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A 3D ANALYSIS OF GEOMETRICAL SURFACE STRUCTURE IN TRIBOLOGICAL TESTS

ANALIZA STRUKTURY GEOMETRYCZNEJ POWIERZCHNI 3D W BADANIACH TRIBOLOGICZNYCH

Key words:

surface geometrical structure measurements, SGS, evaluation of tribological wear

Słowa kluczowe:

struktura geometryczna powierzchni (SGP), ocena zużycia tribologicznego

Summary

The elementary friction phenomena occurs on one momentary surface of actual contact, that is, on the protrusions of irregularities. During operation, a new surface roughness state forms. For measuring the parameters characterizing the geometrical structure of the surface before and after the friction process, a 3D profilometer was used. The obtained full characteristics of the surface geometrical structure (SGS) in the 3D system and the program capabilities enable a more in-depth inference, as compared to 2D analysis, on the mating

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of tribological pair elements in a micro scale. The paper presents the possibilities of using 3D roughness measurements for the assessment of phenomena accompanying the friction and wear processes.

INTRODUCTION

The friction process, which consists of a set of elementary phenomena, occurs on one momentary surface of actual contact, that is, at the peaks of irregularities, and causes specific changes in the geometrical surface structure (SGS) or the top layer state. In the contact period, the most protruding parts of the roughness profile are smoothed down, whereby the roughness parameters of the surface layer, which are the function of the path and the conditions prevailing during the friction process, change **[L. 1, 3, 8]**. If the wear process is a "zero" one, i.e. does not exceed the height of irregularities, then the elementary wear processes proceed at the peaks of primary irregularities. Explaining the origin of wear is associated directly with considering the phenomena that occur at the contact with irregularities and their effect on friction. A direct observation of these phenomena is impossible; therefore, various identification methods are sought. For this purpose, topography measurements in a three-dimensional (3D) system are also frequently used **[L. 14, 15]**. These are methods which are newer from currently utilized approaches **[L. 2, 4–7]**.

They enable the identification of the geometrical structure of the surface before and after the friction process and the spatial identification of the wear zone **[L. 8, 9]**. Under certain conditions, they can substitute for macroscopic or microscopic examinations, thus helping in the identification of the type and mechanism of the wearing process exerted on the studied pair **[L. 11, 14]**.

The determination of 3D surface roughness profilograms is associated with the possibility of determining the number of irregularity micro-contacts for a tribological pair, whereby it is possible to determine the predicted time of mutual contact between the irregularities of the mating surfaces. It becomes possible to acquire the sizes of irregularities and their distribution on the surface. Such data enables the creation of more adequate virtual models of roughness (the sizes and shape of irregularities) for simulation studies with the use of numerical techniques. The 3D method provides such capabilities and enables the creation of a more adequate model that describes the mutual interactions of irregularities in the friction process. Moreover, these measurements enhance the accuracy of wear magnitude determination **[L. 7, 13]**.

The relationships between parameters describing the state of the surface layer SGS and the service properties of machine parts are not sufficiently investigated, because there are no adequately generalized and widespread methods of their identification. Therefore, the authors of the present work have made an attempt to use modern apparatus and software for the measurement and analysis of roughness in a three-dimensional (3D) system for the interpretation of tribological processes. The proper definition of the indicators and the possibility of the graphical representation of surface topography formed can help to interpret the phenomena accompanying the wear process.

SGS CHANGES EXPERIMENTALLY TESTED DURING THE DRY FRICTION PROCESS

For carrying out a series of experiments to determine changes in the geometrical surface structure in a 3D system during technically dry friction, cylindrical test pieces were used. All test pieces were manufactured of C55 steel hardened to 28–30 HRC and worked by oscillatory burnishing (with the following process parameters: F = 450 N; f = 0.18 mm/rev.; e = 0.5; $\varphi = 45^0$) which provided a determined SGS. The control piece was a sample cut out from EN-GJL-250 grade cast-iron bushing. The unit pressure, as well as the relative speed of the test piece were set based on the value of pV = 1.6 MPa x m/s, which is permissible for that particular pair (steel – cast iron). The process was conducted over a friction path of 20 000 m that caused a "zero" wear, i.e. the one whose value did not exceed the height of irregularities obtained from finishing working. The view of the tribological pair used for the wear stand tests is shown in **Figure 1.**

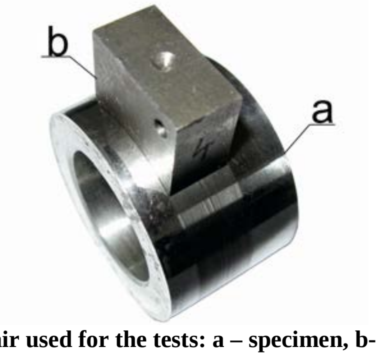

Fig. 1. View of the tribological pair used for the tests: a – specimen, b- counter specimen
Rys. 1. Analiza zjawisk zachodzących w trakcie zużycia: a – próbka, b – przeciwpróbka

SGS measurements were taken on a Taylor Hobson New Form Talysurf 2D/3D 120 profilometer, equipped with 'Ultra Surface 5.16', 'TalyMap Platinium 5.0' and a Talyrond 365 measuring system provided with 'Ultra Roundness 5.17' software used for data analysis.

Figure 2 shows the view of a specimen section with surface texture after working by oscillatory burnishing **(Fig. 2a)** and after wear along a friction path of 20 000 m **(Fig. 2b)** and after wear along a friction path of 40 000 m **(Fig. 2c)**. We can observe regular recesses and protrusions on the surface, whose peaks are worn in the friction process.

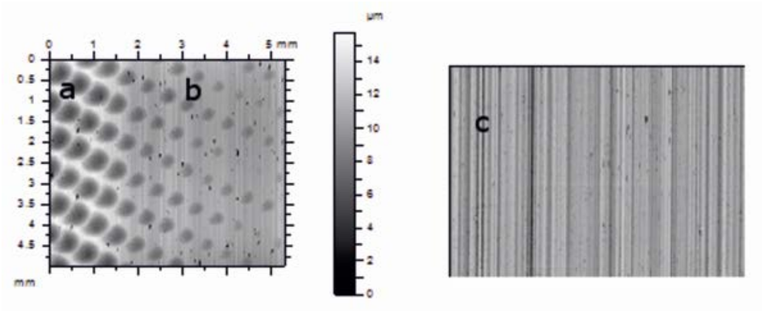

Fig. 2. View of a test piece fragment, a – after burnishing b, c - after the wear proces
Rys. 2. Widok fragmentu powierzchni próbki po nagniataniu (a) i po procesie zużycia (b i c)

Analisys of surface geometrical structure

The possibility of performing microscopic observation of wear surfaces is instrumental in understanding and explaining the mechanism of phenomena occurring during the process of operation. Technical and program capabilities of contemporary apparatuses enable such measurements to be carried out. It is also possible to determine the three-dimensional image of both the worn area and the surface area not subjected to wearing. The changes in surface roughness in the wearing process are reflected accurately by the view of the surface in the three-dimensional (3D) system, as shown in **Fig. 3**.

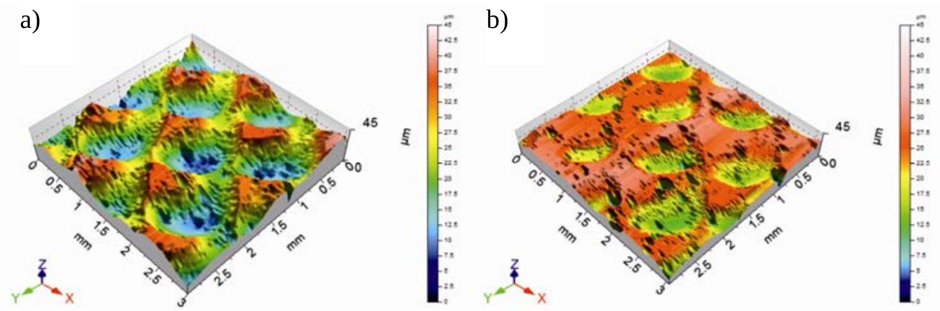

Fig. 3. View of a surface after oscillatory burnishing at φ = 45°: a – after burnishing; b – after wear over a friction path of 20 000 m
Rys. 3. Widok powierzchni po nagniataniu oscylacyjnym przy φ = 45°: a) po obróbce, b) po zużyciu na drodze tarcia 20 000 m

Figure 3a represents the surface after burnishing, while **Figure 3b** shows the same surface after the process of wear over a friction path of 20 000 m. We can see that the peaks of irregularities are smoothed down during wear and a new directional profile is formed on them, which is consistent with the direction of test piece movement in the friction process. A loss of material results at the peaks of irregularities in the technically dry friction process, which can be observed in **Figure 3b**. A new roughness structure forms during wear. The program enables an isolation to be made by cutting out a fragment of interest from the observed surface **(Fig. 3b)**, as shown in **Figs. 4** and **5**.

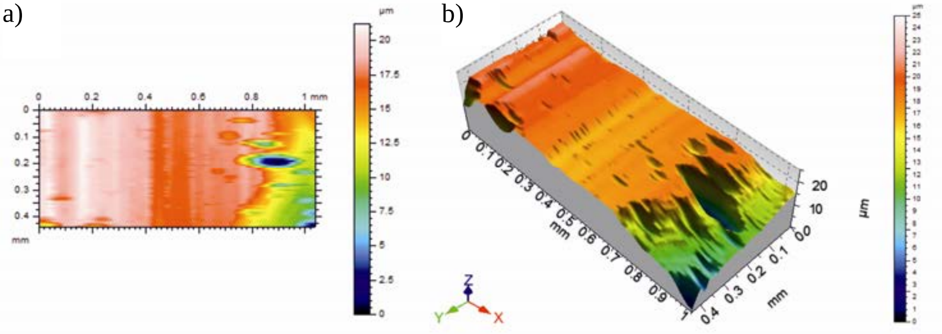

Fig. 4. View of a 0.45 x 1.2 mm peak part irregularity after wear over a friction path of 20 000 m: a) in a flat (2D) system, b) in a three-dimensional (3D) system

Rys. 4. Widok części wierzchołka nierówności o wymiarach 0,5 x 0,8 mm po zużyciu na drodze tarcia 20 000 m: a) w układzie płaskim 2D, b) w układzie przestrzennym 3D

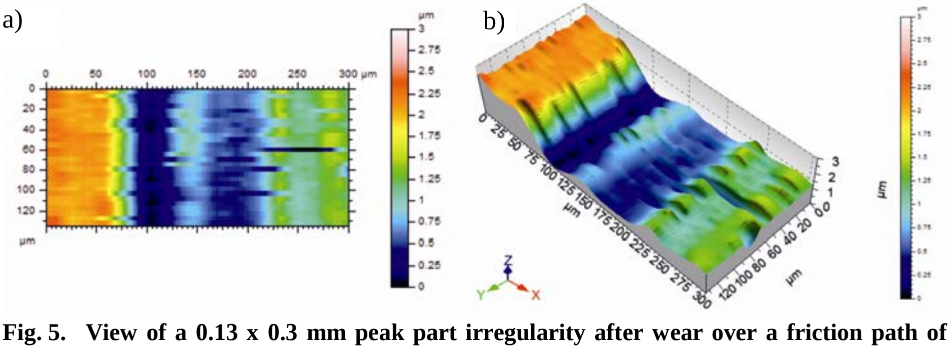

Fig. 5. View of a 0.13 x 0.3 mm peak part irregularity after wear over a friction path of 20 000 m: a) in a flat (2D) system, b) in a three-dimensional (3D) system

Rys. 5. Widok części wierzchołka nierówności o wymiarach 0,012 x 0,03 mm po zużyciu na drodze tarcia 20 000 m: a) w układzie płaskim 2D, b) w układzie przestrzennym 3D

Figure 4 illustrates a surface after wear at a 0.45 x 1.2 mm irregularity peak. We can see grooves formed during wear and micro-cavities that might indicate a process of adhesive wear or the pressing wear products down into the surface. A more detailed picture is shown in **Fig. 5**. This method of analysing a surface after wear can help us identify the character of processes occurring during friction. Having the spatial topography recorded, we can also make an analysis in a 2D system for any cross-section and any fragment of the surface under examination. For example, it will be possible to observe changes in roughness in the direction of motion in the friction process **(Fig. 6a)**, which is very hard to be made by the traditional method due to the need for taking measurement over a cylinder. A further analysis of a selected fragment of that roughness and its magnification is also possible **(Fig. 6b)**. From these profilograms, we can infer the course of the wear process. We can see that the elementary wear processes develop at the irregularity peaks, where a new geometrical surface structure forms. It can be said that this is an operational roughness. These capabilities create a new quality in the observation and analysis of wear processes.

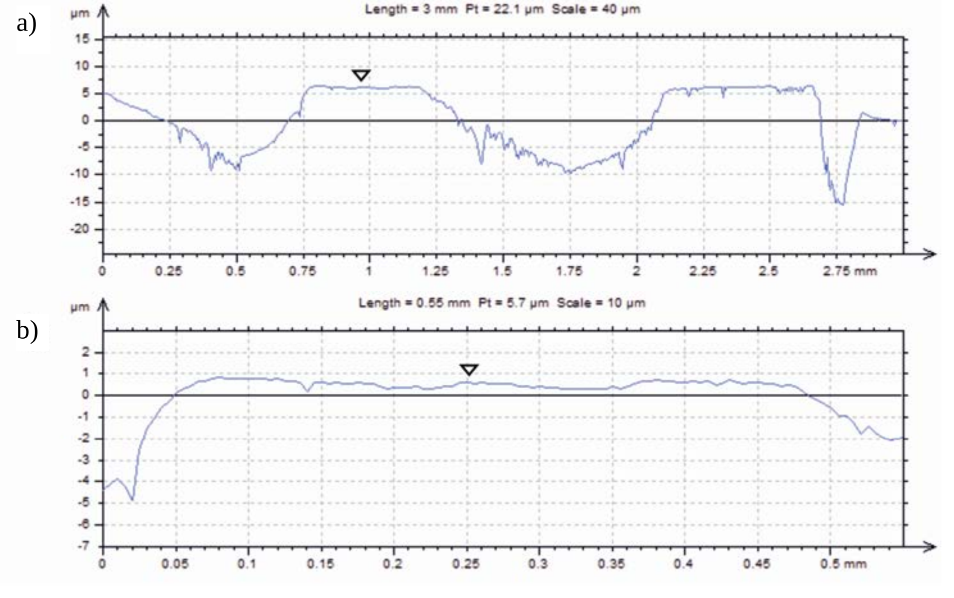

Fig. 6. The surface profilogram from Fig. 2b in the section consistent with wear motion direction for: a – the whole surface analysed, b – a selected peak

Rys. 6. Profilogram powierzchni z **Rys. 2b** w przekroju zgodnym z kierunkiem ruch zużywania: a – całej analizowanej powierzchni, b – wybranego wierzchołka

In addition to the presented analyses, additional surface roughness indicators can be determined and graphically interpreted.

Surface roughness analysis

Analysis of the material ratio curves **(Fig. 7)** makes it possible to observe the change in material load capacity resulting from wear. The initial core roughness height, *Sk*, was 22.5 µm, and the final roughness height was 11.1 µm. The reduced protrusion height, *Spk*, also changed from 3.94 µm for the engineering surface down to 1.12 µm after the operation process, with a simultaneous decrease in the bearing ratio of peaks, *Sr*1, from 8.67 down to 3.65%. In addition, the reduced cavity depth, *Svk*, changed from 4.06 µm at the beginning of the friction process to 6.74 µm after wear. The bearing ratio of cavities did not change significantly. This indicator is a measure of the ability to hold the fluid within a recess on the mating part of the surface.

Figure 8 represents the change in the graphical analysis of volume parameters before **(Fig. 8)** and after **(8b)** the friction process, showing how individual volume indicators reflecting the character of surface load capacity changed at particular stages of operation.

The contour-line maps **(Fig. 9)**, on the other hand, show changes in the size and position of local protrusions and cavities. We can notice that, during the irregularity peak wear process, new surfaces form, which are covered with new micro-irregularities forming a different topography. Recesses remaining after working can be seen, but new micro-cavities also appear, which have formed at the peaks of worn irregularities. They indicate, e.g., the fact that grooving or tearing out of material particles takes place in the friction process.

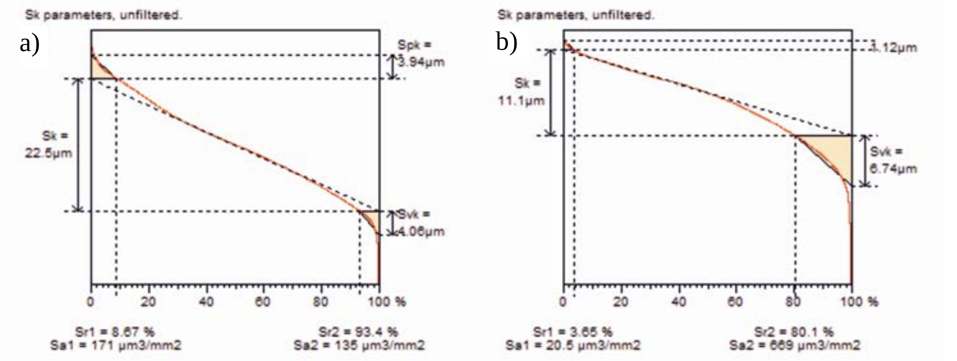

Fig. 7. The surface material ratio curve for a surface oscillatory burnished at φ = 45: a – after burnishing; b – after wear over a friction path of 20 000 m

Rys. 7. Krzywa nośności powierzchni nagniatanej oscylacyjnie przy φ = 45°: a) po obróbce, b) po zużyciu na drodze tarcia 20 000 m

The change in the profile ordinates is shown in **Figure 10**. The cumulated ordinates distribution value enables the observation of the load capacity and characteristic geometrical formations of the surface.

Similarly, the distribution of the peaks of local surface protrusions, characterizing the surface density, also illustrates the change in the form of surface produced during oscillatory burnishing **(Fig. 11a)** and **(Fig. 11b)** at the end of the wear period.

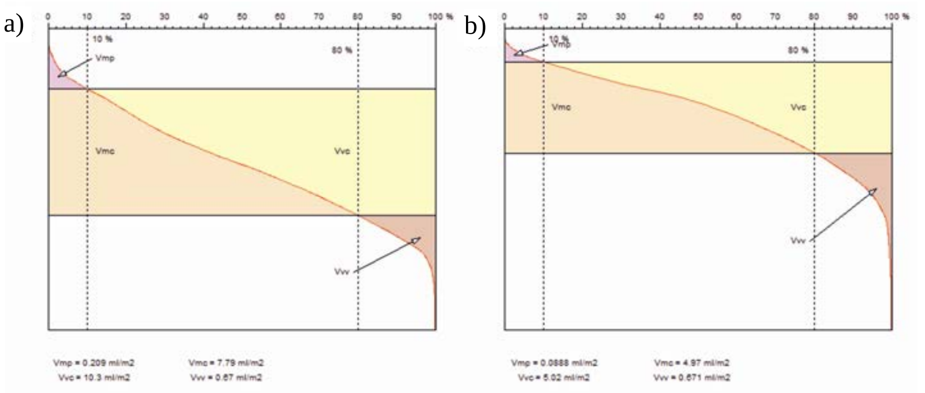

Fig. 8. Volume parameters analysed graphically of a surface oscillatory burnished at φ = 45° a – after burnishing; b – after wear over a friction path of 20 000 m

Rys. 8. Analiza graficzna parametrów objętości powierzchni nagniatanej oscylacyjnie przy φ = 45°: a) po obróbce, b) po zużyciu na drodze tarcia 20 000 m

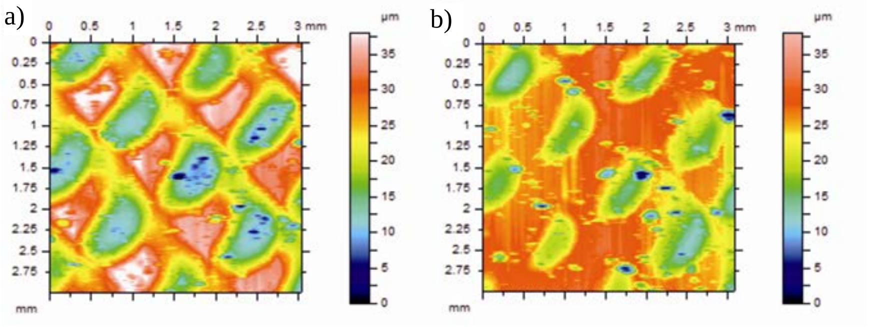

Fig. 9. Contour-line map of a surface oscillatory burnished at φ =45: a – after working; b – after wear over a friction path of 20 000 m

Rys. 9. Mapa warstwicowa powierzchni nagniatanej oscylacyjnie przy φ = 45°: a) po obróbce, b) po zużyciu na drodze tarcia 20 000 m

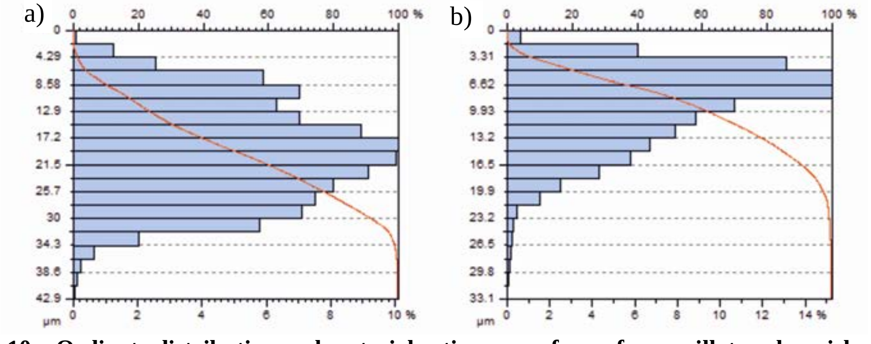

Fig. 10. Ordinate distribution and material ratio curve of a surface oscillatory burnished at φ = 45: a – after burnishing; b – after wear over a friction path of 20 000 m

Rys. 10. Rozkład rzędnych profilu powierzchni nagniatanej oscylacyjnie przy φ = 45°: a) po obróbce, b) po zużyciu na drodze tarcia 20 000 m

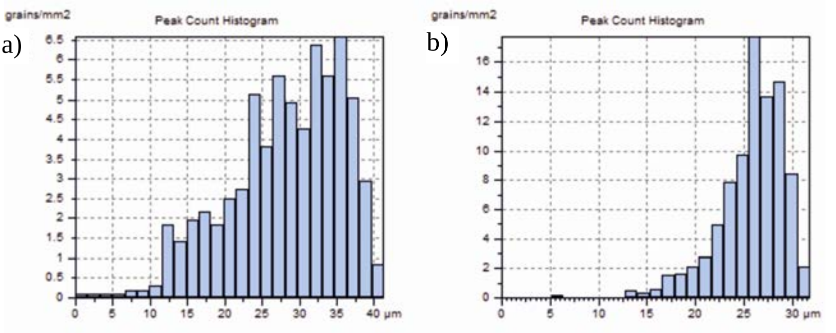

Fig. 11. Distribution of local profile protrusions on a surface oscillatory burnished at φ =45: a – after burnishing; b – after wear over a friction path of 20 000 m

Rys. 11. Rozkład miejscowych wzniesień profilu powierzchni nagniatanej oscylacyjnie przy φ = 45°: a) po obróbce, b) po zużyciu na drodze tarcia 20 000 m

Moreover, the software enables the determination of many roughness parameters that change during wear. Those that are most often used for SGS assessment are summarized in **Table 1.**

Table 1. Change of selected roughness parameters on a surface worked by oscillatory burnishing and subjected to wear over a friction path of 20 000 m

Tablica 1. Zmiana wybranych parametrów chropowatości powierzchni po obróbce nagniataniem oscylacyjnym i po drodze tarcia 20 000 m

Surface state	Amplitude					Spatial			Hybrid		
	Sa	Sq	Sz	Ssk	Sku	Std	Str	Sal	Sdq	Ssc	Sdr
After working	6.39	7.68	42.9	0.0315	2.20	0.312	0.65	0.256	0.172	78.6	1.39
After wear process	4.03	4.92	33.1	-0.779	3.26	0.236	0.526	0.258	0.163	88.1	1.25

In the case under consideration, the average arithmetical roughness parameter, *Sa*, has changed from 6.39 to 4.03 µm, and the average square roughness, *Rq*, from 7.68 to 4.92 µm.

The negative value of the skewness factor, *Ssk,* indicates that the protrusions have the character of a plateau, with the decreasing values showing increasing flatness of that plateau. During the formation of a new surface topography, the irregularity peaks occurrence density, *Sds,* increases from 610 to 1512 pks/mm^2. The concentration factor, *Sku,* also changes; however, because it is susceptible to single cavities, it cannot be a treated as a primary indicator.

As demonstrated by the studies presented, all parameters of the initial--technological surface roughness change during the course of the wear process. The 3D measurement analysis software TalyMap Platinium 5.0 enables the observation of the geometrical surface structure spatial system by separating a specific profile layer and analysing both the remaining and the cut-off layers. Therefore, it can be said that it enables SGS analysis to be made after the virtual wear process.

Simulation of wear process

The results of such analyses are represented in **Figures 12** and **13** which show sample views of surfaces after oscillatory burnishing with specified process parameters (*F*=450 N; *f* = 018 rpm; *e* = 0.5; φ = 30°) **(Fig. 12a)**, and after cutting off the profile in the medium plane **(Fig. 12b)** and another cut-off of the layer **(Fig. 12c)**.

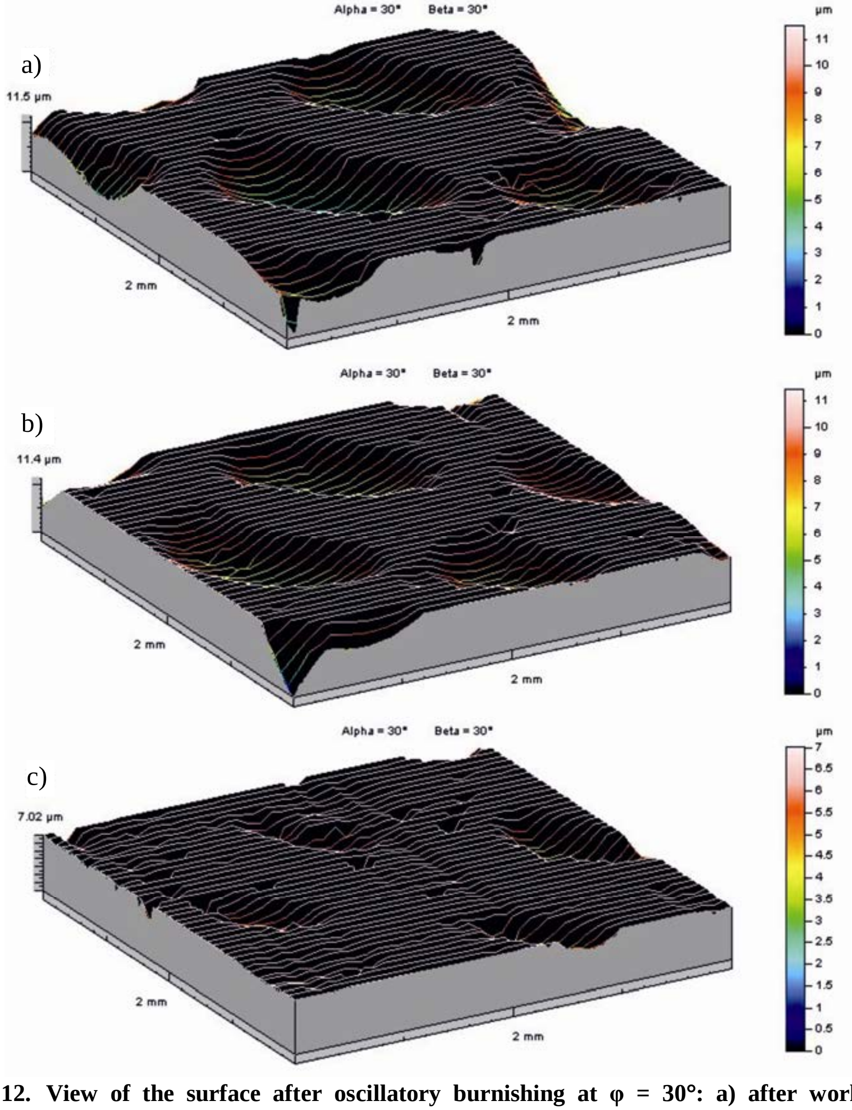

Fig. 12. View of the surface after oscillatory burnishing at φ = 30°: a) after working, b) after cutting off along the medium plane, c) after a following cut-off

Rys. 12. Widok powierzchni po nagniataniu oscylacyjnym przy φ = 30°: a) po obróbce, b) po odcięciu po płaszczyźnie średniej, c) po następnym odcięciu

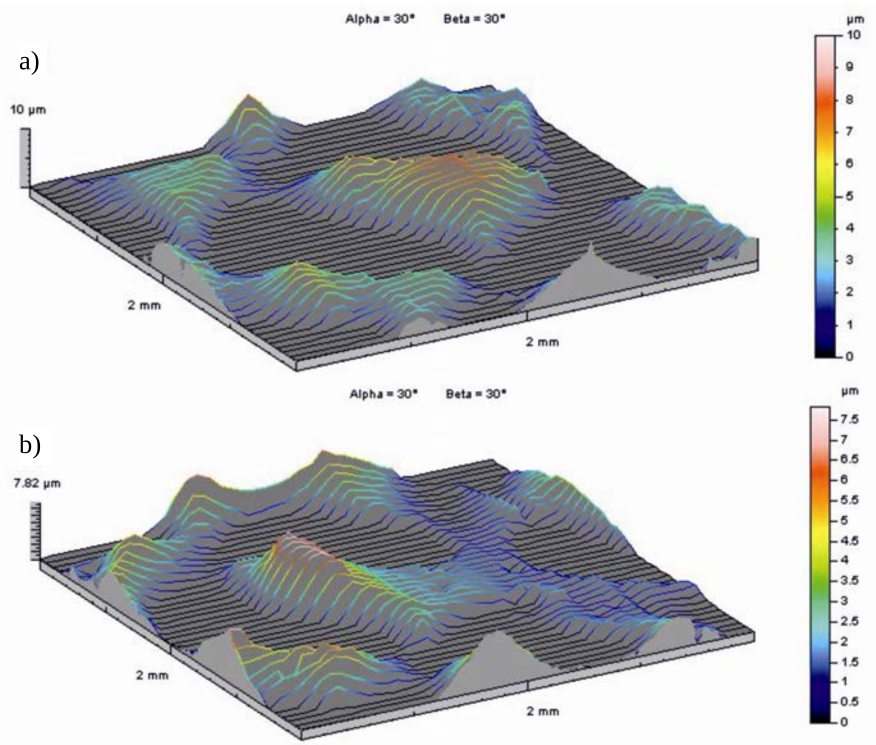

Fig. 13. View of a surface above the medium plane after oscillatory burnishing at φ =30: a) after cutting off along the medium plane, b) after a following cut-off

Rys. 13. Widok powierzchni nad płaszczyzną średnią po nagniataniu oscylacyjnym przy φ = 30°: a) po odcięciu po płaszczyźnie średniej, b) po następnym odcięciu

The view of the surface above the planes (of the cut-off parts) is represented in **Figure 13**. It can be noticed that, in this case, all parameters change and a new roughness structure forms, which resembles the one that forms as a result of wear. In the case under consideration, the average arithmetical roughness parameter *Sa* has changed from 2.78 to 0.609 µm, and the root mean square roughness *Rq* from 3.42 to 0.869 µm. The surface formed as a result of virtual wear still has local cavities visible, as depicted by **Figures 12b** and **c** and **Figures 13a** and **b** showing the view of the surface above the cut-off plane.

Roundness analisys

The measuring set available at the institute's laboratory also includes a Talyrond 365 measuring stand complete with "Ultra Roundness 5.17" software enabling a comprehensive assessment of the shape errors of cylindrical surfaces. The measuring stand consists of a table that allows the precise rotation of the analysed object by an arbitrary angle, as well as a rotary measuring arm moveable in the vertical and the horizontal axes, which enables the selected measuring tip do be set against the examined surface and the measurement to be taken at a resolution from 1.2 nm (being dependent on the adopted measuring head working range). Due to the capability to superpose the rotary motion of the object and the precise rectilinear motion of the measuring tip in the vertical and the horizontal directions and to the possibility of making a precise evaluation of the change in measuring tip deflection in the selected range during measurement, it becomes possible to perform a number of measurements, including the determination of the errors of circularity of cylindrical surfaces. The assessment of the rectilinearity and cylindricity errors is also possible. The measurement method using computerized roundness measurement stands for the analysis of stereometry can be useful in the practice of measuring elements in tribological tests. This is particularly true when a need arises to simultaneously determine the shape of the cylindrical surface being analysed and to determine the errors of roundness, cylindricity, or rectilinearity of selected generating lines of that surface. The method can also be useful for determining the stereometry of areas of considerable widths, being measured on small-diameter cylindrical surfaces, particularly, in cases where the traditional measurement on a profilographometer fails because the measuring range has been exceeded. Therefore, the analysis of geometrical surface structure is also possible on this stand.

Figure 14 represents variations in the circularity of specimens during wear showing that the wear has not been uniform on the entire cylinder surface.

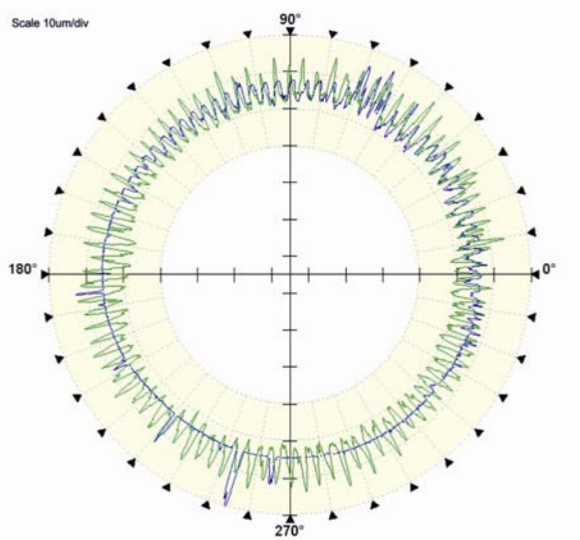

Fig. 14. Variations in the roundness of the specimen during the wearing process
Rys. 14. Zmiany kołowości próbki w trakcie procesu zużywania

Whereas, **Figure 15** represents the analysis of the area including the transition zone, the burnished surface, and the surface after wear, as performed on the equipment under discussion.

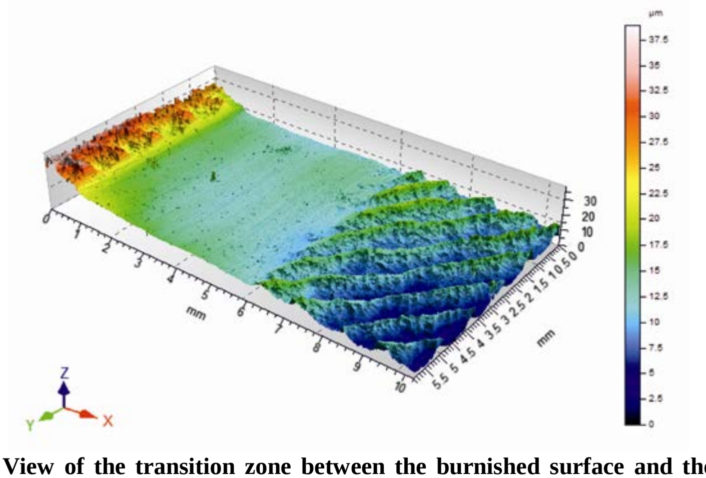

Fig. 15. View of the transition zone between the burnished surface and the surface after wear

Rys. 15. Widok strefy przejścia powierzchni nagniatanej i powierzchni po zużyciu

Wear measurement

The magnitude of linear wear is most often determined by measuring the diameter of the surfaces examined. However, the accuracy of these measurements is often not satisfactory, especially in the first phase of the stand tests, due to the different magnitudes of wear at different points of the examined surfaces and to the variations in the temperature of the examined surfaces, which occur during the wearing process. This undoubtedly contributes to the decrease in the measurement accuracy of the occurred wear. A more precise determination of the magnitude of obtained wear is possible by determining the variation of the roughness profile of the region of transition between the non--worn and the worn surfaces in the spatial (3D) system. To this end, we will have to choose the location of the section and then, considering the reference base, we will be able to determine the magnitude of this wear either by taking into account the scales of the diagram or by using the capabilities of the modern software, as shown in **Fig. 16**.

In fact, it is burdensome in this case to repeatedly remove the measured tribological pair elements from the tester and to take measurement on the profilographometer. It is possible, however, to use portable measuring devices on the test stand, such as the SURTRONIK 25. By utilizing portable measuring devices, we are able to record the changes which occurred along a given friction path and then transform them in suitable software, e.g. the Ultra Surface 5.16.

In this case, we can also control the changes in roughness during surface wear and the formation of operational roughness from the technological roughness.

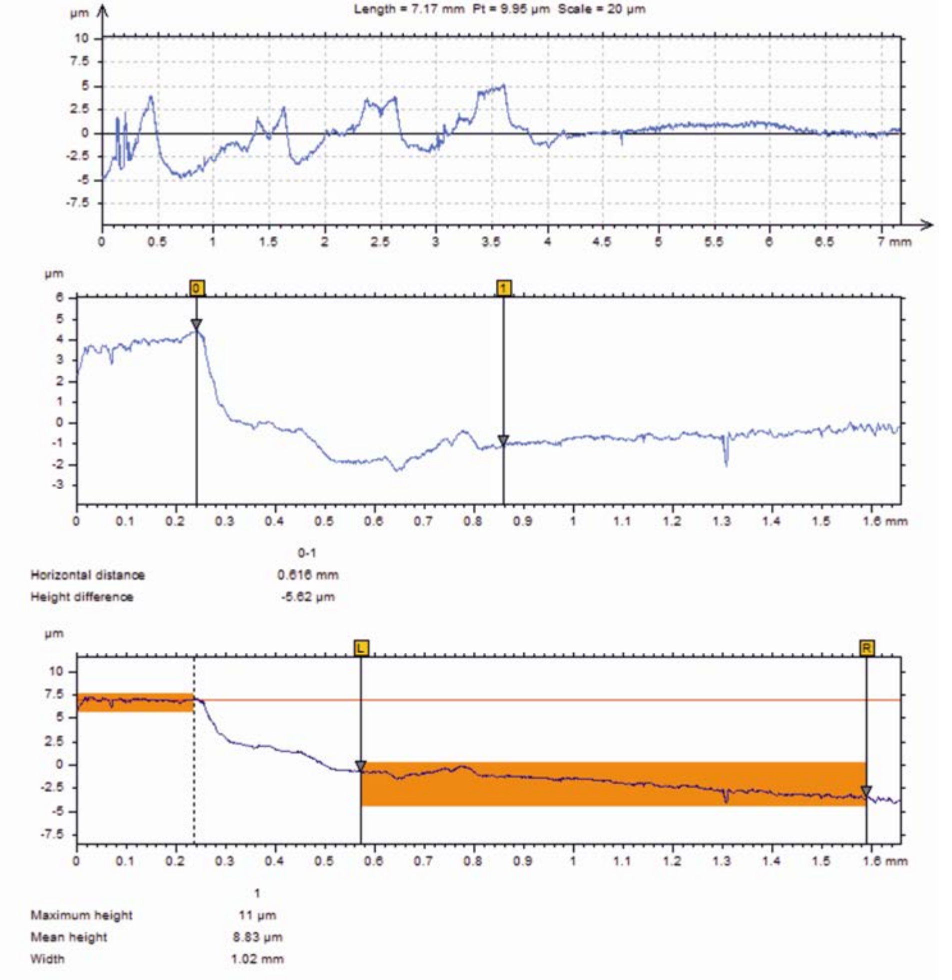

Fig. 16. Measurement of the wear magnitude using the recorded surface profile and the Ultra Surface 5.16 software; a – original profile after filtering, b, c – program determination of the wear magnitude

Rys. 16. Pomiar wielkości zużycia przy wykorzystaniu zarejestrowanego profilu powierzchni i programu Ultra Surface 5.16, a – profil pierwotny po filtrowaniu, b – programowe określenie różnicy wysokości

SUMMARY

– The progress in the construction of roughness measurement instrumentation and the software capabilities enable the analysis of geometrical surface structure to be made in a spatial (3D) system, while making it possible to obtain an image of either the whole surface or a fragment, as well as to determine the characteristics (roughness parameters).

– The employed apparatus and software fully enable surface micro profile measurement and analysis to be performed in a micro-scale with a nanometric accuracy, which allows the observation of changes caused by the friction process either on the entire surface examined or on a fragment.
– It can therefore be said that the currently existing instruments and software create a new quality in laboratory and test-stand testing involving observations and measurements of wear processes. It is therefore possible to discontinue using more laborious and less accurate methods, such as photography.
– The condition for carrying out all of the analyses presented in this work is the application of contemporary computational technology and software. When computer programming is properly selected for the problems it is meant to analyse, the digital processing of the obtained results will be done correctly.

  As a result, a significant increase in the amount of tribological process information will become available.
– It becomes possible to observe selected zones of the geometrical surface structure in the spatial system with accuracies in the order of nm, which can result in a more accurate cause-and-effect assessment of processes occurring at the interface of mating surfaces.

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Streszczenie

Elementarne zjawiska tarcia występują na jednej chwilowej powierzchni rzeczywistego kontaktu, to jest na występach nieprawidłowości. W trakcie eksploatacji formuje się nowy stan chropowatości powierzchni. Do pomiaru parametrów charakteryzujących strukturę geometryczną powierzchni przed i po procesie tarcia użyto profilometru 3D. Uzyskano pełną charakterystykę struktury geometrycznej powierzchni (SGP) w układzie 3D i możliwości programu umożliwiające bardziej szczegółowe wnioskowanie o współpracy elementów pary tribologicznej w skali mikro. W artykule przedstawione zostały możliwości wykorzystania pomiarów 3D chropowatości do oceny zjawisk towarzyszących procesom tarcia i zużywania.