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THEORETICAL ANALYSIS OF SPACING PARAMETERS OF ANISOTROPIC 3D SURFACE ROUGHNESS

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The authors of the research have analysed spacing parameters of anisotropic 3D surface roughness crosswise to machining (friction) traces RSm_1 and lengthwise to machining (friction) traces RSm_2. The main issue arises from the RSm_2 values being limited by values of sampling length l in the measuring devices; however, on many occasions RSm_2 values can exceed l values. Therefore, the mean spacing values of profile irregularities in the longitudinal direction in many cases are not reliable and they should be determined by another method. Theoretically, it is proved that anisotropic surface roughness anisotropy coefficient $c=RSm_1/RSm_2$ equals texture aspect ratio Str, which is determined by surface texture standard EN ISO 25178-2. This allows using parameter Str to determine mean spacing of profile irregularities and estimate roughness anisotropy.

Keywords: *anisotropy coefficient, roughness spacing parameters, surface texture, texture aspect ratio.*

1. INTRODUCTION

As a result of introducing surface texture standard (EN ISO 25178-2) [1], interest in 3D surface roughness parameters is growing. Knowing spacing parameters of the 3D surface roughness, especially if surface roughness is anisotropic, is an important factor in solving different technical tasks (friction, wear, part contacting etc.).

Surface roughness is anisotropic if in different surface directions profiles are different, unlike isotropic surface roughness that has the same profiles in all directions.

The main interest lies in surfaces with anisotropy in mutually perpendicular directions. In such a case, roughness mean spacing of profile irregularities is as follows: RSm_1 – crosswise to machining (friction) traces and RSm_2 – lengthwise to machining (friction) traces (Fig. 1).

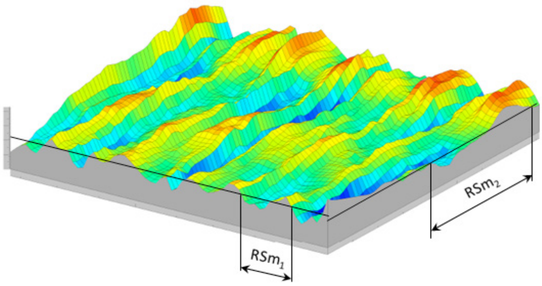

Fig. 1. Example of 3D surface with anisotropic roughness.

Engineering tasks require that the spacing parameters be easily identifiable and technologically feasible in machining. Otherwise, these parameters have no practical value.

In standard EN ISO 4287 [2], spacing parameter *RSm* is defined as mean width of profile elements along the mean line of the profile.

However, the ratio between spacing parameters RSm_1 and RSm_2, which characterises the anisotropy of surface roughness, is not defined in standards. Yet it is an important value that is required for characterising surface anisotropy and is used by surface scientists [5]–[10].

Based on the uniformed surface characterisation, the control bases of these parameters – mean lines – should be located at the level of the mean plane of rough surface (Fig. 2). Then these spacing parameters characterise a 3D surface.

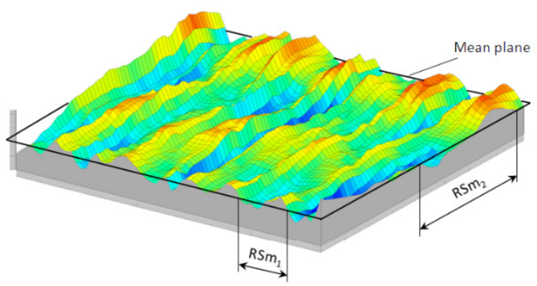

Fig. 2. Placement scheme of 3D surface roughness spacing parameters.

The authors of the paper have designated the ratio between spacing parameters as *c:*

$$c = \frac{RSm_1}{RSm_2}. \tag{1}$$

Parameter *c* is identified as an anisotropy coefficient. If surface is *isotropic*, $RSm_1 = RSm_2$ and $c=1$. However, if surface is anisotropic, $RSm_2 \to \infty$, $c \to 0$.

Current 3D surface roughness measurement devices, for instance, Taylor Hobson Intra 50, identify the spacing parameters without linking the mean line of the profile with the mean plane of the surface. This results in significantly lower *RSm* values and notably influences parameter RSm_2. This can be clearly seen in Fig. 3, which shows values of parameters Sa, RSm_1 and RSm_2 of a grinded surface with irregular surface roughness (Sa – arithmetic mean height of the scale limited surface). Surface roughness measurements that are used in this paper hereinafter were obtained using Taylor Hobson measuring equipment Intra 50.

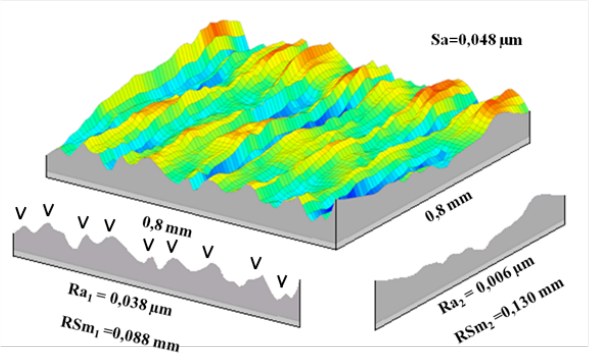

Fig. 3. Parameter values of grinded surface.

3D surface roughness parameter for the grinded surface shown in Fig. 3 is Sa=0.048 µm, and this parameter is identified as a deviation from the roughness mean plane. If the mean plane is also crossed by roughness sections (profiles), profile arithmetic mean deviation value Ra should be close to the 3D surface value Sa (in theory, at infinite number of profiles $Ra \rightarrow Sa$).

In the given example (Fig. 3), surface roughness in crosswise direction is Ra_1=0.038 µm, which is close to Sa=0.048 µm. Thus, it can be assumed that the mean line of crosswise profile of surface roughness is closely positioned to surface roughness mean plane. Thus, the mean spacing of profile irregularities RSm_1 can be assumed as a value of the crosswise mean spacing of profile irregularities belonging to the 3D surface roughness, and in this case RSm_1=0.088 mm. It can be clearly seen from the form of the crosswise profile (Fig. 3). The profile in question has 9 visible irregularities (Fig. 3, marked with a tick) along the evaluation length L=0.8 mm enabling one to approximately estimate that $RSm_1 \approx L/9$=0.8/9=0.089 mm. This value is close to the value determined by the measuring equipment, i.e., RSm_1=0.088 mm. Hereinafter, such a way of determining spacing parameters will be called the *visual* determination method.

This method will also be used for other surface profiles that are given reduced values of mean spacing of profile irregularities by the measuring equipment comparing to the real values.

The example (Fig. 3) shows a slightly different situation regarding surface roughness in longitudinal direction, with Ra_2=0.006 µm substantially differing from Sa=0.048 µm. This shows that the mean line of the longitudinal profile of surface roughness is distant from the mean plane of surface roughness, and the mean value of the mean spacing of profile irregularities is RSm_2=0.130 mm, which is not accurate and does not characterise surface anisotropy correctly. This value cannot be used in formula (1) to determine anisotropy coefficient c. The visual method, in turn, allows one to determine RSm_2 value more accurately. The profile in question has approximately 2 irregularities along the evaluation length L=0.8 mm. Consequently, $RSm_2 \approx L/2$=0.8/2=0.4 mm, which is approximately 3 times the value determined by the measuring equipment, i.e., RSm_2=0.130 mm. It can be seen with unaided eye that this value is more probable (Fig. 3).

It can be concluded that there is a big difference in the results depending on whether the values of mean spacing of profile irregularities RSm_2 (surface in Fig. 3) were measured with measuring equipment or using the visual determination method.

How to determine the value of 3D surface parameter RSm_2? Apparently, one can use parameter *Str* – a texture aspect ratio provided in standard EN ISO 25178-2.

2. TEXTURE ASPECT RATIO

According to American National Standard ASME B46.1-2009 "Surface Texture" [4] and [3]:

$$Str = \frac{L_F}{L_{sl}}, \tag{2}$$

where L_F – length of the fastest decay of ACF;
L_{Sl} – length of the slowest decay of ACF;
ACF – the autocorrelation function.

Mathematical expression of ACF between two points with coordinates $(x_1;y_1)$ and $(x_2;y_2)$ can be written as $\rho(\tau_1;\tau_2)$, where $\tau'_1 = x_2\_x_1$ distance between points on axis x and $\tau_2 = y_2\_y_1$ – distance between points on axis y. When the distance between the points increases (by increase of values τ_1 and τ_2), values $\rho(\tau_1;\tau_2)$ decrease (Fig. 4).

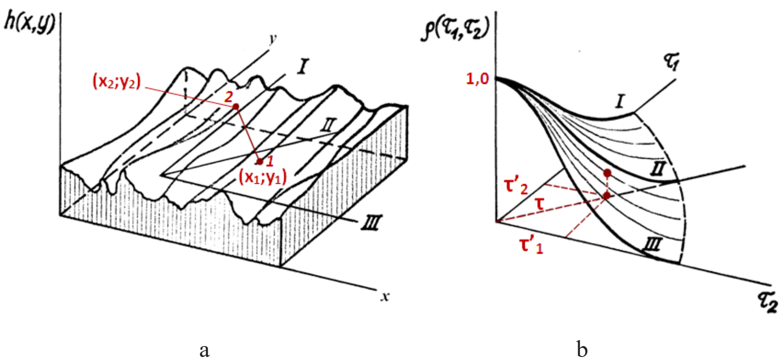

Fig. 4. Schematic representation of surface roughness (a) and corresponding standardised correlation function (b) [7].

Decrease rate of values of the correlation function can be characterised by correlation interval τk , which for the particular section is determined as follows:

$$\tau_k = \int_0^{\infty} |\rho(\tau)| dt, \tag{3}$$

where $\rho(\tau)$ – the autocorrelation function of surface roughness section.

Geometrically, τ_k is length of an edge of a rectangular base, the other edge of which is 1 and the area is equal to an area of a standardized correlation function under the curve. Value of τ_k for surface depends on the properties of the section.

In case of anisotropic surface roughness, the surface correlation function can be placed differently towards axes x, y (Fig. 5).

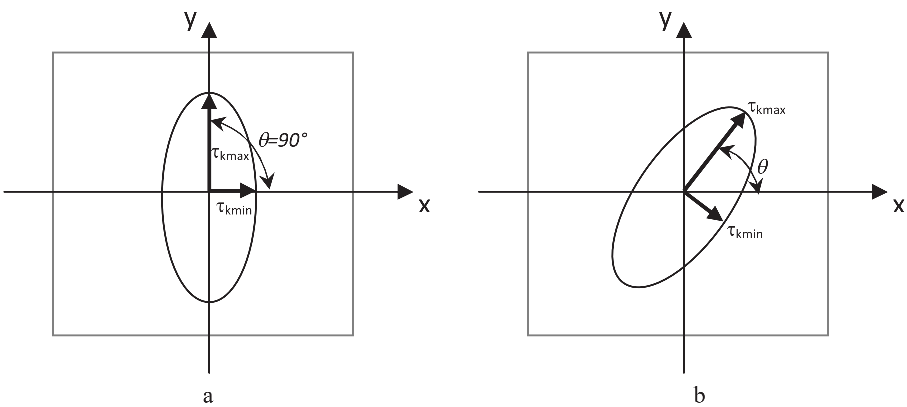

Fig. 5. Schematic placement of τ_k [1]
a – the correlation function is oriented along axes x and y, b – the correlation function is not oriented along axes x and y.

Assuming that the correlation function $\rho(\tau_1; \tau_2)$ is oriented along base-directions of anisotropic rough surface: τ_1 axis along direction x, τ_2 axis along direction y. This means that $L_F = \tau_{kmin} = \tau_{kx}$, but $L_{Sl} = \tau_{kmax} = \tau_{ky}$ because the surface profile has greater irregularity density crosswise to machining (friction) traces and the correlation function is descending faster as well. Thus, according to formula (2), it can be represented as follows:

$$Str = \frac{\tau_{kx}}{\tau_{ky}}. \tag{4}$$

It should be noted that standard EN ISO 25178-2 [1] foresees that the autocorrelation function is determined at level $0 \leq s \leq 1$ (usually s=0.2). However, at any level of s, ratio (4) retains its basic value; therefore, formula (4) can be used to characterise parameter *Str* at any s value, without losing the general approach.

Using studies on correlation functions of profiles of irregular rough surfaces [7], for a monotonically decreasing function:

$$\tau_k = \frac{\tau_{kn}}{E\{n(0)\}}, \tag{5}$$

where τ_{kn} – the standardised value of the correlation interval. It is constant for the particular correlation function.

$E\{n(0)\}$ – mathematical expectation of intersections with the mean line of the roughness profile (zero count).

In accordance with formula (4) for the particular correlation function:

$$Str = \frac{E\{n_2(0)\}}{E\{n_1(0)\}}, \tag{6}$$

where indices 1 and 2 characterise crosswise and longitudinal profiles, respectively. Since $E\{n(0)\}=2/RSm$ [7], then:

$$Str = \frac{RSm_1}{RSm2}. \tag{7}$$

Comparing the obtained formula (7) with (1), one gets important data for determining surface anisotropy coefficient c:

$$Str = c. \tag{8}$$

This means that the correlation function, which is orientated along the surface directions, allows using parameter *Str* to determine anisotropic coefficient c.

3. RSM_2 DETERMINATION

Using oriented correlation function of surface roughness in accordance with formula (8), RSm_2 value can be easily determined:

$$RSm_2 = \frac{RSm_1}{Str}, \tag{9}$$

where parameter *Str* is determined with the corresponding measuring equipment, such as Taylor Hobson Intra 50.

In general situations, when there are no notable mutually perpendicular base-directions of surface roughness, formulas (7), (8), (9) cannot be applied, for instance, for a cylinder liner of an internal combustion engine machined by honing operation.

There is another way to determine RSm_2.

Random field theory, which allows connecting 3D surface parameters with engineering tasks (surface contact, friction, wear etc.), is becoming increasingly popular in the modelling of irregular surface roughness (abrasion, worn surfaces etc.) [6], [7], [8].

If surface roughness is described with a random field, using theory of normal random field [10]:

$$E^2\left\{n_\phi(0)\right\}+E^2\left\{n_{\phi+90^\circ}(0)\right\}=const, \tag{10}$$

where $n_\varphi(0)$ – the number of zeroes of section at angle φ of normal random field (number of intersections between the profile and mean line);

$n_{\varphi+90^\circ}(0)$ – the number of zeroes of section at angle φ+90° of normal random field;

E{} – mathematical expectation of random variable.

According to the given formula, sum of squares of zeroes of any 2 mutually perpendicular sections is constant. Consequently, it can be written as follows:

$$E^2\left\{n_{0^\circ}(0)\right\}+E^2\left\{n_{90^\circ}(0)\right\}=E^2\left\{n_{45^\circ}(0)\right\}+E^2\left\{n_{135^\circ}(0)\right\}. \tag{11}$$

Assuming that section at φ=0° is the first direction (in the direction of axis x) and φ=90° is the second direction (in the direction of axis y), formula (11) can be simplified:

$$E^2\left\{n_1(0)\right\}+E^2\left\{n_2(0)\right\}=E^2\left\{n_{45^\circ}(0)\right\}+E^2\left\{n_{135^\circ}(0)\right\}. \tag{12}$$

If the profiles are taken at φ=45° and 135°, the number of zeroes is the same:

$$E^2\left\{n_{45^\circ}(0)\right\}=E^2\left\{n_{135^\circ}(0)\right\}. \tag{13}$$

From expressions (12), (13) it can be concluded that:

$$E^2\left\{n_2(0)\right\}=2\cdot E^2\left\{n_{45^\circ}(0)\right\}-E^2\left\{n_1(0)\right\}. \tag{14}$$

Dividing both sides by $E^2\left\{n_1(0)\right\}$, one gets:

$$c^2=2\cdot\left[\frac{E\left\{n_{45^\circ}(0)\right\}}{E\left\{n_1(0)\right\}}\right]^2-1, \tag{15}$$

where c – the anisotropy coefficient (see (1)).

$$c=\frac{E\left\{n_2(0)\right\}}{E\left\{n_1(0)\right\}}=\frac{E\left\{RSm_1\right\}}{E\left\{RSm_2\right\}}. \tag{16}$$

Using formula (1),

$$RSm_2 = \frac{RSm_1}{c}. \tag{17}$$

It should be noted that this approach has two disadvantages:

1) a need for additional information to determine $n_{45^\circ}(0)$;

2) the method is limited by expression (15) that determines the following:

$$\frac{\sqrt{2}}{2} \le \frac{E\{n_{45^\circ}(0)\}}{E\{n_1(0)\}} \le 1.0. \tag{18}$$

If the experimental values $n_1(0)$ and $n_{45^\circ}(0)$ do not result in formula (18), parameter RSm_2 should be obtained applying the *visual* method (see paragraph 1).

It should be taken into account that the suggested RSm_2 determination method significantly differs from the classical surface roughness metrology if surface roughness is anisotropic. In compliance with the classical metrology, all surface roughness parameters are determined within the limits of sampling length *l* [2]. However, in the given approach, using formulas (9) and (17), RSm_2 values can even exceed sampling length *l*, which is selected according to the value of parameter *Ra* (see Table 2).

In classical metrology, such RSm_2 values could be viewed as waviness mean spacing; however, mean spacing of profile elements RSm_1 and RSm_2 essentially characterise one but very longitudinally stretched irregularity, which has formed due to friction, wear, grinding or any other similar process. Physically, it is not linked to waviness.

Consequently, this RSm_2 value should be used in friction-, wear- and other technical calculations where mean spacing of profile elements for surface roughness has to be taken into account.

4. CONCLUSIONS

Within the framework of the research, the authors have evaluated anisotropy of surface roughness. First of all, the mean spacing values of profile irregularities obtained by measuring equipment have been analysed for flat grinded surface. It has been stated that mean spacing values of profile irregularities in longitudinal direction are not reliable due to the fact that surface mean plane and profile mean line are located at different levels. In addition, for the initial determination of roughness of mean spacing of profile irregularities RSm_2 the visual method has been proposed. Secondly, anisotropy coefficient *c* and surface texture aspect ratio *Str* have been compared. During the theoretical study, it has been substantiated by formulas that surface texture parameter *Str*, which is standardised in ISO 25178-2:2012, can be used to evaluate roughness anisotropy and calculate spacing parameters.

REFERENCES

1. International Organisation for Standardisation, (2012). Geometrical product specifications (GPS) – Surface texture: Areal – Part 2: Terms, definitions and surface texture parameters. ISO 25178-2:2012.
2. International Organisation for Standardisation (1997). Geometrical Product Specifications (GPS) – Surface texture: Profile method – Terms, definitions and surface texture parameters. ISO 4287:1997.
3. Stout, K.J. (2000). *Development of Methods for Characterisation of Roughness in Three Dimensions*. London: Penton Press.
4. American Society of Mechanical Engineers (2009). Surface Texture (Surface Roughness, Waviness, and Lay). ASME B46.1-2009.
5. Nayak, P. (1971). Random Process Model of Rough Surfaces. *Journal of Lubrication Technology, 93*(3), 398–407.
6. Rudzitis, J. (2007). *Mechanics of Surface Contact. Part 1. Parameters of Surface Roughness pProfile*. Riga: Riga Technical University (in Russian).
7. Kumermanis, M. (2012). *Research of 3D Roughness Parameters for Irregular Surfaces of Solid Bodies*. Riga: Riga Technical University (in Latvian).
8. Linins, O., Boiko, I., Lungevics, J., & Leitans, A. (2016). New Methodology for the Life Time Prediction of Wear Parts in the Mechatronic Systems. In *12th International Conference "MSM Systems"*, 3 – 8 July 2016 (pp.122–122). Bialystok, Poland: Bialystok University of Technology.
9. Kragelsky, I.V. (1982). *Friction Wear Lubrication. Tribology Handbook* (Vol. 1). Moscow: Mir Publishers.
10. Longuet-Higgins, M.S. (1957). Statistical properties of an isotropic random surface. *Philosophical Transactions of the Royal Society of London. Series A, Mathematical and Physical Sciences*, *250*(975), 157–174.

ANIZOTROPĀ 3D VIRSMAS RAUPJUMA SOĻA PARAMETRU TEORĒTISKĀ ANALĪZE

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K o p s a v i l k u m s

Dotajā zinātniskajā darbā veikta anizotropiska 3D virsmas raupjuma soļa parametru analīze, šķērsām apstrādes (berzes) pēdām RSm_1 un paralēli apstrādes (berzes) pēdām RSm_2. Problēmas būtība ir tā, ka RSm_2 vērtības mēraparātos ir ierobežotas ar bāzes garuma l vērtībām, kaut gan vairākos gadījumos virsmas RSm_2 vērtības var pārsniegt l vērtības. Tāpēc arī soļa parametra vērtības garenvirzienā vairākos gadījumos nav ticamas un tās ir jānosaka ar citu paņēmienu. Teorētiski ir pierādīts, ka anizotropa virsmas raupjuma gadījumā anizotropijas koeficients $c=RSm_1/RSm_2$ ir vienāds ar virsmas tekstūras indeksu *Str*, kuru nosaka virsmas tekstūras standarts EN ISO 25178-2. Sakarā ar to, parametru *Str* ir iespēja pielietot raupjuma soļu noteikšanai un raupjuma anizotropijas novērtēšanai.

12.07.2016.