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The methodology of modeling of the grinding wheels active surface

Metodyka modelowania powierzchni czynnej narzędzi ściernych

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In this paper many different methods of generating the topography of the grinding wheel surface and the methodology for assessing the compatibility of models with the surface of real tools was presented. The methodology was indicated that certain features regarding the shape and position of the highest vertices are decisive for assessing the model's conformity with the real surface of the grinding wheel. The significance of not only the form of the distribution of the vertices of the grains was emphasized, but also the significance of the fragment of the probability density function relating to the highest vertices and the autocorrelation of the vertex position as the most important feature, which often are overlooked in the models described in the literature.

KEYWORDS: The grinding wheels active surface, grinding wheel model, verification of the grinding wheel model.

The current stage of industrial development (commonly called the fourth industrial revolution and labeled Industry 4.0) is described by a set of assumptions regarding the integration of intelligent production systems characterized by:

- the ability to communicate cybernetic systems and people,
- global digitalization and virtualization using a large number of object models and processes,
- decentralization of decision-making,
- real-time data processing,
- flexible adaptation of intelligent factories to the changing requirements of recipients.

In the past, empiricism was the basis for seeking and making decisions considered optimal in a set of fairly limited data. The tendency to empiricism resulted mainly from three premises. The first was related to the progress in research methods, the second - with the growing share of engineering works in creating technological progress, and the third - with excessive interest of researchers in the effects of phenomena, not their causes (results of the process, not mechanisms of cumulation and interdependence of elementary interactions of phenomena in the analyzed

processes). Currently, empiricism is often only a method of verifying decisions whose validity results from the models used. It is important to draw conclusions from the large collections of information, as before - on the basis of incomplete, uncertain and inaccurate, but on a different scale.

In creating models there is a need to find a compromise between the detail and the universality of the model. Increasing the level of detail, without seeking to generalize and find conclusions, is only a description of the problem, and not its solution.

The simulation of the grinding process is more and more often recognized by scientific [1, 7-10, 12, 21, 24-27] and industrial environments as a valuable tool for obtaining information on various phenomena accompanying this process [4-6, 17, 18, 24] and related to shaping the surface layer of the workpiece and changes in the topography of the active surface of the grinding wheel [1, 2, 19-23] - also in those areas that may currently not be available from the level of empirical research.

An important element of the grinding process simulation systems is the creation of correct active grinding wheel (CPS) models, because the accuracy of predicting the results of the machining process depends on them. This is not an easy task, especially since the number of features affecting the grinding process is great, the number of events (per unit time) in the form of interactions of individual grain tips often exceeds 106, and the mechanism of effects accumulation is complex and random.

CPS modeling is also useful in scientific work, the purpose of which is to develop new methods and parameters for the evaluation of stereometric features of abrasive tools.

Methods for modeling the active surface of abrasive tools

The methods of modeling the active surface of abrasive tools are presented in Fig. 1. In the further part of the article, the algorithms and results of CPS modeling were developed in the Department of Engineering and Informatics of the Mechanical Faculty of the Koszalin University of Technology (A1-A4 methods).

One can distinguish two basic strategies leading to the formulation of numerical descriptions of the topography of the active surface of the grinding wheel. The first involves the use of data containing the coordinates of points, determined with a specific step of discretization, of the actual surface of the grinding wheel [3, 12, 14, 16] (method E1). The second

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strategy requires the generation of the surface topography of the grinding wheel using procedures that take into account the features of the topography of abrasive tools characteristic for a given method, which are probabilistic in character (A1-A4 methods). In this strategy, two methods for creating an active model of the grinding wheel surface can be distinguished. The first consists in generating the entire surface of the grinding wheel, i.e. grains protruding above the binder, the surface of the binder and cavities being the external pores (methods A2-A4). The advantage of such an approach in CPS modeling is a fast process of creating a surface model, whereas a disadvantage - lack of accurate information about the location of abrasive grains in the grinding wheel model (methods A2 and A3), because they are not isolated. This disadvantage is not found in the Voronoi cell method (A4 method), in which cell regions and the position of the seed tops are known before generating grains occupying a part of the defined cell area.

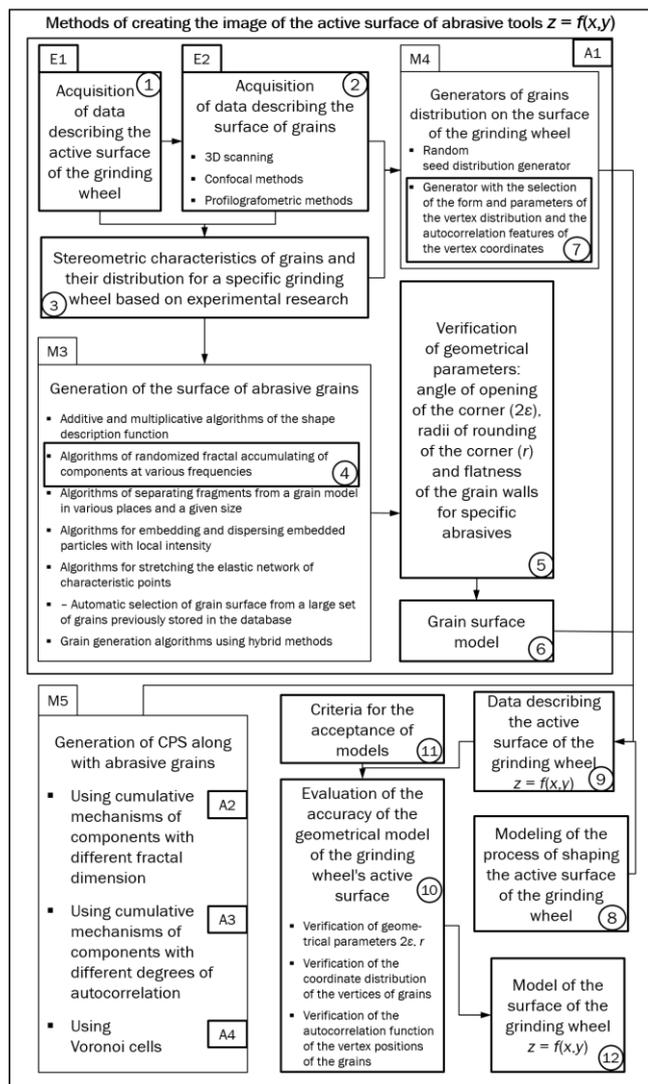


Fig. 1. Methods of modeling the active surface of abrasive tools along with a specific order of operations performed in the A1 algorithm; E1, E2 - stages of data acquisition, M3-M5 - modeling stages; A1-A4 - CPS generation algorithms

Features that distinguish particular methods are:

- Generation of grain surface components with different degree of flatness, their accumulation and verification of the surface of abrasive grains, and then distribution of grains on the surface taking into account two features - the form and parameters of the position distribution of the tops and the autocorrelation of peak heights (A1).
- Randomized, asymmetric mechanism of accumulation of elementary components of surfaces of different fractal

dimension, in which subsequent components have an increasing fractal dimension from 2...3 range and decreasing amplitude and are added additionally to the current cumulative result in a randomized degree - in full value at peak peaks and smaller and smaller at lower levels (A2).

- Randomized, asymmetric mechanism of accumulation of elementary components of surfaces with different degrees of autocorrelation, in which subsequent components have an increasingly smaller length of autocorrelation and decreasing amplitude, and are added additionally to the current cumulative result in a randomized degree - in full value at the tops and smaller and smaller at lower levels (A3).
- Randomized way of generating Voronoi cells and a certain number of points inside these cells, whereby the number of Voronoi cells corresponds - after elimination of fields too small - to the number of grains on the surface of a specific grinding wheel fragment; then, after random addition of additional points around the central point of the cell, which will correspond to the position of the highest peak of the grain, the tool surface is created considering the randomized relationships between the height of the point and its distance from the top (A4).

Another approach to wheel surface generation is given in [2, 26, 27] - according to it, objects that represent abrasive grains are first created, and then these objects are placed in space, which gives a comprehensive description of the grinding wheel's active surface (A1).

Methodology of generating active surface of grinding wheels, taking into account the autocorrelation of the spatial distribution of vertices

The methodology of the A1 algorithm is described in detail in the article [12]. This algorithm includes tasks that in fig. 1 have been numbered in accordance with the order of their implementation.

At the first stage, data acquisition of the actual grinding wheel surface of a specific type (E1) is carried out, and then - using the watershed method - the areas corresponding to the abrasive grains forming the structure are extracted from these data. The numerical description obtained in such a way creates a set of real abrasive grains and allows to determine their statistical geometrical features, which are: the values of apex angles, round radii r and the maximum values of the ordinates of the abrasive grains. Based on these statistical geometrical features of the actual corners of abrasive grains, model abrasive grains can be developed using randomized fractal generation of their surfaces [14] (fig. 2). The maximum values of the ordinates (tops) of the real grains, on the other hand, enable model abrasive grains to be attached to the model of the surface of the grinding wheel in accordance with the function of their autocorrelation.

The latest modifications of the algorithm consist in taking into account the geometric features of the surface of the binder and external pores (fig. 3). Fig. 4 shows the result of the grinding wheel surface algorithm (A1) - the figure shows the developed model with the view of the actual grinding surface

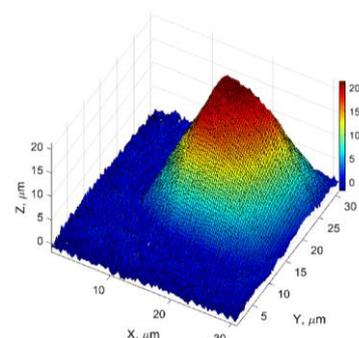


Fig. 2. Example of a model abrasive grain corner generated using a randomized fractal algorithm to create a surface

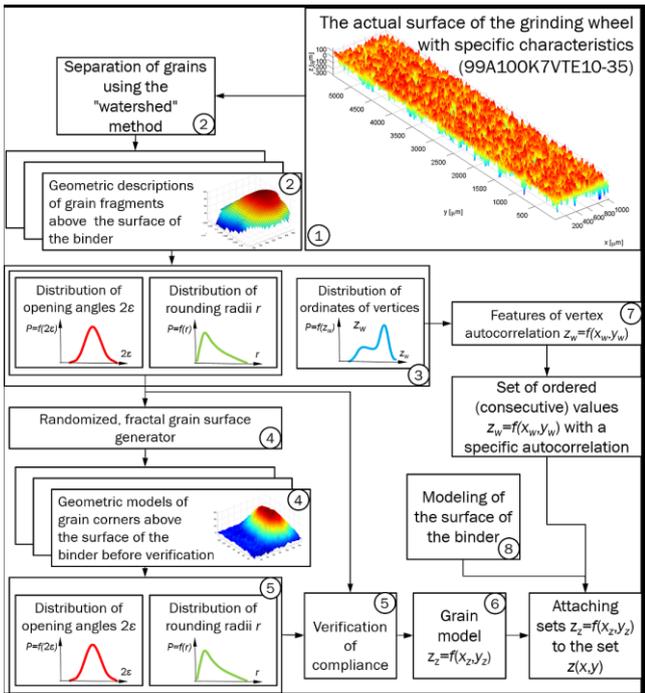


Fig. 3. Algorithm of modeling the surface of abrasive tools with specific characteristics (A1)

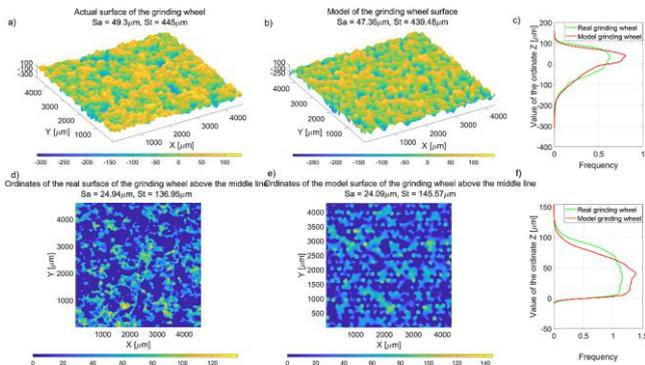


Fig. 4. Views of the active surfaces of grinding wheels: a) real surface, b) model surface, c) comparison of the frequency of occurrence of ordinates for surfaces a) and b); views of the active surfaces of the grinding wheel above the average line: d) actual surface, e) model surface, g) comparison of the frequency of occurrence of ordinates for the surface d) and e)

The model of grinding wheel surfaces, developed according to the A1 algorithm, was verified by comparison [12]:

- fields of areas designated by Voronoi cells on the basis of the coordinates of the highest vertices of the grinding wheel, located above the set level;
- values of the indicator describing the effective outline of the grinding wheel above the determined level of the grinding wheel surface;
- fields of the area under the density function for the vertex pitch distribution, determined for vertex heights above the set level (potentially active vertices).

For each model of the surface topography of the grinding wheel created using the A1 algorithm, the location and geometrical features of each grain on this surface are known, so during simulation of the grinding process, it is possible to analyze the contacts of individual grains with the machined surface in the grinding zone. This allows for modeling the consumption of active abrasive grains [11] and for obtaining detailed information on: grain loads in the grinding zone [7], overloads per one abrasive grain [11] per unit of time, instantaneous and average geometric parameters of each contact (width, grain depression, length of the contact path) [8], instantaneous and average values of grinding forces [10], times of abrasive grains contact with the machined surface

and the influence of individual geometrical features of the wheel surface topography on the course and effects of the machining process.

Generation of active surface of grinding wheels with the use of cumulative components with different fractal dimension

The first applications of this algorithm (A2) are described in [9], and its extended and modified version and application to modeling the surface topography after the grinding process is discussed in detail in [15]. In this article, the authors cited the results of modeling the surfaces of abrasive tools.

The surface topography of grinding wheels differs very much from the surface topography after abrasive machining. For this reason, a new model has been developed, which takes into account that abrasive grains have fragments of flat walls, the size of which depends on the type of abrasive. The surfaces of abrasive tools have isometric features, and the directivity of the structure can only be the result of the grinding wheel process. The abrasive grains on the tool surface are partially coated with a binder, which often has a powder structure. By choosing the amplitude and the fractal dimension and the number of individual components (fig. 5), a surface model can be obtained that is compatible with the actual grinding wheel type (fig. 6).

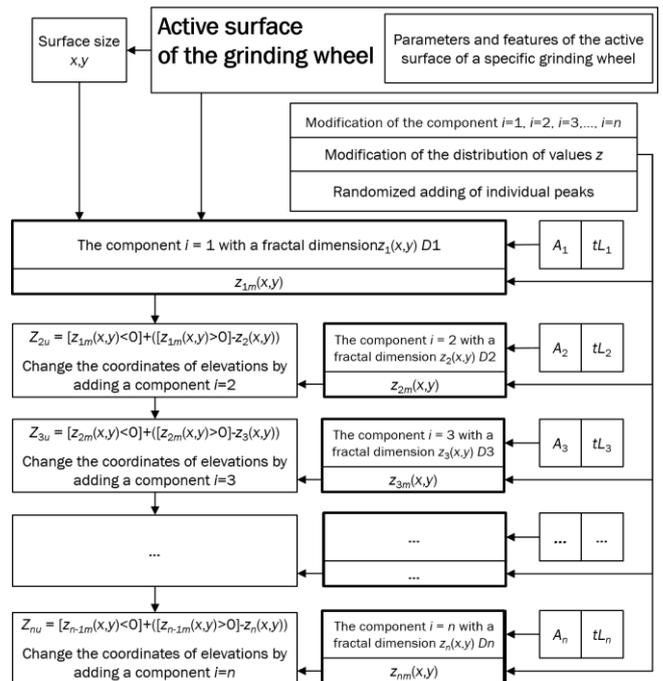


Fig. 5. Scheme for analyzing the CPS generation algorithm with the use of mechanism of cumulation of components with different fractal dimension

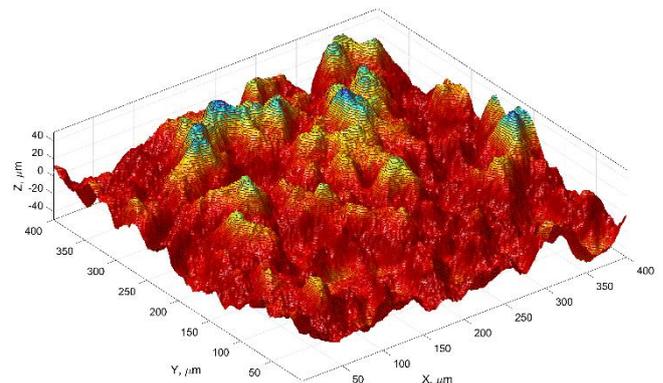


Fig. 6. Image of the surface of a grinding wheel generated using an algorithm with a mechanism of cumulation of components with different fractal dimensions

The advantage of this method is the ability to model the surface of grinding wheels containing - apart from the basic grains - microaggregates composed of small grains.

Generation of the active surface of the grinding wheel using the accumulation of components with different degrees of autocorrelation

Randomized, asymmetric mechanism of accumulation of components of elementary surfaces with various degrees of autocorrelation, in which subsequent components have an increasingly smaller length of autocorrelation and decreasing amplitude and are added additively to the current cumulative result in a randomized degree - in full value at tip peaks and at a lower level at lower levels (A3) - is shown in fig. 7.

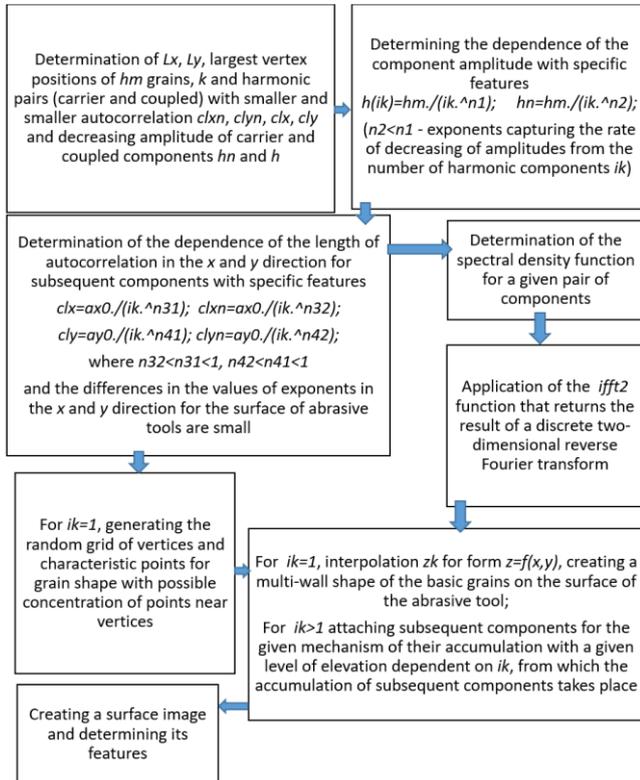


Fig. 7. Scheme for the analysis of the grinding wheel methodology with the use of a component accumulation algorithm with various degrees of autocorrelation

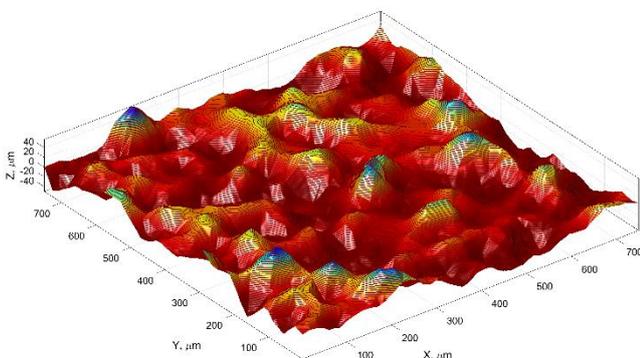


Fig. 8. Image of the surface of the grinding wheel generated using the component accumulation algorithm with various degrees of autocorrelation

This algorithm uses known surface features on the principle that they contain components that differ in frequency, amplitude and length of autocorrelation. However, the statistical parameters of pitch height and variability in the unevenness of the abrasive grains protruding above the surface are variable in the direction perpendicular to the

nominal face of the tool, which means that the accumulation of components is not a simple sum but refers to vertices more than recesses being pores in which microdissection products remain in the treatment zone for some time (fig. 8).

Methodology of CPS formation using Voronoi cells

In [16], it was shown that Voronoi cells allow for simple determination of mean distances between adjacent grains on the surface of an active grinding wheel. Based on these conclusions, the CPS creation algorithm was developed using Voronoi cells (fig. 9). The algorithm divides the active surface of the abrasive tool into Voronoi polygons according to the random distribution of potential abrasive grains on the surface of the grinding wheel. When the Voronoi cell surface is smaller than the assumed minimum size of the abrasive grain, aggregation and correction of the position of the vertices of adjacent grains occurs (fig. 10a).

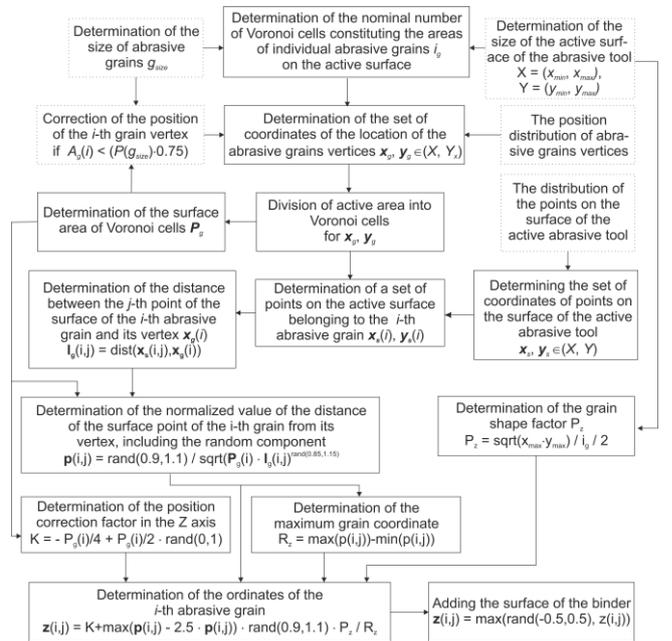


Fig. 9. Diagram for analyzing the CPS model generation algorithm using Voronoi cells

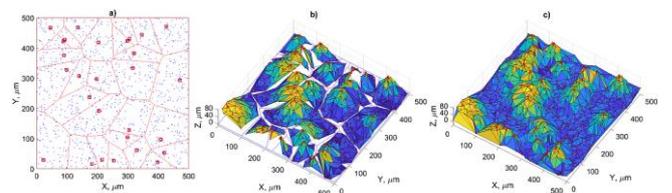


Fig. 10. Scheme for visual analysis of stages of CPS creation using Voronoi cells: a) determination of the set of coordinates of the position of the abrasive grains tops, b) view of the surface of abrasive grains, c) view of the CPS model

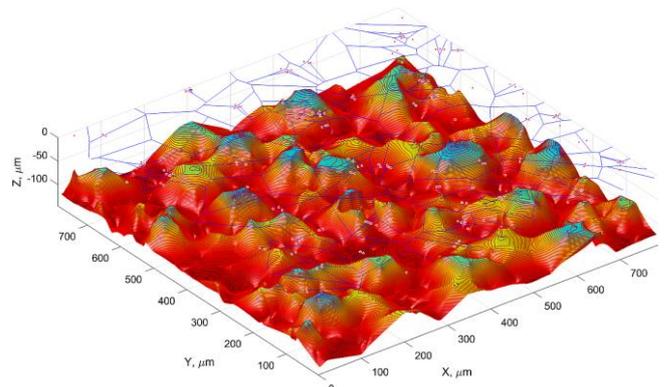


Fig. 11. Result of modeling the grinding wheel surface using Voronoi cells

The surface of an abrasive grain is created using randomized relations, taking into account the location of points (blue points in fig. 10a) belonging to a given cell (red lines) with its focal point (the point marked with red square in fig. 10a), which corresponds to the position of the highest peak of the grain abrasive (fig. 10b). In the final phase, the surface of the binder is added to the surface of the abrasive grains (fig. 10c).

As a result of the algorithm, the active surface of the abrasive tool is obtained with the number of abrasive grains identified and their separated boundaries (fig. 11). As a result, it is possible to determine parameters describing both the location and shape of abrasive grains, which significantly facilitates the verification of the developed model of the active surface of the abrasive tool with digital recording of the real surface.

CPS model verification methods

In the A1 algorithm, before developing the CPS model, models of corners of abrasive grains should be developed, whose geometrical features will be consistent with the characteristics of their actual counterparts. This requires the verification of corner models of abrasive grains. Therefore, the methodology of verification of conformity of modeled corners of abrasive grains with real corners was developed, which consists in analyzing the scatter and the expected value of 2ϵ angles and radii of rounding r of corners as a function of hypothetical depression of grain into HP material [12, 14].

Fig. 12 presents a comparison of geometrical features (expected values of apex angle 2ϵ and rounding radius r) corners of model abrasive grains with real ones, from 99A alumina with the number 100, as a function of hollow corner in the HP workpiece.

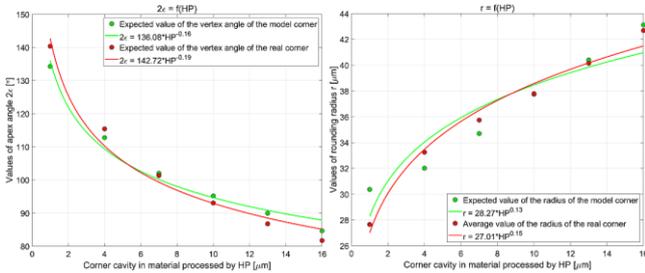


Fig. 12. Comparison of geometric features (expected Values of apex angle 2ϵ and rounding radius r) corners of model abrasive grains with real as a function of Corner cavity in material processed by HP

To compare the model surface (developed using A1-A4 algorithms) with the actual surface of the abrasive tool, the methods proposed here can be used. The first consists in comparing the average value of Voronoi cell fields, determined at specific levels from the highest peak of the analyzed area. In the second method, you can compare the vertex elevation function fields for potentially active abrasive grains.

■ **Verification of the CPS model using Voronoi cells.** The methodology for the evaluation of the surface of abrasive tools using the decomposition of the studied area for Voronoi cells was developed at the Koszalin University of Technology in the Department of Technical and Information Systems Engineering [17].

On the model and actual basis the values of the highest peak S_p are determined, and then the levels of potential contact h_s of the active surface of the grinding wheel with the machined surface are determined. Then, the intersections of the analyzed surface are made with the plane distant from the highest peak S_p by the value of h_s . Above the plane at a given level h_s , the elevations are determined, the highest points of which are input elements to the algorithm enabling

determination of Voronoi cells. The elevations at each level h_s are counted (L_{iw}) and their P_w surface area and their average \bar{P}_w values are calculated.

For determined Voronoi cells at specific h_s levels, the values of their P_v surface area and the average value of these \bar{P}_v fields were calculated (fig. 13).

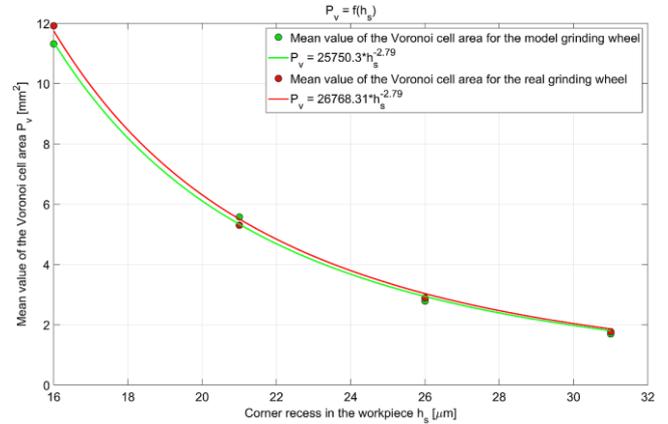


Fig. 13. Comparison of the mean value of the Voronoi \bar{P}_v cell field of the model grinding wheel with the actual grinding wheel as a function of the corner recess in the workpiece h_s

In addition, a dimensionless L_{ze} index was developed to evaluate the effective profile of the abrasive tool:

$$L_{ze} = \frac{\sqrt{|\bar{P}_w|_{h_s} * L_{iw} h_s}}{L_p} \quad (1)$$

where: $|\bar{P}_w|_{h_s}$ - average value of the elevation field at a given level of potential contact h_s of the grinding wheel's active surface with the machined surface, - number of elevations at a given potential contact level h_s for the entire grinding wheel active surface, L_p - width of the grinding surface analyzed.

The comparison of the L_{ze} index value of the effective grinding wheel model with the actual grinding wheel as a function of the corner recess in the workpiece material h_s is shown in fig. 14.

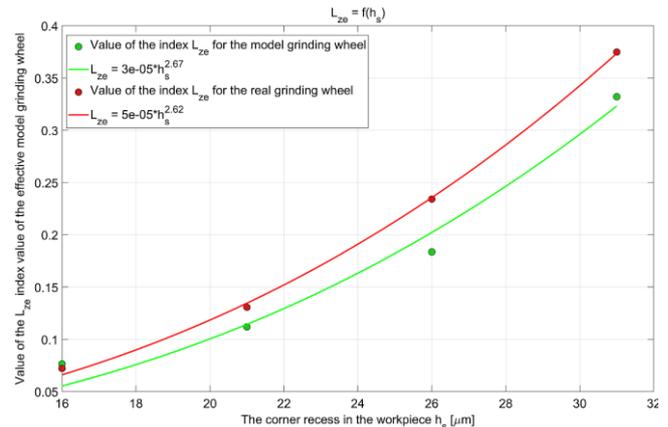


Fig. 14. Comparison of the L_{ze} index value of the effective model grinding wheel with the actual grinding wheel as a function of the corner recess in the workpiece h_s

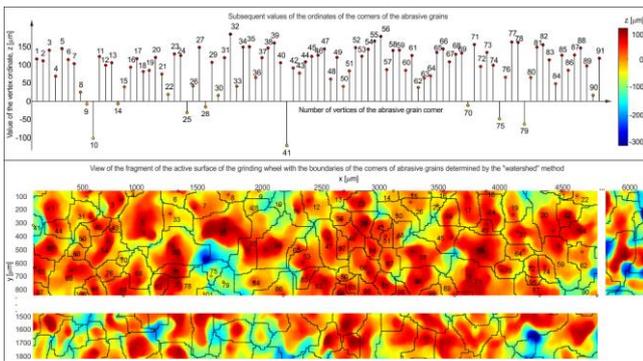


Fig. 15. Values of ordinates of successive peaks of corners of abrasive grains counted by the watershed method

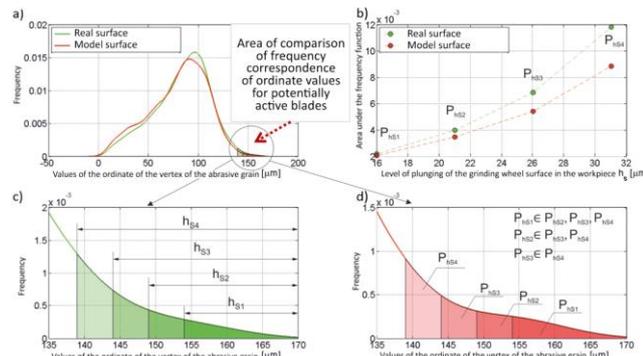


Fig. 16. Scheme for the analysis of the frequency of the values of ordinates of the abrasive grains vertexes: a) distributions of aperture ordinates frequency and highlighted area for further comparisons; b) a comparison of the accumulated frequencies of the peak values of the grain tops for the actual grinding wheel (green) and the model wheel (red); c) the frequency of the values of the ordinates of the grain tops in the area of the highest vertices for the actual grinding wheel; d) the frequency of the peak values of the grain tops in the area of the highest vertices for the model wheel

■ **Verification of the CPS model using the density function for vertex pitch distribution.** The method of verifying the active model of the grinding wheel's surface with the actual surface with a specific characteristic consisted in comparing the frequency of the ordinates of the abrasive grains tops, which were counted using the watershed method (fig. 15). Fig. 16 presents a diagram for the analysis of the frequency of maximum values of individual abrasive grains. Field values under the frequency function for the model and real surface were compared, which are determined for specific levels of potential contact h_s of the grinding wheel's active surface with the machined surface.

The presented analyzes show that the grinding wheel model developed in accordance with the A1 algorithm is characterized by high compatibility with the compared surface of the actual grinding wheel in the range of the potentially active grains.

Conclusions

Methods of generating the surface topography of a grinding wheel and the methodology for assessing the conformity of models with the surface of real tools are presented. It has been shown that in this assessment specific features concerning the shape and position of the highest vertices are decisive. It has been proved that the development of the correct model requires taking into account not only the form of the distribution of the height of grain peaks, but also a specific fragment of the probability density function, which refers to the highest vertices. In addition, it is necessary to ensure compliance of the autocorrelation of the position of the grain tops according to modeling results with the autocorrelation of the position of the grain tops on the actual grinding wheel surface with a given characteristic.

The methods discussed differ in the way that the model is compatible with the actual surface of the tools. The first method generates grain surface components with different degree of flatness, their accumulation and verification of the surface of abrasive grains, and then the distribution of grains on the surface, taking into account two characteristics: the form and parameters of the vertex position distribution and autocorrelation of the vertex heights. The second method uses a randomized, asymmetric mechanism of accumulation of components of elementary surfaces with different fractal dimension, in which successive components have an increasing fractal dimension and decreasing amplitude and are added additively to the current cumulative result in a randomized degree - in full value at tip peaks and less and less on the lower levels. The third method uses a randomized, asymmetric mechanism of accumulation of elementary components of surfaces with different degrees of autocorrelation, in which subsequent components have an increasingly smaller length of autocorrelation and decreasing amplitude and are added additively to the current cumulative result in a randomized degree - in full value at tip peaks and less and less on the lower levels. The fourth method is dominated by the randomized way of generating Voronoi cells and a certain number of points inside these cells, where the number of cells, after elimination of fields too small, corresponds to the number of grains on the surface of a specific grinding wheel fragment; then, after random addition of additional points in the central region of the cell, which will correspond to the position of the highest peak of the grain, the tool surface is created, taking into account the randomized relationships between the height of the point and its distance from the apex.

In each of the methods, it is possible to ensure a high level of model compliance with the actual features of the surface topography of grinding wheels by appropriate selection of its parameters. The compatibility level of the surface features of the tool according to the model and the surface of a given grinding wheel can be assessed jointly by comparing the geometric mean calculated from the relative values of the features considered important.

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