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Experimental study of the relationship between the vibro-acoustic parameters of the grinding process and the macro-roughness of the treated surface

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ABSTRACT

Introduction. To assess the current state of the technological system (TS) during grinding, it is preferable to use indirect criteria. Such approaches, in contrast to direct measurement methods, can be carried out without interrupting the production process. The main parameters used in the indirect assessment of the state of the cutting tool are the state of the workpiece (before and after processing), thermal and electrical characteristics of the cutting zone, vibroacoustic vibrations of the process, and force measurements. The work is devoted to the study of the acoustic parameters of grinding as a sufficiently informative and least resource-intensive characteristic. **The relevance** of the development of methods for assessing the state of the vehicle based on sound and topographic characteristics has many aspects, the main of which are applicability in grinding control, predicting the state of the cutting tool and planning the operations of the technological process. **The aim of the work** is to develop a mathematical model of the dependence of the vibroacoustic parameters of the external circular plunge-cut grinding process on the macro-roughness of the polished sample. The development of such a model is a necessary step in the design of a methodology for predicting the state of a tool. Accordingly, **the subject** of work is presented by two parameters simultaneously – the sound level arising in the process of grinding and the deviation of the surface shape of the ground images from cylindricality. **The research methods** used to achieve the designated aim were following: an experiment to study the sound phenomena accompanying round external plunge-cut grinding; measurement of macro-roughness of the surface of the samples, subjected to processing, using a coordinate measuring machine; correlation and regression analysis to obtain mathematical dependencies. **Results and discussion.** Two particular multiple linear regression models are obtained that describe the effect of the infeed rate and the operating time of the grinding wheel on the sound level during grinding and on deviations from the cylindricality of the processed samples. On the basis of particulars, a general model is developed that establishes the relationship between the sound characteristic and the macro-roughness index of the treated surface. It is shown that the sound characteristics (for example, the sound level) can be used as an indirect indicator of the current state of the vehicle, which makes it possible to assess the level of vibrations and, accordingly, to predict the quality of products.

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Introduction

The problem of ensuring the requirements of the surface shape during external grinding is not less important than the problems of ensuring the required roughness [1] or accuracy of the diametrical size. Compliance with the requirements for the shape of workpiece surfaces is a priority for such parameters as the wear resistance, performance, reliability, and durability of the joints of machine parts; in particular, deviations from circularity and cylindricality.

There are many factors influencing the parameters of the surface cylindricality during external circular plunge-cut grinding (ECPCG). The influence of all or most of these factors on the state of the treated

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surface can be taken into account by the use of the amplitude-frequency characteristics of the technological system (TS).

Many mathematical models, methods of diagnostics and forecasting of the states of various parameters of the technological system (TS) are based on taking into account the vibration characteristics of the grinding process today: the technical condition of the grinding equipment [2]; the current state of the grinding wheel (GW) [3-5]; the quality of the processed surface [6]; deviations from circularity taking into account the kinematics of the process during centerless grinding [7, 8], etc.

The negative impact of high-amplitude vibrations on the TS in general (increased wear of machine components and the increased likelihood of its premature failure) and on the product quality in particular (reduced accuracy and roughness parameters and shape deviations) is beyond doubt and requires the development of methods and techniques for its early detection [9] and subsequent elimination or minimization [10–12].

We can see from the literature that the solutions to most problems related to production planning, predicting the state of TS, optimizing grinding modes, and leveling processing errors, etc. are based on the development of mathematical models.

The advantage of using mathematical modeling to describe complex processes and production systems is that this method allows one to study a specific parameter irrespective of its insignificant characteristics and avoids the high costs of direct study. The construction of a model and establishing a connection between the factor(s) and the response allows one to identify the new qualitative characteristics of an object which are not obvious when other methods are used.

In the light of this, **the purpose** of this work is to develop a mathematical model of the relationship between the vibro-acoustic parameters of ECPCG and the macro-roughness of the grounded sample.

To achieve this purpose, the following tasks should to be solved:

– setting up an experiment;
– processing of experimental results;
– development of a mathematical model of sound characteristics;
– development of a mathematical model of deviations from the cylindricality;
– development of a generalizing mathematical model of the relationship between (3) and (4).

This study is carried out to develop a methodology for predicting the durability of the grinding wheel based on the sound level of the grinding process, which does not require significant resources for measurement and processing. Such a methodology increases the efficiency of grinding operations in high-variety production settings.

Research methodology

The object of the experimental research is ECPCG. The subject of research is the acoustic characteristics of this process.

The experiment (Fig. 1) was carried out on the 3M151F2 circular grinding machine using a grinding wheel 1 600×50×305 25A F46 L 6 V 50 2cl GOST R 52781–2007.

Processing modes:

– wheel rotation speed V = 50 m/s;
– radial feed rate of the wheel S_R, depending on the experiment = 0.2; 0.3; 0.5; 0.8 mm/min;
– rotation speed of the workpiece in the centers S_C = 25 m/min;
– grinding width l_g = 10 mm;
– duration of processing t_1 = 1 min, t_2 = 2 min, t_3 = 5 min.

The samples used for the experiment are steel 45 disks with a diameter of 70 mm and a hardness of 50-55 HRC.

When planning the experiment, we took into account existing studies of the wear of grinding wheels [13]. The process conditions are taken from the conditions often used in production and which have already been investigated.

Before the experiment begins, the allowance and traces of the previous operation are removed from the sample surface. The GW is corrected before each new experiment to ensure equal initial conditions and reduce the probability of a corresponding error. The signal was recorded via a compact microphone. The PC program "SOUNDFORGEPro 13.0" was chosen as a tool for working with the received acoustic data, as the most acceptable in terms of functionality, accessibility and ease of use.

The coolant-cutting fluid (CCF) was fed into the cutting zone by the jet-pressure method through a nozzle located near the protective casing of the GW. The capacity of the feed pump is 12 l/min.

Each experiment recorded the signal of the acoustic vibrations at a certain combination of experimental conditions (S_{pi}; t_i).

In addition, the real profile of each grinded sample in two sections was determined. The distance between the sections was 5 mm. The determination of the size of the deviations in the shape of the samples was made using the coordinate measuring machine KIM-1000. The scanning method with a discreteness of 0.1 mm was applied. As a result, data on the coordinates of the point cloud for each sample were obtained, which are subject to further processing and analysis.

Results and discussion

The sound recorded on a digital medium represents a volume of data containing information on the change in the amplitude and frequency of the sound wave over time.

The spectral analysis of the sound generated by the grinding process allowed us to determine the distribution of frequencies over the spectrum and its amplitudes at each moment in time.

The amplitudes were recorded within the so-called informative frequency band of 700–780 Hz, established in the works of V. F. Guryanikhin [14–15]. The informative frequency band is directly related to the cutting process. Other sounds present in the recordings (e.g. of hydraulic pumps; of the high-frequency rotation of the grinding slide and other machine components; of the coolant-cutting fluid washing the cutting zone and returning to the system reservoir) differ from the grinding acoustics and have other frequency values, therefore, only the sound within the informative frequency band was analyzed.

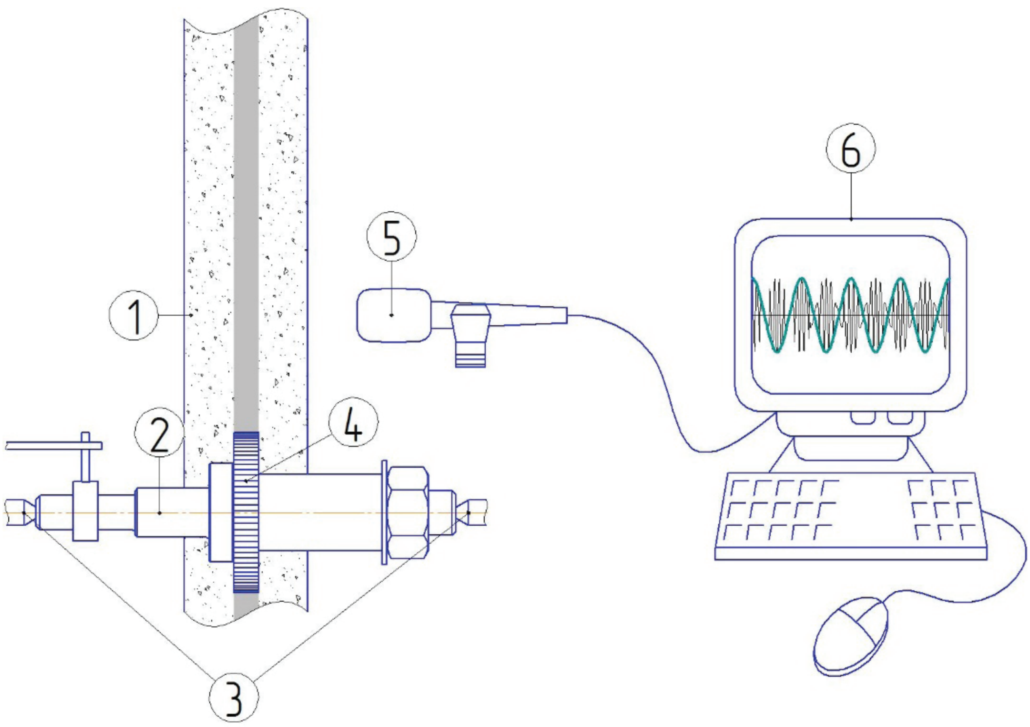

Fig. 1. Experiment scheme:

1 – grinding wheel; *2* – mandrel installed in the center of *3*; *4* – steel 45 sample; *5* – microphone; *6* – personal computer

To increase the reliability of the experimental results, each experiment with unchanged factors was carried out three times. Table 1 summarizes the data on the magnitude of the sound averaged from the three experiments. The data were graphically displayed in the form of point dependences of the sound level distribution on the amplitude-time plane (Fig. 2, 3).

Having analyzed the acoustics graphs, two characteristic stages can be distinguished. The first is the intensive growth of the sound level. Here, the workpiece is processed with a GW profile formed by dressing. The duration of this stage depends on the radial feed rate of the GW. Grinding at the second stage is performed with a run-in GW. The sound level continues to grow; however, this growth is much slower than at the first stage.

G. B. Lurie, in his works studying vibrations of a TS during grinding [16–18], justified the division of the abrasive grains wear cycle between dressings into three stages:

– initial – the period after dressing, when there is increased wear of the cutting grain peaks and grains defective in shape and unfavorably oriented break off; the bunch is removed from the surface of the GW. This stage is characterized by a short duration, which depends on the dressing and processing modes.

– normal – the period characterized by the mechanical wear of the cutting edges of abrasive grains. Compared to the initial stage, the wear slows down, and worn areas are formed on the grains. In advanced modes, when the load on the abrasive grains is significant, we observe the splitting of larger particles from the grains, called self-sharpening.

– emergency – the period when the wear of the abrasive grains again increases, partly due to an increase in the amplitude of vibrations. However, the wear during the emergency stage is much slower than during the normal stage.

Table 1

Average sound level data for various process conditions

Grinding wheel running time t, min	Radial feed rate S_r, mm/min			
	0.2	0.3	0.5	0.8
	Average sound level β, dB			
0.25	–54.67	–58.00	–62.67	–59.33
0.50	–52.00	–54.67	–59.33	–44.00
0.75	–48.67	–50.33	–47.33	–39.33
1.00	–50.00	–46.33	–42.33	–34.33
1.25	–46.67	–45.33	–37.33	–34.67
1.50	–45.33	–44.67	–34.33	–33.33
1.75	–42.33	–45.67	–33.67	–29.67
2.00	–42.67	–45.67	–34.67	–31.33
2.25	–41.00	–42.33	–34.33	–28.00
2.50	–39.67	–39.00	–31.67	–27.67
2.75	–41.33	–37.67	–32.67	–28.33
3.00	–39.67	–36.33	–32.00	–29.00
3.25	–38.00	–33.00	–31.67	–27.00
3.50	–37.33	–32.33	–30.67	–29.67
3.75	–35.67	–33.67	–32.00	–27.33
4.00	–34.67	–33.67	–32.00	–29.67
4.25	–33.67	–32.00	–32.00	–28.00
4.50	–34.67	–32.00	–30.67	–27.00
4.75	–34.00	–30.67	–30.67	–27.67
5.00	–32.00	–31.67	–31.33	–29.00

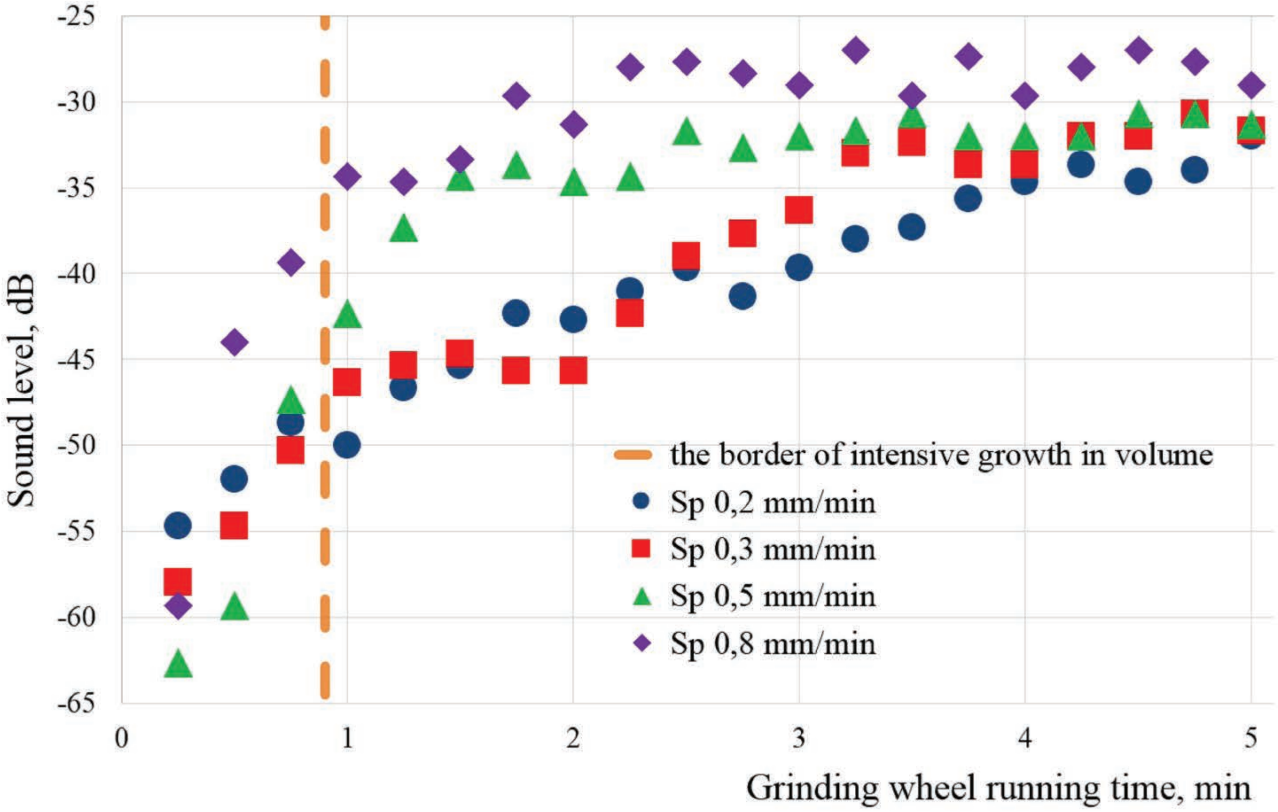

Fig. 2. Distribution of sound level amplitudes in time

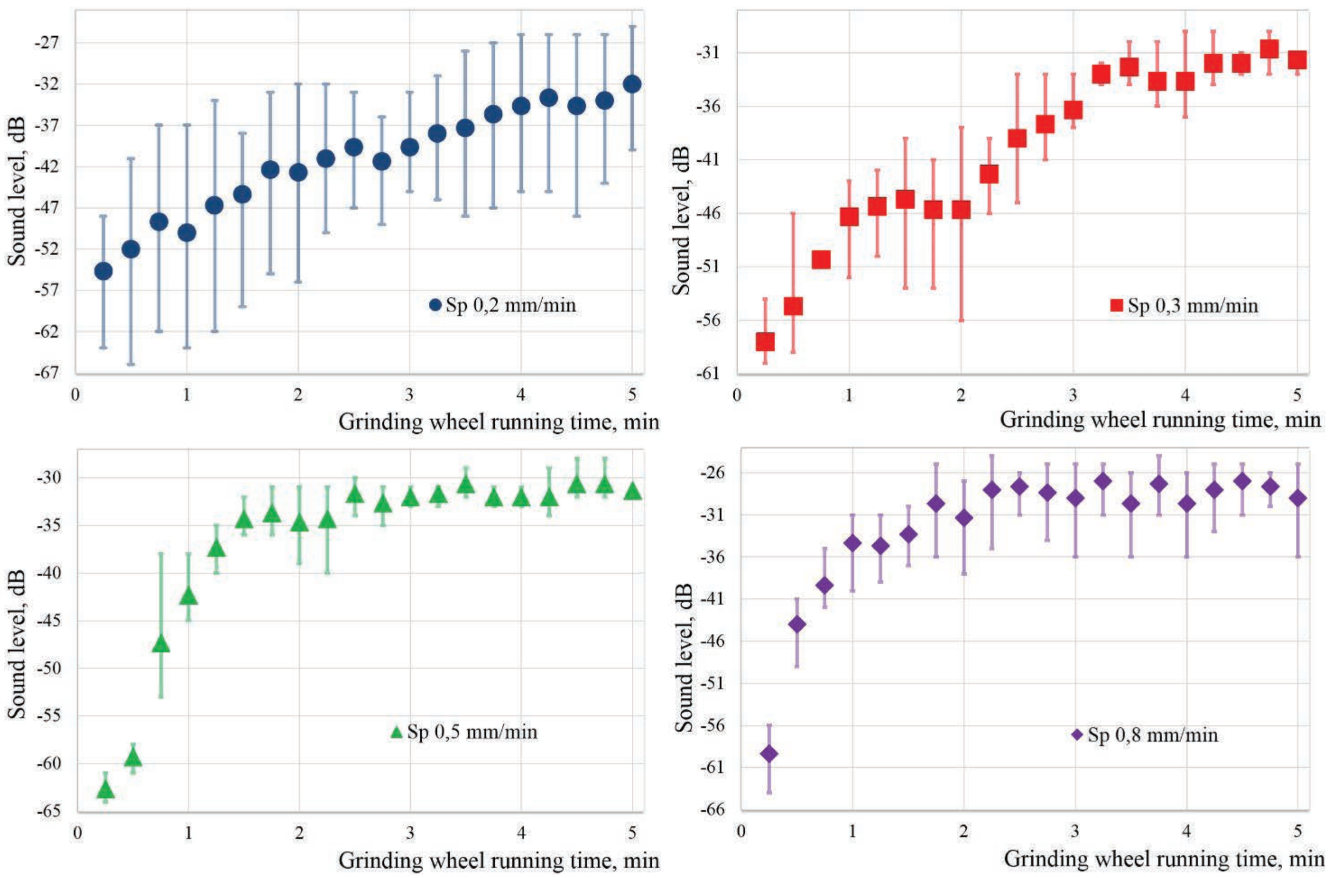

Fig. 3. Confidence intervals of the sound level

More recent experimental studies of the wear of grinding wheels [13] qualitatively confirm the presence of the initial and normal stages of the abrasive grain wear rate using the example of changes in the size of the blunting areas of the grinding wheel 1 600×50×305 24A F60 L 7 V 50 2cl GOST R 52781–2007 (Fig. 4 [18]). A stage of acceleration in blunting areas and a stage of a moderate rate of increase in wear areas are clearly marked for various feeds. The authors also determined the time values for GW with different characteristics corresponding to the duration of the initial stage.

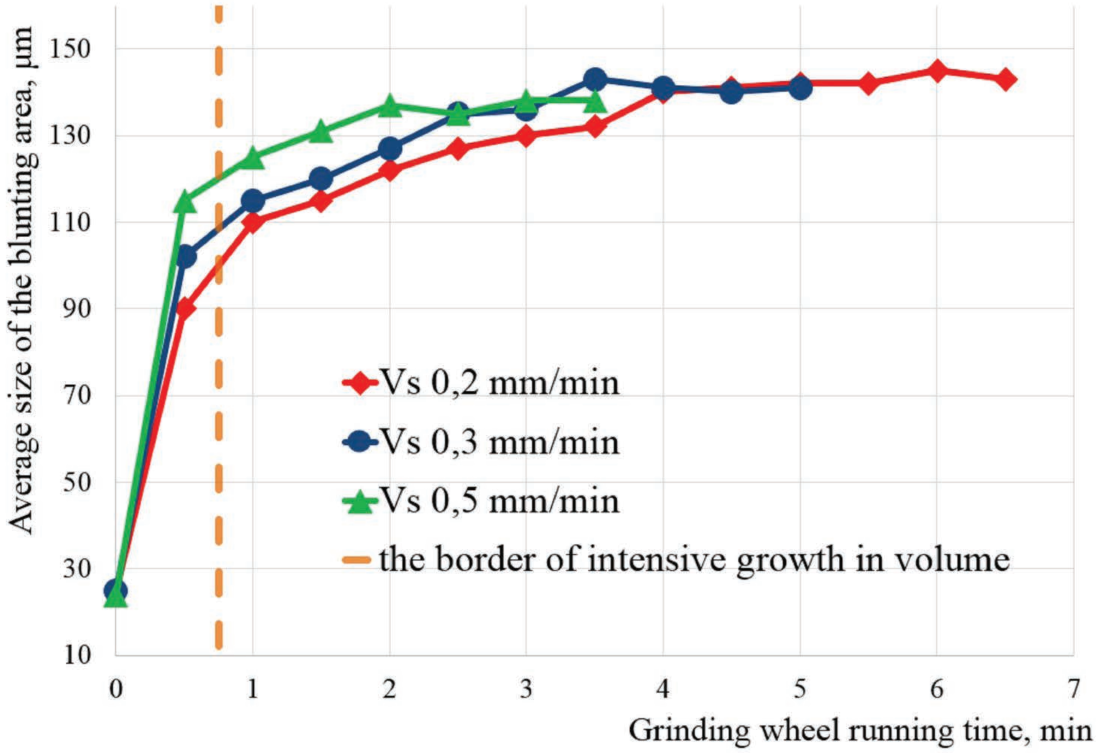

Fig. 4. Curves of dependences of the size of the blunting area for different feeds over time

The data obtained during the experiment are consistent with [13, 16–18]. It is definite that an increase in the sound level correlates with an increase in the blunting areas during grinding; there are similar divisions of the characteristic stages of the behavior of the sound parameters and wear indicators of the GW over time.

A correlation and regression analysis of the experimental data on the features of the acoustics accompanying the grinding process is explained by the need to transform the qualitative dependences into a mathematical form.

After performing a number of calculations using mathematical statistics techniques, a multiple linear regression model was obtained that establishes the relationship between the factors of the in-out feed rate (SP, mm / min) and the operating time of the GW (t, min) and the sound level parameter (β, dB):

$$\beta = -56.5 + 15.4 \cdot S_R + 4.5 \cdot t. \quad (1)$$

The significance of the regression model is verified using Fisher's criterion. The table value of Fisher's criterion for the significance level P = 0.05 and the values of the degrees of freedom $f_R = 2$ and $f_e = 77$ is $F_{table} = 3.115$.

$$F_{cal} = 115.2 \rhd\rhd F_{table} = 3.115. \quad (2)$$

Since the calculated value of Fisher's criterion is much larger than the table value, we can conclude that the regression equation is statistically significant and can be used to determine and predict the sound level value depending on the in-out feed rate and the time from the beginning of processing.

Further research was focused on studying the macro-roughness of the ground samples. The criterion for evaluating the macro-roughness was the value of the deviation from the cylindricality of the sample surface. GOST 24642–81 defines cylindricality as the maximum distance from the real surface points to the adjacent cylinder within the rated area, i.e., the cylindricality value of the measured samples is the difference between the maximum and minimum radii in two sections.

Since cylindricality includes such parameters as roundness, straightness, and parallelism [GOST R ISO 230–1–2010] and can also indirectly characterize the size accuracy, this criterion should be recognized as the most convenient for a comprehensive assessment of macro-roughnesses.

The analysis of data on the coordinates of the points of the real surface of the ground samples collected with the help of CMM made it possible to form polar lobe diagrams (round charts) (Fig. 5), which give a visual and graphical representation of the macro-dimensions of the processed workpieces.

The analysis of the round charts showed that the irregularities of the sample surfaces, expressed in terms of the differences in the coordinates of neighboring points, have a non-constant character.

It is known that the real profile of a surface obtained by mechanical processing is formed from the following components: deviations in shape, waviness, and roughness [19-21], each of which has a unique nature and characteristic parameters. The round charts have all the profile formation components. Using the round chart data, we determined the values of the samples' cylindricality by the simplest calculations (Table 2). Based on the assumption that the shape of the samples was initially an ideal geometric cylinder, it was possible to construct a chart of the dependency of the cylindricality on the infeed rate over time (Fig. 6).

We can see from the chart that the deviations from cylindricality increase over time and also have a direct dependence on the infeed rate. There is also a slight deviation from the similar nature of the deviations from cylindricality increasing over time at a feed rate of 0.8 mm/min. Such a deviation may be caused by the presence of the self-sharpening mode of the grinding wheel, which later passes into the stage of predominant blunting.

For better visualization, Figure 7 shows the distribution curves of the radius values measured by the coordinate measuring machine – the so-called size distribution polygons for the workpieces ground at a feed rate of 0.8 mm/min.

The sharpest peaks of the distribution curves are characteristic of the steady-state grinding mode (the second minute). In this mode, the spread of values is minimal and the deviations from the ideal geometric shape are small. The initial running-in stage is characterized by a flatter (hill-like) shape of the curve, which indicates a wider spread of values and less constancy of the size. After five minutes of processing, the distribution of the values forms two distinct hills, showing that the sample values drive towards two dominant values, which once again confirms the presence of a prominent deviation from cylindricality.

According to [19], if a periodic component is not found when studying the profile of the workpiece, the empirical distribution law should be close to normal since there is no reason to believe that any technological factor has a dominant effect on the surface profile, changing its distribution from normal.

This is exactly what we observe in Figure 7. The distributions of the values after the first and the second minute of grinding are Gaussian.

The curve drawn according to the data collected after five minutes of grinding has two vertices. This may indicate deviations of the actual distribution from normal due to the presence of a systematic component in the profile; however, when we consider the round chart, it is obvious that the reason for this distribution is the presence of the cone shape of the ground surface. According to [19], the double-peaked shape is more characteristic during processing with a powerful systematic basis: turning, milling, rolling, etc. This phenomenon is characteristic of external circular grinding operations to a much lesser extent.

Using the method of correlation and regression analysis again, we formed a mathematical model of the dependence of the deviation from cylindricality (Δ, mm) on the infeed rate (S_R, mm/min) and the grinding wheel running time (t, min):

$$\Delta = 0.006 + 0.012 \cdot S_R + 0.046 \cdot t. \tag{3}$$

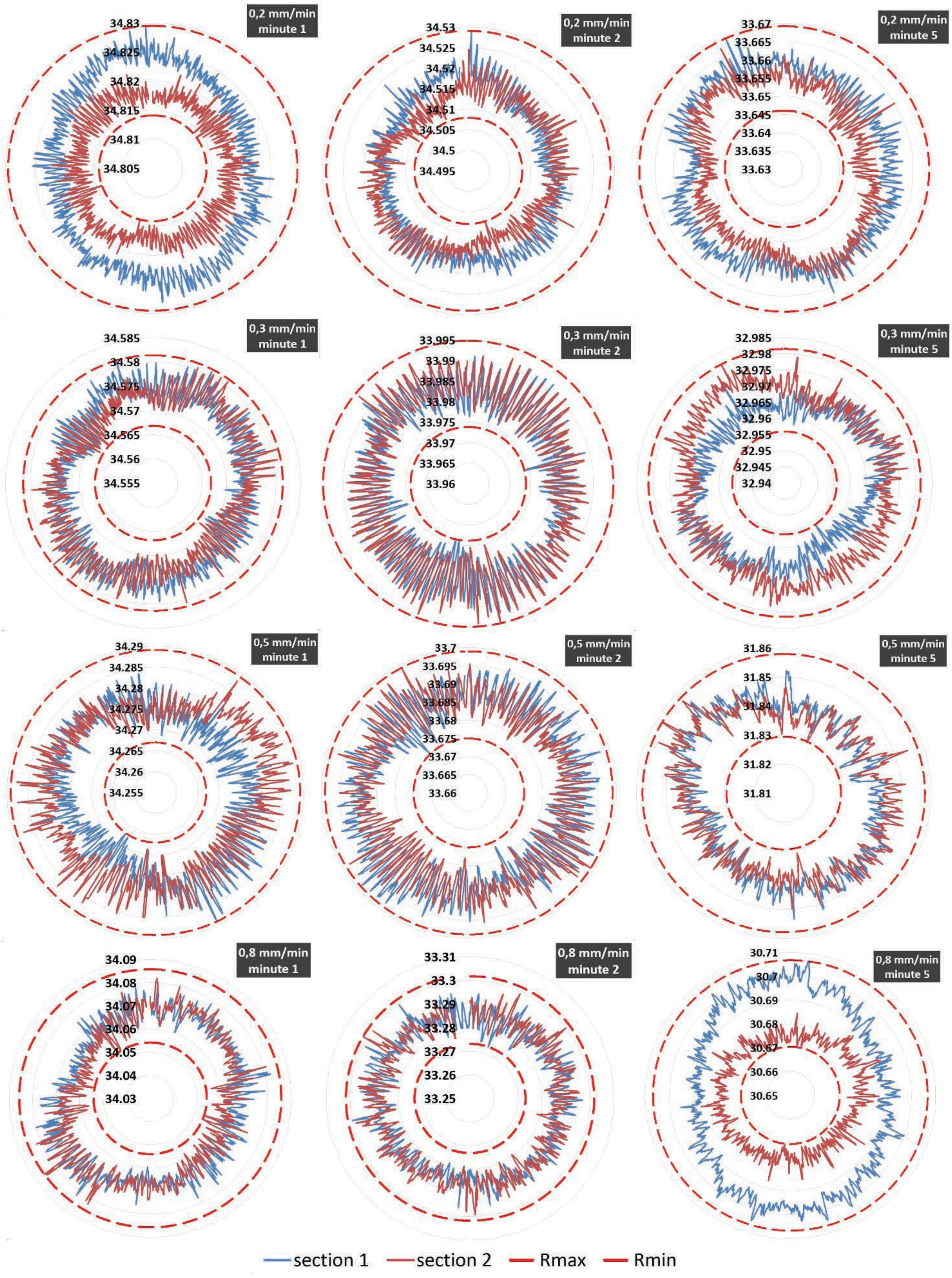

Fig. 5. Roundness charts

Table 2

Values of deviations from cylindricality

Grinding wheel running time t, min	Radial feed rate S_R, mm/min			
	0.2	0.3	0.5	0.8
	Cylindricality deviation Δ, mm			
1	0.01542	0.01459	0.02214	0.03165
2	0.02115	0.02097	0.02401	0.02863
5	0.02323	0.02558	0.02849	0.03629

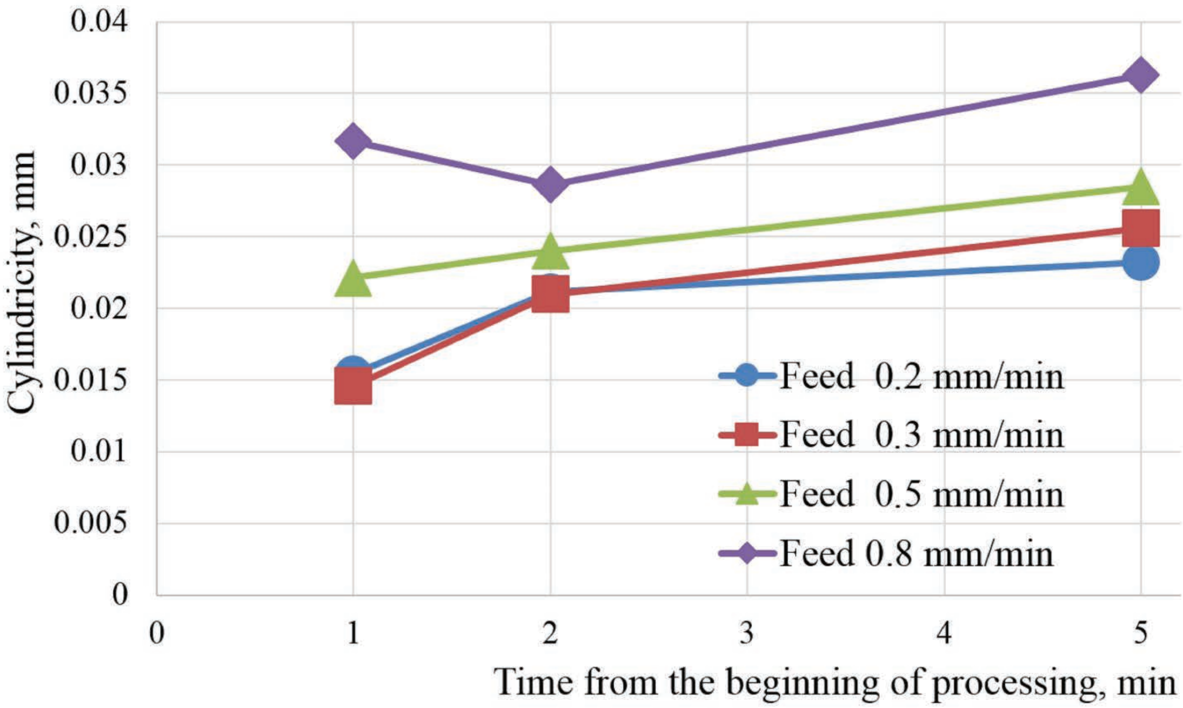

Fig. 6. Broken line of cylindricality

The table value of Fisher's criterion for the significance equation $P = 0.05$ and the values of the degrees of freedom $f_R = 2$ and $f_e = 13$ is $F_{table} = 3.8$. The calculated value is 9.75:

$$F_{cal} = 9.75 \triangleright F_{table} = 3.8. \quad (4)$$

Therefore, the resulting model can be considered statistically significant.

We can combine Equations (1) and (3) by expressing the common time variable and equating the resulting expressions. The final expression is:

$$\Delta = 0.001 \cdot \beta + 0.004 \cdot S_R + 0.065. \quad (5)$$

Mathematical model (5) reflects how the deviation from the cylindricality of a circular profile sample correlates with the level of sound generated during grinding, taking into account the infeed rate.

The main factors, the influence of which is considered in the work are the infeed rate and the running time of the ground wheel. The influence of other conditions should be investigated separately, and adjustments should be made to the dependence to expand the applicability of the mathematical model.

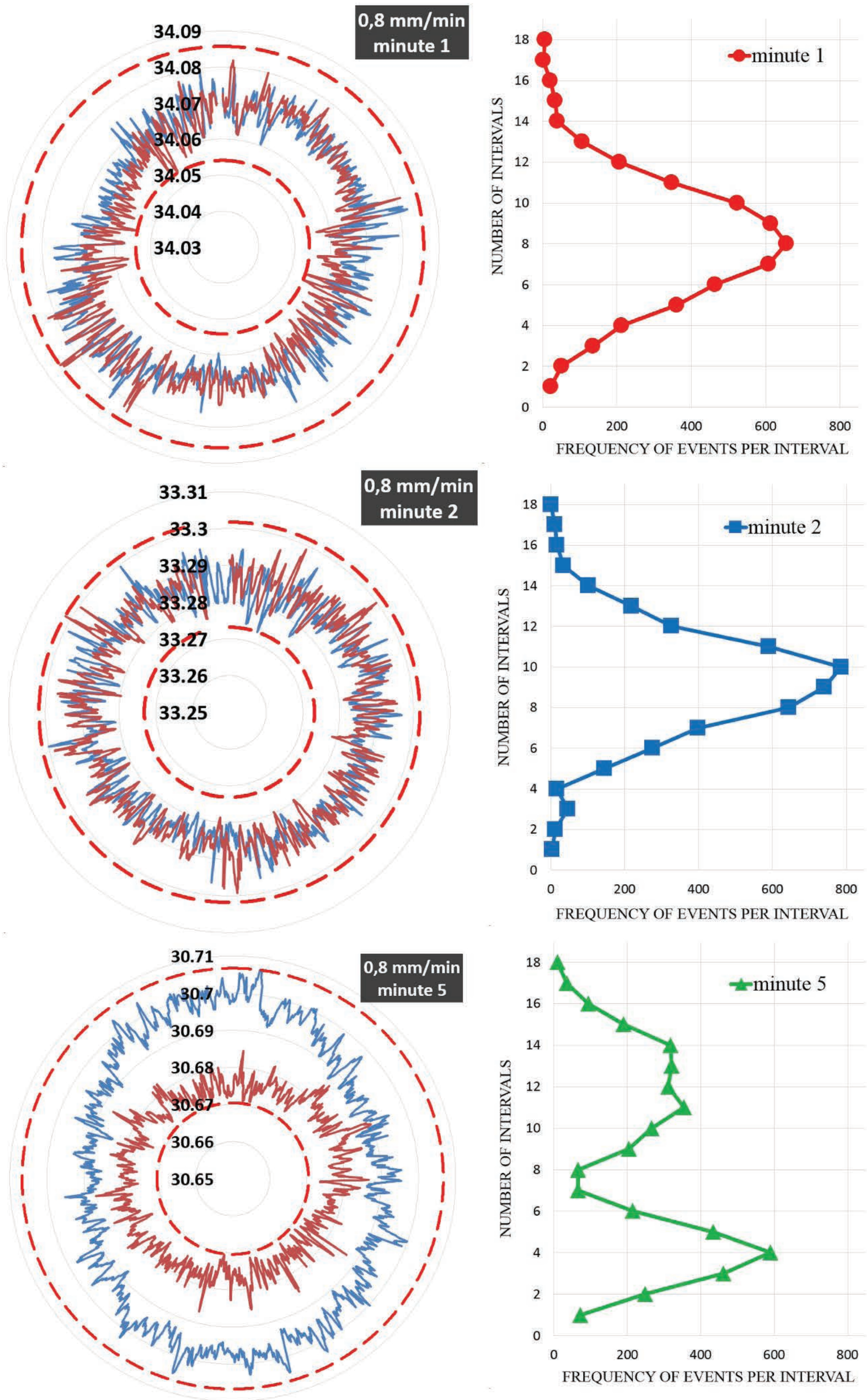

Fig. 7. Empirical distribution of macro-roughness

Conclusions

1. The parameter of the sound level measured during grinding is complicated due to the stochastic nature of the grinding process; however, there is a general increase in the course of processing.

2. We qualitatively showed the presence of two characteristic stages in the increase of the sound level of the grinding process, which are consistent with the blunting stages of the grinding wheel according to [13, 16–18].

3. The growing amplitudes of the TS vibrations during grinding directly influence the formation of the macro-profile of the workpiece surface being processed. The increase in vibration during processing depends on the infeed rate.

4. We developed mathematical regression models reflecting the influence of the factors of the radial feed rate (SR, mm/min) and the running time of the grinding wheel (t, min) on the sound level (β, dB) and the deviation from the cylindricality of the grounded sample (Δ, mm).

We also developed a general model of the dependence of the cylindricality deviations on the sound level, which allows the prediction of the deviation from cylindricality in terms of the sound level at a given infeed rate. The practical application of this model is limited by the following process conditions:

– rotation speed of the wheel V = 50 m/s ;
– infeed rate of the wheel SR, depending on the experiment, = 0.2; 0.3; 0.5; 0.8 mm/min;
– rotation speed of the workpiece in the centers SC = 25 m/min;
– duration of processing is up to 5 min;
– for grinding wheels made of white fused alumina on a ceramic bond;
– for steel 45 workpieces with a diameter of 60–80 mm.

5. The sound level can be used as an indirect indicator of the current state of the cutting tool, which allows one to assess the level of vibrations and to predict the product quality using the macrotopography of the treated surface.

References

1. Puerto P., Fernández R., Madariaga J., Arana J., Gallego I. Evolution of surface roughness in grinding and its relationship with the dressing parameters and the radial wear. *Procedia Engineering*, 2013, vol. 63, pp. 174–182. DOI: 10.1016/j.proeng.2013.08.181.

2. Ahmer M., Marklund P., Gustafsson M., Berglund K. A unified approach towards performance monitoring and condition-based maintenance in grinding machines. *Procedia CIRP*, 2020, vol. 93, pp. 1388–1393. DOI: 10.1016/j.procir.2020.04.094.

3. Taewan Lee E., Fan Z., Sencer B. Real-time grinding wheel condition monitoring using linear imaging sensor. *Procedia Manufacturing*, 2020, vol. 49, pp. 139–143. DOI: 10.1016/j.promfg.2020.07.009.

4. Ignatyev A.A., Konovalov V.V., Kozlov D.V. Opredelenie periodichnosti pravki shlifoval'nogo kruga po vibroakusticheskim kolebaniyam [Grinding wheel dressing frequency based on vibroacoustic fluctuations]. *Vestnik Saratovskogo gosudarstvennogo tekhnicheskogo = Vestnik Saratov State Technical University*, 2014, no. 1 (74), pp. 71–74.

5. Zakhezin A.M., Malysheva T.V. Opredelenie iznosa shlifoval'nogo kruga po parametram vibratsii stanka [Determination of grinding wheel wear by vibration parameters of the machine]. *Vestnik YuUrGU. Seriya: Mashinostroenie = Bulletin of the South Ural State University. Series: Mechanical Engineering*, 2007, no. 11, pp. 48–53.

6. Mahata S., Shakya P., Babu N.R., Prakasam P.K. In-process characterization of surface finish in cylindrical grinding process using vibration and power signals. *Procedia CIRP*, 2020, vol. 88, pp. 335–340. DOI: 10.1016/j.procir.2020.05.058.

7. Otaghvar M.H., Hahn B., Werner H., Omiditabrizi H., Bahre D. A novel approach to roundness generation analysis in centerless through-feed grinding in consider of decisive parameters of grinding gap by use of 3D kinematic simulation. *Procedia CIRP*, 2018, vol. 77, pp. 247–250. DOI: 10.1016/j.procir.2018.09.007.

8. Otaghvar M.H., Hahn B., Werner H., Omiditabrizi H., Bahre D. Optimization of centerless through-feed grinding using 3D kinematic simulation. *Procedia CIRP*, 2019, vol. 79, pp. 308–312. – DOI: 10.1016/j.procir.2019.02.072.

9. Ahrens M., Fischer R., Dagen M., Denkena B., Ortmaier T. Abrasion monitoring and automatic chatter detection in cylindrical plunge grinding. *Procedia CIRP*, 2013, vol. 8, pp. 374–378. DOI: 10.1016/j.procir.2013.06.119.

10. Viitala R. Minimizing the bearing inner ring roundness error with installation shaft 3D grinding to reduce rotor subcritical response. *CIRP Journal of Manufacturing Science and Technology*, 2020, vol. 30, pp. 140–148. DOI: 10.1016/j.cirpj.2020.05.002.

11. Ahrens M., Dagen M., Denkena B., Ortmaier T. An active damping method for chatter vibration in plunge grinding using electromagnetic actuators. *Procedia CIRP*, 2016, vol. 46, pp. 197–200. DOI: 10.1016/j.procir.2016.03.200.

12. Ahrens M., Damm J., Dagen M., Denkena B., Ortmaier T. Estimation of dynamic grinding wheel wear in plunge grinding. *Procedia CIRP*, 2017, vol. 58, pp. 422–427. DOI: 10.1016/j.procir.2017.03.247.

13. Dyakonov A.A., Ardashev D.V. Prediction of blunting area of abrasive grains on a grinding wheel. *Journal of Manufacturing Science and Engineering*, 2017, vol. 139 (12), art. 121004.

14. Guryanihin V.F., Arinin D.V. Vliyanie rezhimov shlifovaniya na intensivnost' akusticheskogo signala i pokazateli protsessa kruglogo naruzhnogo vreznogo shlifovaniya [The influence of grinding regimes or acoustic signal intensity and process parameters of round outside cut-in grinding]. *Vestnik Ul'yanovskogo gosudarstvennogo tekhnicheskogo universiteta = Bulletin of Ulyanovsk state technical university*, 2000, no. 4, pp. 79–83.

15. Guryanikhin V.F., Agafonov V.V., Pankov A.A. Upravlenie protsessom kruglogo naruzhnogo vreznogo shlifovaniya s ispol'zovaniem akusticheskogo signala [Control of the process of external circular plunge-cut grinding using an acoustic signal]. *STIN = Machines and Tooling*, 2009, no. 2, pp. 35–40. (In Russian).

16. Lurie G.B. *Shlifovanie metallov* [Metal grinding]. Moscow, Mashinostroenie Publ., 1969. 172 p.

17. Lurie G.B. Vibratsii pri shlifovanii [Vibrations during grinding]. *Stanki i instrument = Machines and Tooling*, 1959, no. 1, pp. 15–17. (In Russian).

18. Lurie G.B. Avtokolebaniya pri shlifovanii [Self-oscillation during grinding]. *Abrazivy* [Abrasives]. Moscow, TsBTI Publ., 1961, iss. 27, pp. 78–83.

19. Lopovok T.S. *Volnistost' poverkhnosti i ee izmerenie* [Surface waviness and its measurement]. Moscow, Standards Publ., 1973. 184 p.

20. Raja J., Muralikrishnan B., Fu S. Recent advances in separation of roughness, waviness and form. *Precision Engineering*, 2002, vol. 26, pp. 222–235. DOI: 10.1016/S0141-6359(02)00103-4.

21. Molotnikov V.Ya. *Tekhnicheskaya mekhanika* [Technical mechanics]. St. Petersburg, Lan' Publ., 2017. 476 p.

22. Ardashev D.V., Anel'chik D.E., Butorin G.I., D'yakonov A.A. *Rezhimy rezaniya na raboty, vypolnyaemye na shlifoval'nykh i dovodochnykh stankakh s ruchnym upravleniem i poluavtomatakh* [Cutting modes for work performed on grinding and lapping machines with manual control and semiautomatic devices]. Chelyabinsk, Atokso Publ., 2007. 384 p.

Conflicts of Interest

The authors declare no conflict of interest.