parallel profile constituted surface in two orthogonal directions was established. The parameters were calculated in relation to a reference plane. Other profile parameters were also analysed. It was found that for isotropic and anisotropic surfaces with a small degree of anisotropy the coefficient of variation of average slope was similar or smaller than of height parameters in two orthogonal directions. Variation of rms slope is bigger than of average slope. Slope repeatability was independent of the method of its calculation (slope was calculated basing on 2 and 7 neighbouring points). For strongly anisotropic surfaces (where the relation of average slopes in orthogonal directions was bigger than 3) the repeatability of height parameters could be better than that of the slope, particularly in the direction orthogonal to lay). After analysis of 15 machined random isotropic and anisotropic surfaces it was found that the average value of the coefficient of variation (relation of the standard deviation to mean parameter value) of profile average slope was the smallest (15 %). The following values for other analysed parameters: rms slope 19%, *Rq* 31%, *Ra* 24%, *Rt* 35%, *Rku* 45%, *Rp/Rt* 21%, *pc* 17%, λa 22% were obtained.

3.6. Ratio of average and rms slope as a measure of asymmetry of random surface ordinate distribution

Relation $\Delta a/\Delta q$ ($S\Delta a/S\Delta q$) can be a measure of asymmetry of the surface profile (topography) ordinate distribution. The interdependencies between $\Delta a/\Delta q$ ($S\Delta a/S\Delta q$), skewness *Rsk (Ssk)*, the emptiness coefficient *Rp/Rt (Sp/St)* and *Ra/Rq (Sa/Sq)* were studied based on simulated and real random profiles and surface topographies (about 20 profiles and 20 3-D surfaces were analysed). These parameters for profiles and surfaces were intercorrelated (the linear coefficient of correlation was always bigger than 0.6). Figure 6 presents the dependence between the $\Delta a/\Delta q$ relation and the emptiness coefficient *Rp/Rt* for plateau honed and worn profiles (the correlation coefficient was about 0.8).

The effects of sources of errors (digital filtration, sampling interval change, mechanical filtration, skid effect) on $\Delta a/\Delta q$ value are small (similarly to *Ra/Rq*), except on mechanical filtration by the flat tip and quantisation errors (see chapter 4.2). This tendency was confirmed during the analysis of surfaces in 3 dimensions. Changes of other analysed parameters were bigger. The repeatability of $\Delta a/\Delta q$ profile parameter on a random surface is the biggest of the mentioned parameters. The *Ra/Rq* parameter value is also constant on the surface profiles.

Repeatability of parameters *Sa/Sq* and *S*Δ*a/S*Δ*q* on surface topographies was also the biggest. The effect of individual scratches on Δ*a*/Δ*q* parameter was the smallest from the analysed parameters. The sensitivity of *Ra/Rq* on individual scratch existence was a little bigger. Similarly, in a 3D system the effect of an individual scratch on *S*Δ*a/S*Δ*q* and *Sa/Sq* was the smallest. When the number of valleys increased – change of average/rms slope relation became bigger. This reaction is opposite to skewness changes.

However the Δ*a*/Δ*q* (*S*Δ*a/S*Δ*q)* relation should be used with caution – it could be smaller in the case of some non statistical peaks existence, when the emptiness coefficient was big and the skewness positive.

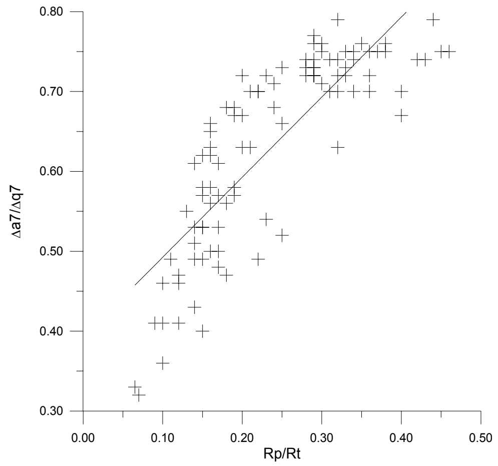


Fig. 6. Dependence between relation of average slope and rms slope and emptiness coefficient *Rp/Rt*

3.7. Presentation of slope distribution

There are various possibilities of presenting the slope distribution. the profile of local slope can be presented, its abscissa corresponds to the profile length. From the local slope graph one can obtain information about surface irregularities of very big local slope (profile defects [19]). This graph can be analysed in various ways similarly to profile analysis.

Another method of slope presentation is based on the conformal profile model [13, 14]. An equivalent profile is built by gathering segments of similar slope. It can be used for example to the analysis of profile asymmetry. The slope distribution versus height is very interesting. It can be obtained by summation of absolute local slope in the same height intervals and dividing it by the number of points within its interval. That graph can be very important from a tribological or contact point of view, especially during the study of a surface after two processes. For profiles of normal ordinate distribution the slopes of valley and peak parts are rather similar. When the plateau part has a smaller slope than the valley part - its slope part is smaller. Figure 7 presents slope distribution versus profile height for a profile of normal ordinate distribution (dashdot line) and after two processes, when the slope of fine part is smaller (solid line).

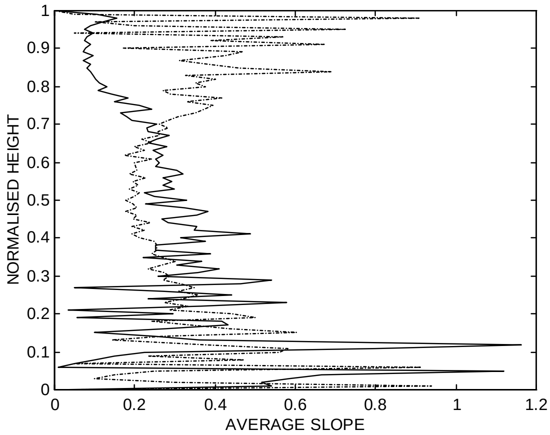


Fig. 7. Average slope distribution for profile of normal ordinate distribution (dashdot line) and profile after two processes (solid line).

3.8. Prediction of profile slope after 2 processes

The possibility of predicting the profile slope after two processes is interesting, when the slopes of Gaussian profiles constituted final profile are known. The resulted slope Δ_r should be:

$$\Delta_r = \Delta_p Rmq + \Delta_v (1 - Rmq) \ , \tag{14}$$

where: Δ_p and Δ_v - slopes of plateau and valleys parts, (*Rmq* should be linear from 0 to 1).

The computer experiment was done in order to confirm it. About 80 computer generated profiles were analysed. *Rmq* parameter in linear scale was between 50 and 90 %, but the *Rvq/Rpq* ratio was between 6 and 17. It was found that errors of obtaining average slopes Δa were very small (average errors were about 4%). This tendency was confirmed for $S\Delta a$ slope of isotropic random surfaces.

The errors of parameter Δq assessment were bigger (average values about 20%), which were possible to predict, because rms slopes are sensitive to the existence of valleys.

3.9. Prediction of 3-D surface slope

Surface slope at any point is equal to the square root of sum square of slopes in two orthogonal directions. The dependence between surface and profile average slopes (Eq. (3)) was confirmed independently of the method of slope determination for simulated Gaussian random isotropic surfaces. The differences were not bigger than 6%.

For two-dimensional surface spectral moments of second and fourth order should be equal to the square root of the product from moments obtained in two perpendicular directions [10].

So the equivalent rms slope and average slope of profile surfaces of normal ordinate distribution should be equal to the geometric mean from average slopes from perpendicular directions, for example:

$$\Delta a = \sqrt{\Delta a_x \Delta a_y} \tag{15}$$

and the surface average slope should be equal to this value multiplied by $\pi/2$. The suffixes x and y refer to directions across and parallel to lay.

During the investigation of computer created two-dimensional surfaces this dependence was confirmed. Errors of determining the surface average slope usually were smaller than 4%, only for strong anisotropy they were bigger. In these cases the errors were smaller when the equivalent slope was an arithmetic mean of average slopes in perpendicular directions:

$$\Delta a = \frac{\Delta a_x + \Delta a_y}{2}. \tag{16}$$

It was found that if the relation of bigger to smaller average slope values in 2 perpendicular directions was greater than 3.5 the smaller error was obtained if the 3-D surface (of Gaussian ordinate distribution) slope was equal to the bigger slope.

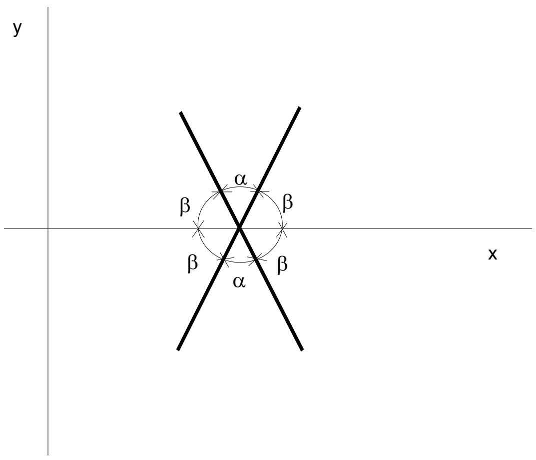
An attempt was made in order to find if this relation can be used to simulated two-dimensional surfaces inclined to the axis of measurements. For geometric mean, the average errors after using 2-, 7- and 3- point equations were equal to 5, 4.8, 2.2 %, arithmetic mean reduced errors to: 2.4, 3.4, 0.9 %.

Computer generated isotropic and anisotropic 3D surfaces after 2 processes (procedure of generation was the same as for profiles) were analysed in order to find out if the described dependence between surface and profile slope takes place in this case (it was predicted only for surfaces of normal ordinate distribution [11]). The slope was calculated based on 2- and 7-point formulae. When the equivalent average profile slope of two-dimensional surfaces was equal to the geometric mean of slopes from two perpendicular directions, mean errors of surface average slope were in the range 3.5 - 4.1%. For the case of anisotropic surfaces (the ratio of average profile slopes in orthogonal directions was smaller than 3) a change of geometric mean into arithmetic mean caused decreasing errors, they amounted to 1.8 - 2.9%, for the whole surface population.

Some measured random and deterministic surfaces of various shapes of ordinate distributions were tested. The slope was calculated based on a 7- point equation. For nearly isotropic surfaces (after vapour blasting, shot peening, barrel finishing and other processes) the average errors of determining 3D surface slope using Eq. (3) were small (always smaller than 2%) independently on the method of equivalent slope calculation. For honed and plateau honed cylinders (30 surfaces were analysed) the average error using the geometrical mean was 3.3%, arithmetical mean 1.4%. For some cylinder surfaces after running in the average errors of surface average slope calculation using geometrical mean was 4.5%, arithmetic mean 2.7%. For strongly anisotropic surfaces (after grinding, turning, and face milling) when slope division was bigger than 3.5 it is better to use the bigger value of average slopes in 2 orthogonal directions as the 3-D surface average slope. The presented results were obtained when profile slopes in perpendicular directions (strictly mean slope values) used in calculations, were received from whole surface topography samples.

3.10. Slope relations in perpendicular directions as a measure of anisotropy of honed cylinders

For measured surfaces after honing [32], the dependence between angle β (see Fig. 8a - x is the cylinder axial direction) and division among average slopes in two perpendicular directions (axial to circumferential - see Fig. 8b) was studied. The division between profile slopes is smaller than tan(β). Bigger values of relation between slope values in axial and circumferential directions were found when sampling interval was smaller. It was found that this relation using the 3-point method is a little smaller [33].



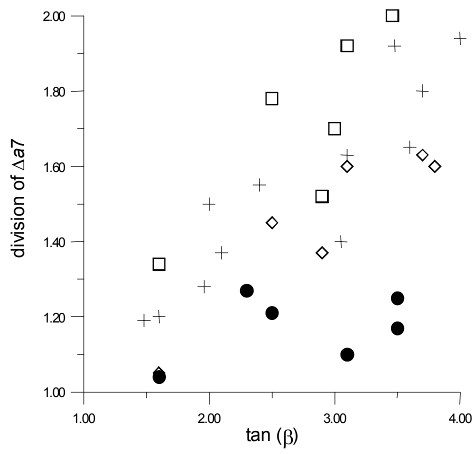


Fig. 8. Definitions of angles on cylinder surface (a), dependence between sampling interval SI (squares SI = 5 μm, crosses - SI = 10 μm, rhombus - SI= 20 μm, circles - SI = 30 μm) tan(β) and relation between average slopes in two perpendicular directions. Slope values were calculated based on the 7-point formula (b)

There is a possibility of obtaining a computer generated honed surface. It was found that the 2-point method is the most affected by the angles β (or α), than methods based on 7 and 3 points. It was confirmed that when the sampling interval was smaller, the relation of the slopes was more sensitive to the honing angle change.

After a study of real and simulated anisotropic surfaces it was found that a similar relation of average slopes in perpendicular directions (>1) was bigger than of rms slopes, and the ratio of values of slope based on the 2-point method was a little bigger than based on the 7-point formula.

The relation between surface average slopes in perpendicular directions is sensitive to zero-wear process of piston skirts and cylinders.

4. CONCLUSIONS

1. Surface slope calculation based on 2-and 7- point formula should be preferred. The 7-point differentiation should be used for small sampling intervals, as ISO recommends for a profile. This method assures generally more stable slope values, independently of measurement errors. For bigger sampling intervals (for example in 3D systems) the 2-point method seems to be better. The slope obtained by the 2-point formula profile is the closest to theoretical predictions, so this method should be used in a scientific investigation.
2. Because average and rms slopes are intercorrelated, only the rms slope should be used during production control. It is sensitive to extreme surface features unlike the average slope which is very stable on surface. In a scientific investigation these two parameters should be used jointly together with other parameters in order to assess the character of surface topography (existence of outliers, symmetry of ordinate distribution etc).
3. The conditions influencing the short-wavelength limit (sampling interval, short-wavelength cut-off, stylus dimensions) affect slope values. So information about measurement conditions should be stated. The other sources of errors, like quantisation errors, high-frequency noise caused slope value distortions. In spite of it the repeatability of profile slope (particularly average) on measured random surfaces is good, for the same measurement conditions. Profile slope is very similar with or without eliminating the trend. Profile mean slope (not modulus) measured by the stylus method usually tends to zero.

4. Slope characterises the hybrid surface property. Any changes in amplitude or spacing affect slope values. However measured random surfaces slope is more correlated with height than spacing. Surface slope is connected with developed interfacial area ratio. For the family of random surfaces, slope is strongly correlated with summit (peak) curvature.
5. It is possible to predict average profile slope after 2 processes when the slopes of Gaussian profiles constituted final profile are known. One can also predict 3D surface topography average slope of isotropic and weakly anisotropic random surfaces after one and two processes basing on profile average slopes in perpendicular directions.
6. The relation between slopes in two orthogonal directions depends on honing angle, so it can be a measure of anisotropy.

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ANALIZA POCHYLENIA TOPOGRAFII POWIERZCHNI

Streszczenie

Podstawowym celem pracy jest ocena różnych metod obliczania pochylenia powierzchni. Przedmiotem analizy były generowane komputerowo oraz mierzone struktury geometryczne powierzchni losowych o różnych kształtach rozkładu rzędnych w układach 2D i 3D. Analizowano przydatność różnych wzorów stosowanych przy obliczaniu pochylenia. Badano wpływ błędów pomiarów na zniekształcenie pochylenia powierzchni losowych; określano wpływ błędu kwantowania, błędu spowodowanego kształtem i wymiarami końcówki pomiarowej, filtracji cyfrowej, zakłóceń wysokoczęstotliwościowych, obecności pojedynczych rys głębokich. Analizowano zależności między wartościami pochylenia i innych parametrów, analizowano też zmienność pochylenia powierzchni losowych. Badano stosunek średniego arytmetycznego i średniego kwadratowego pochylenia jako parametr określający kształt rozkładu rzędnych. Określono możliwość przewidywania pochylenia powierzchni dwuprocesowej. Określono błędy obliczenia pochylenia powierzchni losowych na podstawie pochyleń w dwóch prostopadłych kierunkach. Określono przydatność stosunku wartości pochyleń w dwóch prostopadłych kierunkach jako potencjalnego parametru opisującego stopień anizotropii powierzchni cylindrów po gładzeniu.