INFLUENCE OF VARIOUS FACTORS ON DETERMINATION ACCURACY OF SURFACE PROFILE ELEMENTS FOR ENGINEERING CALCULATIONS

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Abstract. As known, surface quality plays a special role in determining wear resistance because roughness greatly influences wear intensity, so the roughness parameter values must be defined with high precision. Since contact surfaces in friction pairs predominantly have pronounced anisotropy, it is important to study in detail the roughness profile parameter *RSm* (Mean profile element spacing) parallel to the processing traces, i.e. in the friction direction. The first problem concerns the choice of the sample evaluation area/length size to ensure the required determination accuracy of *RSm*. Secondly, there are difficulties with selecting filtering operations for texture/profile computer processing because they can completely change the surface geometry. Thirdly, it is important to understand whether filtered topography profiles can be used for 2D roughness parameters analysis or separate profile measurements are required. In addition, there are difficulties with determining RSm_2 at standardised height and depth discrimination because the local roughness of profile dales and hills is taken into account in computer calculations. For this purpose, 3D and 2D measurement experiments for flat-grinded surfaces were carried out at different evaluation lengths. The obtained data were processed and analysed using the computer program McubeMapUltimate10. It was established that performing surface filtering line-by-line levelling with LS polynomial 2 should be used. The proposed waviness step WSm_2 fully corresponds to the RSm_2 values at thresholds 30-50% from *Rp* and *Rv*. The values of the filtered surface profile parameter $WSm_{2\text{-}v}$ coincide with the values of $WSm_{2\text{-}p}$ of the separately taken profiles with a relative error of 16%. Using the proposed correction coefficient $k_{kor} = 1.16$ in roughness step determination, it is not necessary to perform separate measurements to determine the roughness step.

Keywords: friction, wear intensity, roughness, anisotropy.

Introduction

The type of surface contact under friction conditions plays a huge role in ensuring the wear resistance of parts; therefore, the question of surface quality, specifically surface roughness, requires particular attention. As is known, the type of surface irregularities and their distribution determine the operational properties of the part. The height and step of the surface roughness directly affect the wear intensity and contact area [1-6]. In many engineering calculations of wear under sliding friction conditions, including finite element analysis (ANSYS, ABAQUS, Prepromax), only height parameters of roughness, such as *Sa* and *Sz*, are included, which, in turn, simplifies the calculation algorithm and reduces the reliability of the results. However, many factors and parameters that affect the friction process must be considered to determine the wear intensity correctly. The scientists Kragelsy and Rudzitis suggested using additional roughness step parameters RSm_1 and RSm_2 for wear determination. As contact of the parts occurs basically in the direction of the surface processing traces, it is important to determine the average roughness step RSm_2 along the Y-axis.

Ground surfaces are mostly used in sliding friction pairs because of their high quality; Defects that occur after rough processing are eliminated, and roughness values are in the range $Sa = 0.025…6.3$ µm. Knowing the surface characteristics makes it possible to determine and provide the necessary roughness parameters to reduce wear. During the grinding process, abrasive grains in the contact zone cut into the surface layer of the part to a different depth, cutting off the specific metal part and leaving a ground pit. Each grain leaves several pits, which are located at a certain distance from each other. Thus, ground surfaces are characterized by chaotically arranged micro-asperities and expressed processing traces, respectively, roughness has an irregular character.

The standards ISO 21920 and ISO/TR 23276 provide an algorithm for determining the parameter *RSm* without specifying the surface type [7; 8]. In addition, the authors of the standards recommend using a height and depth discrimination of at least 10% of *Rv* and *Rp* to exclude unnecessary components from the roughness step structure. In turn, for surfaces with irregular roughness, it is quite difficult to accurately determine RSm_2 values due to the arrangement of microasperities and sub-roughness. Computer processing programs do not recommend using calculated *RSm* values for surface characterization [9]. In scientific work [10] it was proposed to express the roughness step RSm_2 with the texture aspect ratio *Str* and roughness step RSm_1, but only a few surface profiles were considered in the

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study, as well as RSm_2 values were determined at the standardized evaluation length. It means that the required number of measurements of evaluation length at the specified accuracy and reliability was not taken into account.

In addition, there are difficulties with computer processing of surface topography because inappropriate levelling, form and waviness removal operations strongly affect the surface geometry and can change its structure. As a result, the roughness parameter values will no longer be reliable [11-14]. The recommendations of surface standards do not provide accurate surface filtering for a specific surface type; therefore, it is important to perform a separate analysis to select a more suitable filtering operation for surfaces with irregular roughness and pronounced anisotropy.

To achieve the goal, the following tasks were set:

1. Determination of the measurement accuracy of the parameter RSm_2;
2. Measurement of 3D and 2D surface roughness;
3. Analysis of the impact of surface filtering operations on profile geometry;
4. Determination of the roughness parameter RSm_2.

Materials and methods

The first step in solving the defined problems was determining the measurement accuracy of the parameter RSm_2. The measurement accuracy of surface roughness is related to determining the dimensions of the surface evaluation area. In this work, the emphasis was placed directly on this factor of measurement accuracy. The larger the dimensions of the evaluation length/area, the more reliable and accurate the measurement results will be. In practice, however, the number of measurements is limited by the dimensions of the sample and the design features of the measuring equipment, therefore, it is necessary to determine the optimal evaluation area that would ensure sufficient accuracy for engineering calculations.

The number of measurements at the specified accuracy and reliability is determined by the following formula [15]:

$$n = \frac{t_{\beta^2} D\{z\}}{\varepsilon^2 E^2\{z\}}, \tag{1}$$

where t_β – tabulated value, depending on the confidence interval β;
$D\{z\}$ – dispersion of the parameter, mm^2;
$E\{z\}$ – mathematical expectation of the parameter, mm;
ε – relative error of the parameter.

In engineering calculations, the permissible relative error ε should not be greater than 0.1, and the confidence interval is usually in the range of 0.8-0.95. The confidence interval and the corresponding coefficient t_β do not particularly affect the number of measurements n [3], while small values of the relative error ε increase the volume of experiments. Therefore, in this work, the measurement accuracy of the roughness parameter RSm_2 was determined at $\varepsilon = 0.1$ and $\beta = 0.9$ (respectively $t_\beta = 1.643$). In addition, the length of the edges of the measurement area required for one measurement experiment was calculated.

The mathematical expectation of the given roughness parameter $E\{RSm\}$ and the dispersion $D\{RSm\}$ in any chosen direction can be determined by formulas:

$$E\{RS_m\} = \frac{2\pi}{\sqrt{2\alpha}}, \tag{2}$$

$$D\{RS_m\} = \frac{\pi^3}{2\alpha L}\sqrt{\frac{\pi}{\alpha}}, \tag{3}$$

where α – correlation function approximation parameter;
L – evaluation length, mm.

To determine the approximation parameter α of the correlation function, separately taken profilograms are used, from which the number of profile intersections with the mean line along the evaluation can be determined.

$$\alpha = \frac{\pi^2 N(0)^2}{2L}, \tag{4}$$

where $N(0)$ – number of profile intersections with the mean line.

Accordingly, the required number of measurements to determine the parameter RSm_2 is calculated according to the formula:

$$n_{RSm} = \frac{t_{\beta^2}\pi\sqrt{\pi}}{4 \cdot \varepsilon^2 \cdot L\sqrt{\alpha}}. \tag{5}$$

When performing 2D roughness measurements, attention should be paid to evaluation length, which, according to the standard EN ISO 21920-2:2022, should equal 5 sampling lengths.

Accordingly, the second step was the measurement of the 3D and 2D surface roughness parameters, which was carried out by the contact method on the profilometer Mitutoyo Formtracer avant S-3000 (Fig. 1). The main advantage of this type of measurement equipment is the additional *Y* coordinate axis, with the help of which it is possible to take several parallel profilograms and create a 3D image of the surface from them, which more clearly and fully characterizes the microtopography of the surface. This profilometer has a diamond tip 178-396-2 (12AAC731), the radius corner of which is 2µm, the cone angle is 60 degrees, and the measuring force is 0.75 mN.

A roughness specimen, TESA RUGOTEST 104 made of stainless nickel (Fig. 2), was selected for the experiments. The surface treatment type of this specimen is flat grinding; the surfaces differ in the arithmetic mean height *Sa*.

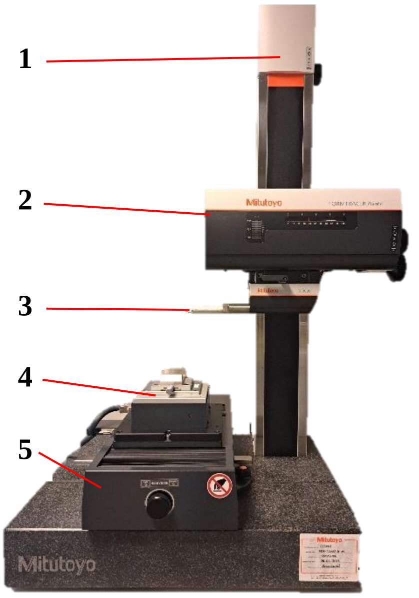

Fig. 1. **Profilometer Mitutoyo Formtracer avant S-3000:** 1 – Z2-axis column unit; 2 – X-axis unit; 3 – Z1-axis detector; 4 – Positioning table; 5 – Y-axis table

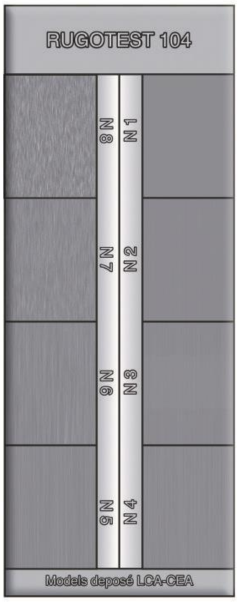

Fig. 2. **TESA Rugotest 104 specimen – flat grinding [16]**

Surface roughness measurement experiments were performed according to the requirements and recommendations of the standards LVS EN ISO 25178-2, -3; LVS EN ISO 21920-3:2022 [17], as well as according to the M. Kumermanis methodology [18] and the Mitutoyo manual [19], observing the requirements for evaluation length, maximum sampling distance and cut-off values. The processing of the obtained data was carried out using the computer program McubeMapUltimate 10.

The third step is filtering the taken topography and analyzing its impact on the geometry of individual profiles. Various filtering operations were applied to the measured surfaces with the aim of determining the optimal filters to ensure the accuracy of the roughness parameters. The first point was the application of the S-filter. This filter separates microroughness from the surface to reduce the noise generated by the measuring instrument and weaken the effect of the stylus tip. It is a low-pass filter that separates the finest components from the surface, the wavelength of which is less than the Ls cut-off value. The use of this filter depends on the selected distance between the surface points in the X and Y axis directions.

As it is impossible to ensure full contact between the sample surface and the measuring table, levelling and the F-operator are used. These operations provide the generation of the surface mean plane or profile mean line. The F-operator works according to the least squares method, levels the surface at polynomial degree $P = 1$ (the same as LSPL), and separates the basic shape at $P = 2$. At higher polynomial degrees, waviness is also separated along with the shape. Choosing the appropriate degree of the least square polynomial is important not to separate the necessary components from the surface. The least squares plane/line (Fig. 3) becomes the horizontal reference and serves as a reference plane/line for the surface/profile points. The local structure and geometry of the surface can affect this reference, shifting the mean plane. Table 1 shows different levelling methods that can be used depending on the surface structure.

Table 1

Levelling operations

Type of levelling operations	Description of levelling operations
Least squares plane levelling LSPL	The computer program models the least squares plane, provided that the sum of the squares of the distances to this plane is the smallest. In this case, the distance between the surface point and the LS plane is determined in the Z-axis direction (vertically). After subtracting the LS plane, the distance between the surface points does not change, but the surface geometry may deform. If the surface slope angle is large, it is better to use TLSPL (Fig. 4).
Total Least squares plane levelling TLSPL	The computer program models the total least squares plane, provided that the sum of the squares of the distances to this plane is the smallest. In this case, the distance between the surface point and the TLS plane is determined along the normal (perpendicular to the TLS plane). The surface geometry is preserved after subtracting the TLS plane, but the distance between the surface points changes (Fig. 5).
Minimum zone plane levelling MZPL	The computer program models two parallel planes that delimit the surface and searches for a better orientation to minimize the distance between these two planes.
Levelling line by line - subtract the mean + LS-polynomial	The computer program models the mean line for each set of points in the X-axis direction and levels them. Additionally, the form removal is performed using the LS polynomial, selecting the required polynomial degree (from 1 to 4).
Levelling column by column - subtract the mean + LS-polynomial	The computer program models the mean line for each set of points in the Y-axis direction and levels them. Additionally, the form removal is performed using the LS polynomial, selecting the required polynomial degree (from 1 to 4). This method is used if the surface topography is taken parallel to the processing traces.

Sometimes, vertical displacements between profiles are visible on surfaces taken with a profilometer; this is due to the deviation of the Y axis from straightness. In this case, a special levelling operation must be performed – line-by-line levelling.

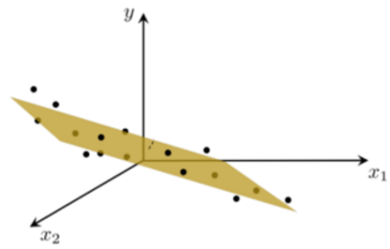

Fig. 3. **Generation of a reference plane by least squares method [20]**

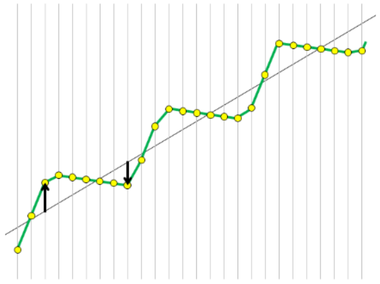

Fig. 4. **Generation of the mean line by the method of subtraction along the Z-axis [21]**

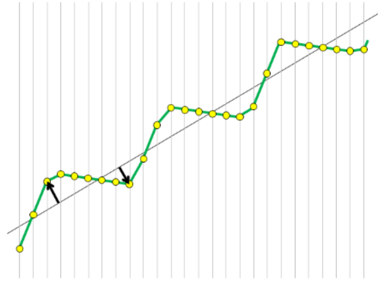

Fig. 5. **Generation of the mean line by the method of subtraction along the normal [21]**

Fourth step – determining the roughness parameter RSm_2. The ISO 21920-2 standard defines that the mean profile element spacing *RSm* is the average value of profile elements spacing *Xs*. A profile element is considered to be a hill followed by a dale (or a dale followed by a hill); the starting and ending points of *Xs* are profile crossings with the mean line at a certain threshold. Thus, profile elements are determined according to the Crossing-The-Line Segmentation method [22]. An important element in determining the parameter *RSm* is the height discrimination *H*, which delimits the geometry of the hill and dale and excludes unnecessary components from the roughness step – "noise". The standard recommends using *Hu* = 10% of *Rp* (mean peak height) and *Hl* = 10% of *Rv* (mean pit depth) subtracted from the mean line. Fig.6 and Fig. 7 schematically depict the principle of determining profile elements. The profile has 6 visible profile elements from the start of the evaluation length to the last profile element and the same number of roughness steps from the end of the evaluation length to the last *Xs* at the defined thresholds *Hu* and *Hl*. The zero element is visible for the profile elements *Xs*3 and *Xs*10, which is part of the dale because the profile does not cross the set threshold. The geometry of the profile elements changes depending on the direction; therefore, the average *Xs* value is counted in the *RSm* calculations.

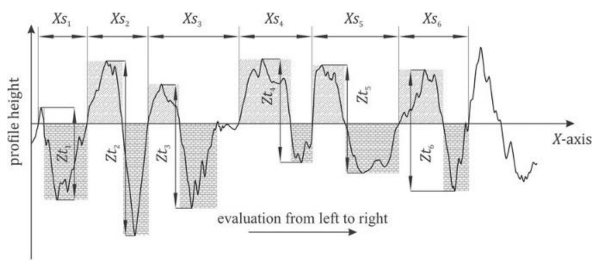

Fig. 6. **Principle of determining the parameter *RSm* in the direction from the beginning of the evaluation length to the last profile element [22]**

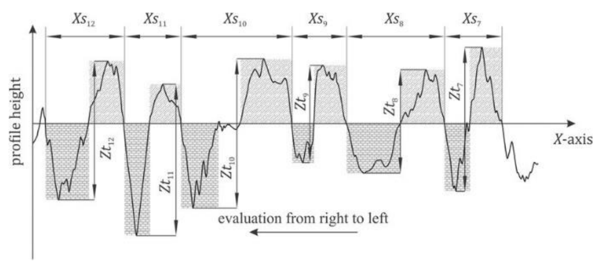

Fig. 7. **Principle of determining the parameter *RSm* in the direction from the end of the evaluation length to the last profile element [22]**

Results and discussion

The results of calculating the determination accuracy of the roughness parameter *RSm* in the X-axis and Y-axis directions at $\varepsilon = 0.1$ and $\beta = 0.9$ are presented in Table 2. The *N*(0) values determined from the profilograms once again prove that the smaller the *Sa* values, the finer the roughness step and, accordingly, the greater the number of profile intersections with the mean line along the evaluation length. In the direction perpendicular to the processing traces, the number of *N*(0) is approximately 30 times greater than in the direction parallel to the processing traces, again indicating the anisotropy of the flat-ground surfaces.

According to the results of the calculation of determination accuracy of the *RSm* parameter, it can be concluded that in the direction perpendicular to the processing traces, it is necessary to perform 1-2 2D profile measurements, but in the *Y*-axis direction - more than 30 measurements, to obtain reliable *RSm* values at the evaluation length $L = 5l$. When performing one measurement experiment in the direction parallel to the processing traces at the given $\varepsilon = 0.1$ and $\beta = 0.9$, a significantly large evaluation length is required. Still, not in all cases the sample dimensions are sufficient to take a long profilogram.

Table 2

Calculation results of determination accuracy of the roughness parameter *RSm*

Surface	*Sa*, µm	*axis*	*l*, mm	*L*, mm	*N*(0)	α_1, mm^{-2}	n_{RSm}	$L_{for\ 1\ measurement}$, mm
N1	0.025	X	0.25	1.25	150	70989.7	2	1.41
		Y			5	79.2	34	42.28
N2	0.05	X	0.25	1.25	175	96624.5	1	1.21
		Y			5	79.2	34	42.28
N4	0.2	X	0.8	4	136	5699.6	2	4.97
		Y			4	4.9	43	169.12
N6	0.8	X	0.8	4	130	5207.2	2	5.20
		Y			4	4.9	43	169.12
N8	3.2	X	2.5	12.5	185	1079.3	1	11.52
		Y			6	1.1	29	352.33

In the case of 3D roughness measurements, several profiles are captured within one experiment; respectively, theoretically, additional experiments are not required to ensure the accuracy of RSm_2; The number of profiles in the X-axis direction is several thousand, and in the Y-axis direction - several hundred. It means that one 3D roughness measurement experiment includes the calculated n_{Rsm} for the profile. However, such an option raises the question of how correct it is to use the roughness step values of profiles extracted from the 3D surface because, as was mentioned above, there is a possibility of obtaining different results at the same surface and profile filtering modes. In addition, it is important to check whether the average *RSm* of all extracted profiles will equal the *RSm* of the separately taken 2D profile with an increased evaluation length.

Fig. 8 shows two profilograms of the flat-ground surface. The blue profilogram was obtained by extracting the profile from the initial surface and separating the form from it using the "Remove form" function, *P* = 2. In this case, the form removal was unrelated to the form deviations appearing during the grinding process. Here, the form of the sample was formed by a slightly curved plastic base glued to the sample's metallic surface. The red profilogram was extracted from the filtered surface using the same form removal operation. It can be concluded that form removal from the surface and profile at the same regimes gives different results. The geometry of both profiles is supposedly preserved, while the number of intersections with the mean line and their placement are different.

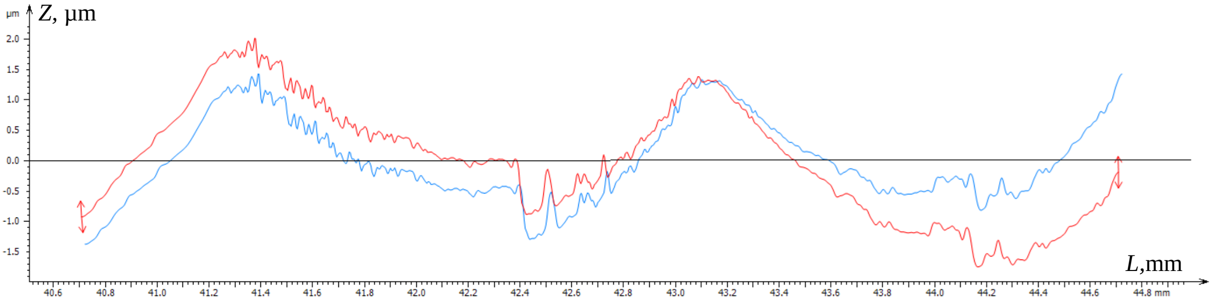

Fig. 8. **Comparison of the original profile (blue) and the extracted profile (red) after form removal, *P* = 2**

To check the degree of similarity of the compared profiles geometry, the *RMS* parameter by the function "*Subtract*" of the computer program was used; *RMS* is the root mean square deviation, which is calculated over the length of the overlap zone. Table 3 shows the *RMS* values, comparing the original profile after form removal, *P* = 2, and the extracted profile after the form removal from the surface, using combinations of levelling and F-operator. The smaller the *RMS* value, the greater the similarity of the profiles. As part of the study, 100 profiles were selected for comparison in the *X*-axis direction and the same number of profiles in the *Y*-axis direction to check which of the directions is more affected by the surface filtering operations.

Table 3

***RMS* values for profiles after different levelling and form removal operations**

Levelling + Form removal	RMS_{vid}, nm (X-axis)	RMS_{vid}, nm (Y-axis)
LSPL + F-operator, P = 2	1.45e-7	2.59e-7
TLSPL + F-operator, P = 2	1.28e-7	2.66e-7
MZPL + F-operator, P = 2	1.87e-7	2.78e-7
Levelling line by line - subtract the mean + LS-polynomial, p = 2	2.35e-10	3.54e-7
Levelling column by column – subtract the mean + LS-polynomial, P = 2	1.09e-6	2.89e-10

According to the data in Table 3, it can be concluded that Leveling line by line + LS-polynomial 2 gives the most accurate match between the *X*-axis profiles while Leveling column by column + LS-polynomial 2 provides an almost complete match between the *Y*-axis profiles. Because the 3D geometry of the surface must be taken perpendicular to the machining traces, choosing Levelling column by column is incorrect. The ISO 25178-3 standard recommends using the TLSPL method, but the Mitutoyo manual offers LSPL as the best option for surfaces with a random distribution of irregularities, but surface defects, extreme peaks and dales greatly affect the LS plane, so levelling line by line together with LS-polynomial is the best option.

As mentioned above, the profile of the flat-ground surface in the direction parallel to the machining traces crosses the mean line only in a few places; respectively, the roughness step in this direction is significantly larger compared to the *X*-axis direction. This is observed for all anisotropic surfaces. In several cases, it is quite difficult to determine the boundaries of peaks and dales because the roughness step includes sub-roughness or defects that change the *RSm* values. For the profile from Fig.9 two roughness steps $Xs_{1\text{-}viz}$ and $Xs_{2\text{-}viz}$ can be visually distinguished in both directions of the profilogram (from left to right – l-r and vice versa – r-l); in addition, the local irregularities of these roughness steps intersect the mean line in several places, which strongly affects the values of the parameter RSm_2. According to the computer program calculations at the standardized threshold – 10% of *Rp* and *Rv*, the RSm_2 value is only 0.29 mm, which does not correspond to the real geometry of the profile. Such an RSm_2 value is not correct to use in surface contact and friction calculations because it is greatly reduced due to local micro-irregularities. By increasing the threshold to 30% and higher, the RSm_2 value is already 0.73 mm, corresponding to the real scene. The error of the RSm_2 value at the threshold H = 10% is 151%. So, for the given profile, H = 30% must be chosen to obtain a reliable RSm_2 value. However, each profile will have different threshold values. The question arises, how can the average RSm_2 value be determined among all *Y*-axis profiles at a single threshold *H*.

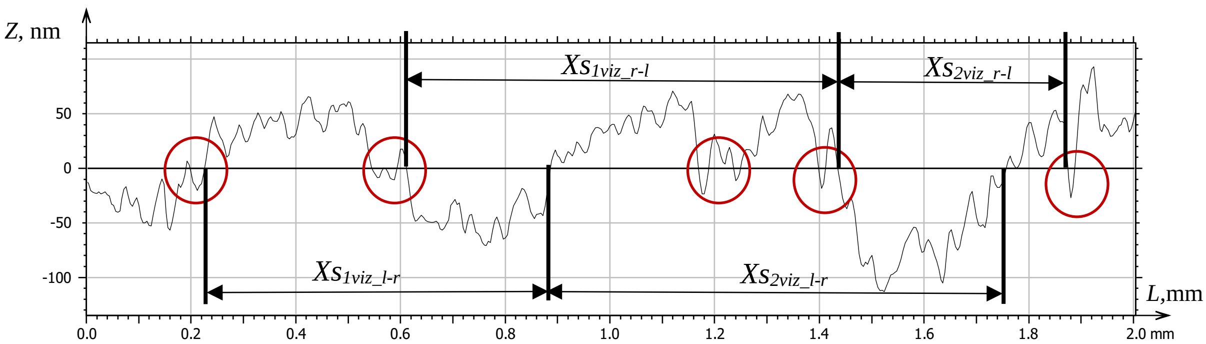

Fig. 9. **Effect of the sub-roughness of the Y-axis profile of a flat-ground surface on the value of the parameter RSm_2**

The work proposed to determine the value of RSm_2 using the waviness step since its size at a correctly selected cut-off is comparable to the step of roughness profile elements. It is important to note that in this case, the waviness profile reflects not the shape deviation that occurs during the processing of the part but directly the size of the roughness step in the direction of the processing traces. With the help of the function "Filtered profiles" it is possible to obtain a waviness profile by selecting a Robust Gaussian filter, which is not affected by local surface defects, measurement noise, extreme peaks and dales. As a result, a waviness profile is obtained that accurately describes the basic geometry of the roughness profile (without sub-roughness) [23, 24]. The average value of the waviness elements WSm_2 is determined at a standardized threshold of 10% at a specific cut-off value depending on the parameter *Sa*. Fig. 10 shows the waviness of the previously considered profile; Here, the four intersections of the waviness profile with the centerline are clearly visible, WSm_2 at the threshold of 10% is 0.74 mm, which exactly coincides with the RSm_2 value at $H = 30\%$, the relative error is 1%. The parameter *WSm*, according to the ISO 21920-2 Standard, is determined as follows:

$$W_{sm} = \frac{1}{n_{pe}} \sum_{i=1}^{n_{pe}} W_{s,i} \tag{6}$$

where n_{pe} – total number of profile elements;
$W_{s,I}$ – profile element spacing of the *i*-th profile element, mm.

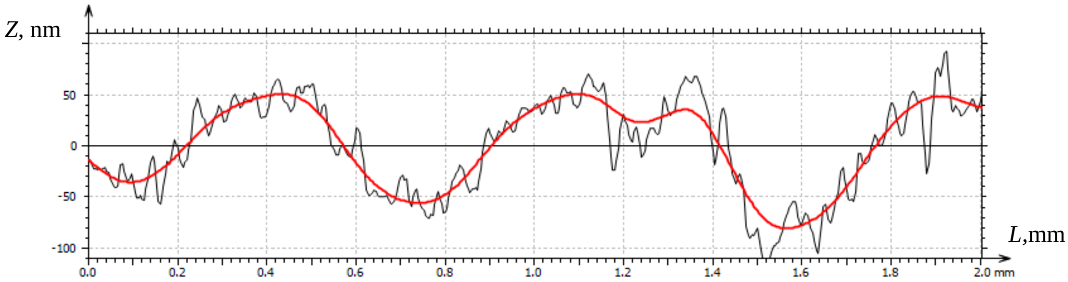

Fig. 10. **Waviness profile of flat-ground surface**

To check the correspondence of the WSm_2 parameter value to the roughness step RSm_2, 100 profiles were selected, for which RSm_2 values at the thresholds H = 30-90% and WSm_2 values at $H = 10\%$ were determined using computer program calculations and visual analysis. The study results show that the WSm_2 parameter values completely coincide with RSm_2 at $H = 30\text{-}40\%$. In turn, the question arises as to what cut-off value should be chosen so that the waviness profile does not lose important elements and vice versa – does not repeat the sub-roughness. Fig.11 shows waviness profiles at different cut-offs. The larger the L-filter value, the wider the waviness step will be.

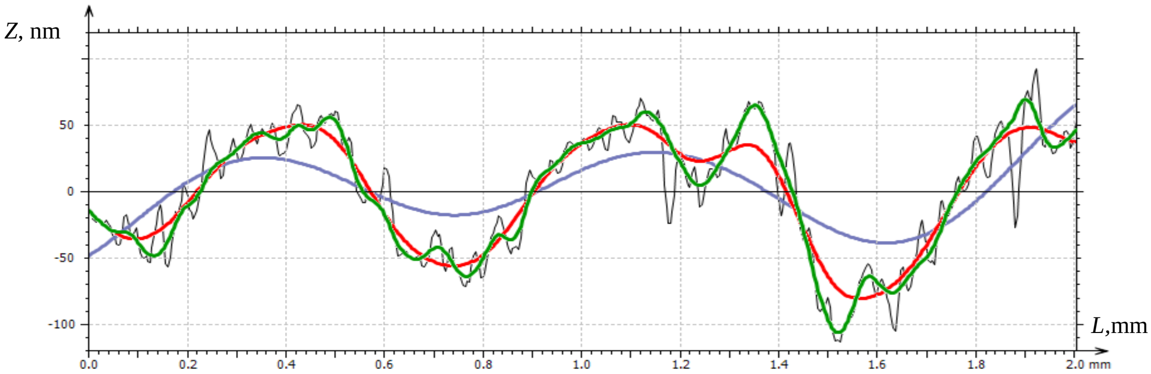

Fig. 11. **Effect of the cut-off size on the waviness step:**
λc =0.08 mm (green), λc = 0.25 mm (red), λc = 0.8 mm (blue)

Table 4 shows a comparison of the values of the parameters RSm_2 and WSm_2 at different cut-offs. According to the data in the table, it can be concluded that the value of the L-filter depends on the arithmetic mean height *Sa*. For example, for the profiles of the sample N6, the most suitable cut-off is 0.25, since the difference between the RSm_2 and WSm_2 values is only 4%. In turn, it can be noticed that for some profiles, the waviness step coincides with the roughness step at different cut-offs, which can be explained by cases when the roughness profile elements do not have a pronounced sub-roughness.

After analysis, it can be concluded that a cut-off of one unit smaller than the standardized one should be chosen.

Table 4

Comparison of the values of the parameters RSm_2 and WSm_2 at different cut-offs

Surface No. λc standartized	**RSm_2 H = 30 %, mm**	**WSm_2, mm**	**Δ, %**	**WSm_2, mm**	**Δ, %**	**WSm_2, mm**	**Δ, %**	**WSm_2, mm**	**Δ, %**
		λc=0.08 mm		λc=0.25 mm		λc=0.8 mm		λc=2.5 mm	
N2, λc=0.25 mm	**0.83**	0.840	1	0.891	7	0.928	12	-	-
	0.363	0.407	12	0.380	5	0.924	155	-	-
	0.405	0.393	-3	0.426	5	0.964	138		
	0.5102	0.4958	-3	0.645	26	0.836	64	-	-
N6, λc=0.8 mm	**1.289**	0.992	-23	1.294	0	1.322	3	-	-
	1.747	1.746	0	1.745	0	1.793	3	-	-
	1.588	1.305	-18	1.655	4	1.705	7	-	-
	2.001	1.839	-8	1.985	-1	2.217	11	-	-
N8, λc=2.5 mm	**6.51**	-	-	6.555	1	6.554	1	6.587	1
	4.998	-	-	3.009	-40	5.007	0	5.071	1
	4.693	-	-	4.219	-10	4.629	-1	4.969	6
	4.557	-	-	4.137	-9	4.528	-1	5.431	19

The next point was the comparison of WSm_2 values for profiles after 2D and 3D measurements. Fig.12 shows the values of the waviness step $WSm_{2\text{-}p}$ for separately taken profiles at an increased evaluation length and the average values of $WSm_{2\text{-}v}$ for profiles extracted from the filtered surface. For 2D measurements, the maximum evaluation length L = 20mm was chosen, which is limited by the dimensions of the sample. According to Table 1, the evaluation length L for surfaces N1 and N2 of the Rugotest 104 sample is 80l, respectively, 3 profilograms must be taken to ensure accuracy, for surfaces N4 and N6 L = 25l and 9 profilograms, for surface N8 L = 8l and 18 profilograms. It should be noted again that in the case of 3D measurements the evaluation length was L = 5l.

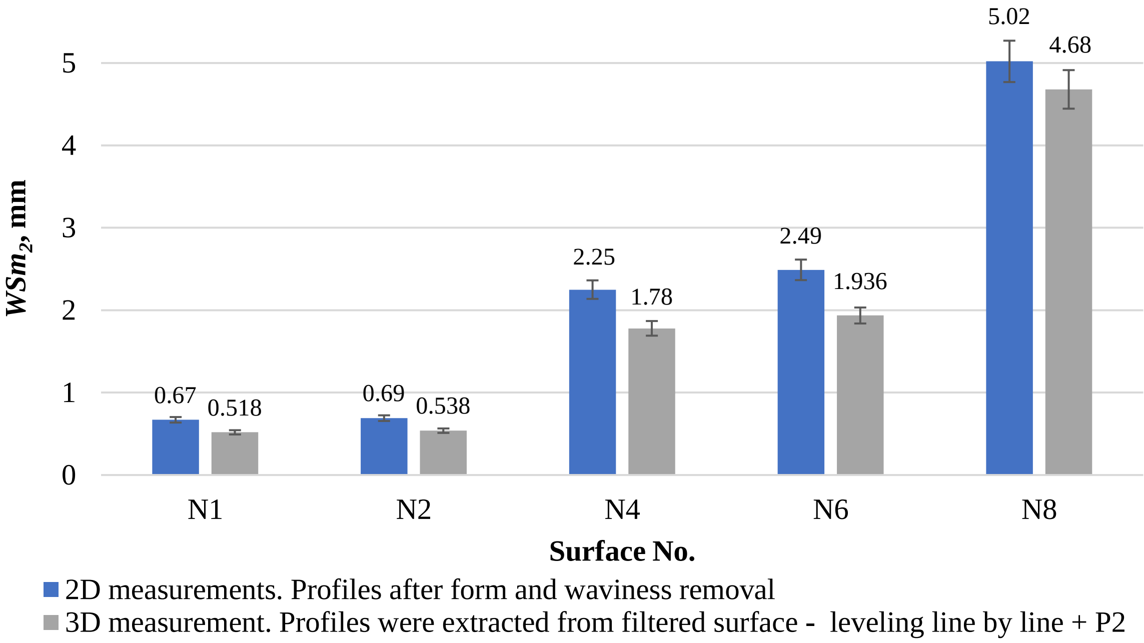

Fig. 12. **WSm_2 parameter values for profiles after 3D and 2D roughness measurements**

According to the graph data, it can be concluded that for profiles with an increased evaluation length, the *WSm*$_2$ parameter values are greater than for profiles extracted after 3D measurements; the difference is 8-25% (average 16%). It is also important to note that at 5 sampling lengths, the ordinate distribution does not correspond to the Gaussian distribution law (Fig. 13) for any of the *Y*-axis profiles; only at an increased evaluation length, the normal distribution of the ordinates of the *Y*-axis profiles can be seen. The large roughness step in the direction of the processing traces relative to the evaluation length explains this.

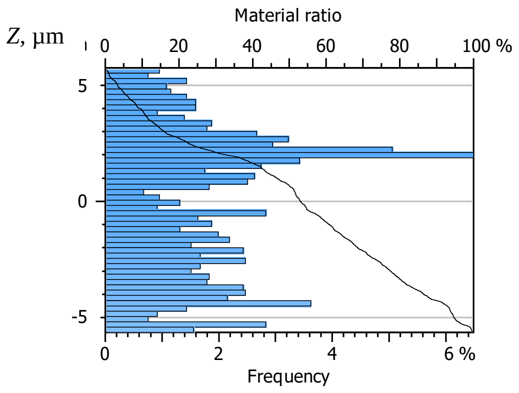

Fig. 13. **Distribution of roughness profile points at *L* = 5*l* for flat ground surface**

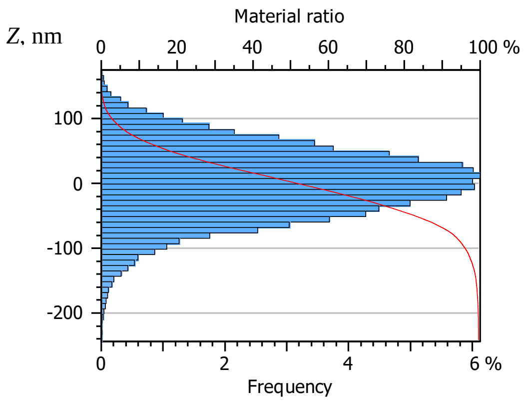

Fig. 14. **Distribution of roughness profile points at *L* = 80*l* for flat ground surface**

The question arises: which of the *WSm*$_2$ values to choose for wear intensity calculations? Here, it is important to note the role of the roughness parameter *Str* (texture aspect ratio). In previous work [10], the relationship between surface roughness steps and the parameter *Str* was determined. As a result of the study, it was proven that the ratio of roughness steps *RSm*$_1$ and *RSm*$_2$ expresses the texture aspect ratio. Therefore, it is useful to compare the ratios of all extracted profiles in *X* and *Y*-axis directions of the filtered surface with the surface roughness parameter *Str* and the ratios of roughness steps *RSm*$_{1\text{-}p}$ and *WSm*$_{2\text{-}p}$ of separately taken profiles with the same parameter – *Str*. For this purpose, additional roughness measurement experiments for *X*-axis profiles were performed over an increased evaluation length. A comparison of the values of the parameter *RSm*$_{1\text{-}p}$ for separately taken profiles and *RSm*$_{1\text{-}v}$ for profiles extracted from the filtered surface is shown in Fig. 15.

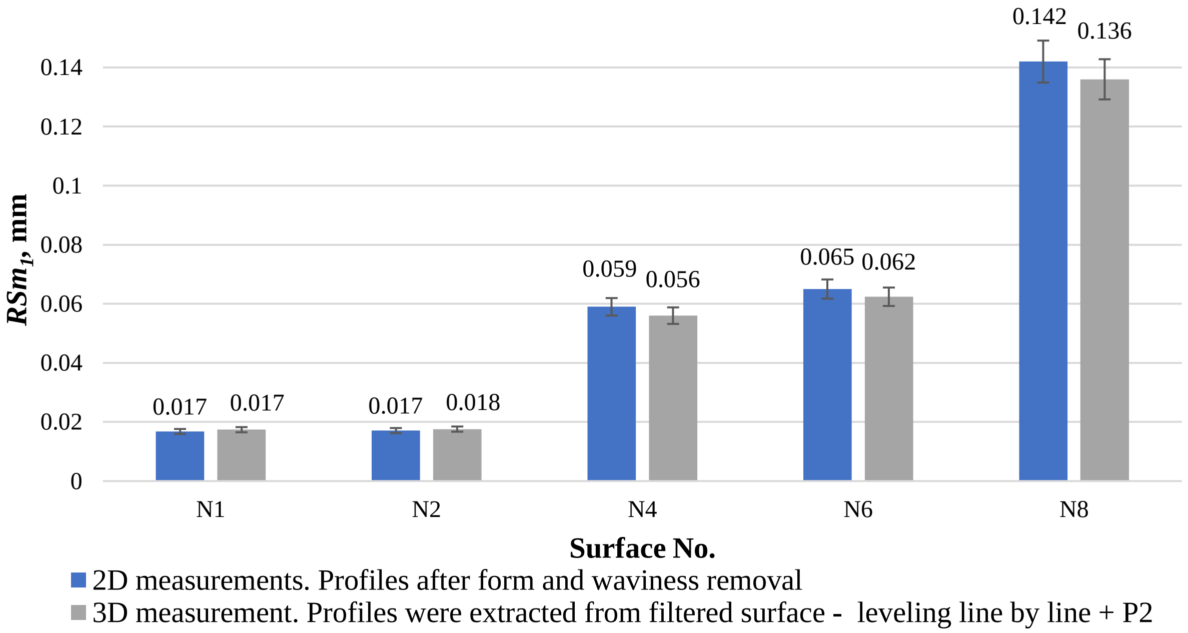

Fig. 15. ***RSm*$_1$ parameter values for profiles after 3D and 2D roughness measurements**

A comparison of the roughness step values perpendicular to the processing traces shows that the RSm_1 values after 3D and 2D measurements coincide very precisely; the difference in values is a maximum of 5%. Accordingly, it can be concluded that the $RSm_{1\text{-}v}$ values of the profiles extracted from the surface can be used in the calculations of the texture aspect ratio.

Fig. 16 shows three values of the texture index *Str*, which were determined: 1) by computer program calculations, 2) by the ratio of average roughness step values of the *X* and *Y*-axis profiles extracted from the surface, 3) by the ratio of average roughness step of the *X*-axis profiles extracted from the surface and the average roughness step of the 20 mm *Y*-axis profiles. According to the graph data, it can be concluded that the values of the parameter $WSm_{2\text{-}p}$ ensure full correspondence between the roughness step ratio and the texture aspect ratio.

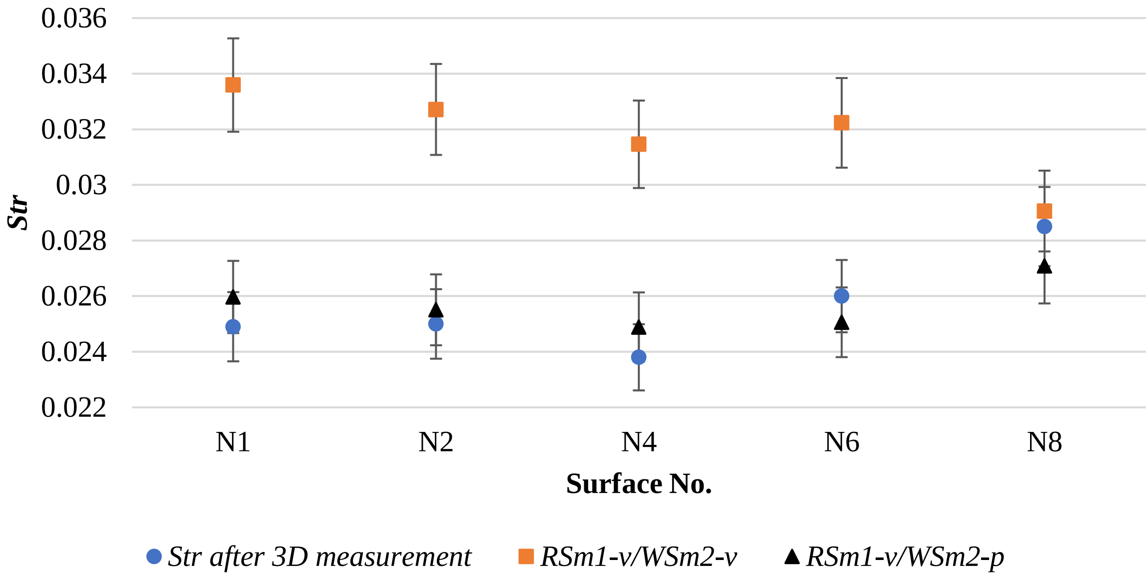

Fig. 16. **Correspondence of the roughness step ratio to the surface texture aspect ratio *Str***

Based on the results obtained from the study, it was proposed to use the correction coefficient k_{kor} to determine the surface roughness step in the *Y*-axis direction at the evaluation length $L = 5l$. Accordingly, the roughness step WSm_2` can be determined by the following relationship:

$$WSm_2' = k_{pr} \cdot WSm_2 \tag{7}$$

where k_{kor} – roughness step correction coefficient. $k_{kor} = 1.16$.

Conclusions

1. The surface levelling operation - levelling line by line together with the LS 2nd order polynomial most accurately generates the mean plane and preserves the profile geometry for surfaces with an irregular character.
2. To determine the surface roughness step in the direction parallel to the processing traces, the waviness step value WSm_2 at the threshold $H = 10\%$ should be used.
3. When determining the WSm_2 parameter, a cut-off should be selected that is one unit smaller than the standardized one (depending on the value of the *Sa* parameter).
4. When determining the value of the WSm_2 parameter for profiles taken at 5 sampling lengths, the correction coefficient $k_{kor} = 1.16$ should be used.

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