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Experimental study of the dynamics of the machining process by ball-end mills

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ABSTRACT

Introduction. Due to a significant number of factors affecting the change in the properties of a dynamic system, excessively conservative processing conditions are chosen to ensure the high quality of the resulting product. This limits the efficiency of the process and leads to an increase in the cost of production. Accordingly, modern approaches are needed that will allow diagnosing the current state of processing and making timely decisions to replace the tool, correct or change the control program. The significance of the ongoing research is to propose a real-time monitoring approach to milling control to identify emerging processing errors, predict potential problems and improve uptime. **Subject.** The paper discusses the features of the real-time monitoring system during mechanical processing with a single- and double-edge cutting tool, taking into account acoustic wave filtering, minimizing surface roughness. **The purpose of the work** is to determine the effect of the inclination orientation of the ball-end tool on the surface roughness value using real-time monitoring during milling on *CNC* process equipment. **Methods.** The study provides methods of correlation and regression analysis. The calculated data were obtained by means of vibroacoustic diagnostics and measured in the range of values of the variable angle of inclination of the surface for single- and double-edge cutting tool based on the provisions of the theory of oscillations and vibroacoustic diagnostics, cutting theory, digital processing and digital filtering of signals. **Results and discussions.** Experimental data obtained during machining made it possible to determine that an increase in the angle of inclination of a single-edge cutting tool has practically no effect on the change in the amplitude parameters of roughness. The values of vibroacoustic diagnostics and roughness, when using a double-edge ball-end tool, show a consistent picture with the effects created by the angles of inclination and advance. The obtained solutions to the problems of monitoring and analyzing the roughness parameters can significantly reduce the amount of experimental research and clarify the idea of the practical implementation of the method of acoustic monitoring of the cutting process.

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Introduction

One of the main directions in the development of machine-building production is to increase the reliability of mechanical processing of spatially complex surfaces by using a real-time monitoring system designed to obtain reliable information on the state of the milling process and make the necessary control decisions [1–6].

To solve the problems of controlling the milling process, many authors study the change in the active contact zone of the end milling tool and the workpiece. *Pimenov D. et al.* [7] presented practical recommendations for assigning the orientation of the tool to the workpiece, taking into account the milling dynamics to ensure surface roughness. *Tan L. et al.* [8] studied the effect of tool path contours on ball-end tool wear and surface roughness during milling. The results showed that the use of the bottom-up tool path contour makes it possible to ensure the minimum amplitude parameters of roughness, and the prevailing type of tool wear is adhesive.

Issues related to monitoring the state of technological equipment at industrial enterprises are considered in the works of scientists *Kozochkin M.P.*, *Sabirov F.S.* [9]. In the work of *Shaffer D. et al.*, acoustic signals were investigated as a way to control the operation of technological equipment [10]. Experimentally with different cutting conditions, mathematical models were statistically determined showing the change in acoustic signal for end milling with a single cutting edge. *Kozlov A.A.*, *AL-Jonid Khalid*, in their study determined the basic requirements for diagnosing and predicting the wear of a cutting tool in real time [11]. *Chen et al.* proposed a real-time monitoring system [6] with error compensation to improve accuracy in the production of spatially complex parts [12]. *Cheng DJ. et al.* [13] studied the effect of cutting parameters on the roughness of the machined surface [6]. *Clayton Cooper* [14], *Anayet U Patwari et al.* [15] analyzed the correlation of surface roughness parameters with the sound level based on the acoustic signal. Authors *Sahinoglu A.* and *Rafighi M.* [16] investigated the effect of cutting parameters on surface roughness, vibration, sound intensity of technological equipment during machining. Many authors have proposed ways to ensure the output characteristics of processing by controlling the elastic deformations of the tool relative to the workpiece, taking into account the state of the dynamic system (*DS*) [17–20].

The analysis of scientific works made it possible to formulate the direction of this research: to generalize and gain new knowledge, as well as to clarify the applicability of an acoustic complex that registers a signal through the air to control the cutting process, with filtering interference and noise in real time. The purpose of the work is to determine the effect of the inclination orientation of the ball-end tool on the surface roughness value using real-time monitoring during milling on *CNC* process equipment. At the same time, on the basis of empirical data, it is necessary to develop a model for the dependence of the roughness of the machined surface on the feed rate, diameter and orientation of the tool with the correlation of the obtained values and vibroacoustic diagnostics.

Research methodology

Machining was carried out in climb milling using a cutting fluid (coolant) on workpieces with *Al-Mg6* properties, by hard alloy ball-end mills with a *TiN* coating with a diameter of $D = 8$ mm and a number of teeth $z = 1$, $z = 2$. The feed per tooth was $fz = 0.2$ mm/tooth, the allowance for all specimens was $a_p = 0.4$ mm, the lateral pitch $a_e = 0.2$ mm. The overhang ratio of the tool is assumed to be $l/D = 4$. The rotation frequency (n) of the milling machining center *DMG DMU 50 Ecoline* was for a double-edge cutting tool 1,500 min^{-1}, for a single-edge cutting tool 3,000 min^{-1}.

The use of coolant is an important factor in the intensification of the cutting process, since the hard alloy has a low resistance to tensile stresses [21]. When using coolant, films are formed on the contact surfaces of the tool and workpiece material, which help to reduce adhesive wear.

Dimensional wear control of the cutting tool was carried out using a *Heidenhain TT140* contact measuring sensor. The accuracy of straightness when measuring the roughness parameters with the *Surfcom 1800D* instrument was $\Delta = \pm (0.05 + 1.5L / 1{,}000)$. Vibroacoustic diagnostics (Fig. 1) was carried out us-

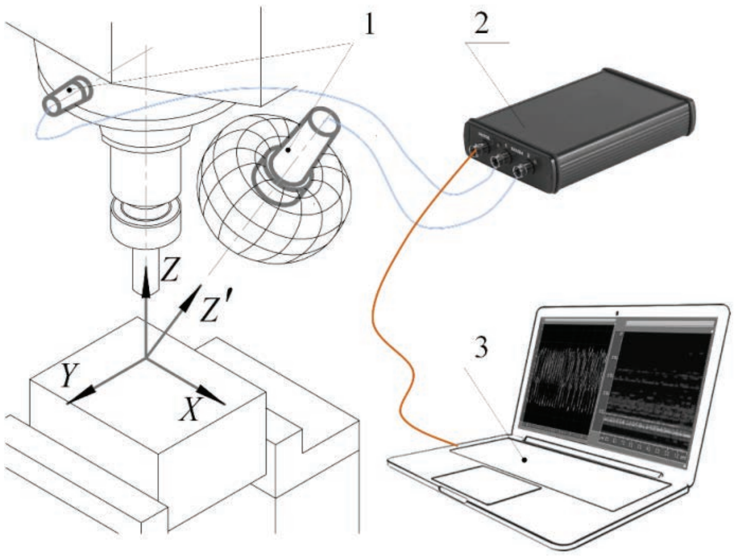


Fig. 1. Real-time monitoring in milling:

1 – vibration sensor and microphone with cardioid orientation;
2 – spectrum analyzer «*ZetLab 017-U2*»; *3* – PC with *ZETLAB* software (*Formulated by the authors*)

ing the spectrum analyzer «*ZetLab 017–U2*», piezoelectric vibration sensors «*BC 110*», microphone «*Zet BC 501*» with a perceived frequency range of 20 Hz–13 kHz and *Samson Meteor Mic* cardioid directivity with a range of 20 Hz–20 kHz. The roughness parameter *Rz* (μm), vibration displacement *S* (μm) and the amplitude–frequency characteristic of the acoustic signal *A* (dB), ω (Hz) were used as the output evaluation of the processing efficiency.

The use of a condenser microphone has a number of advantages – low frequency response, low level of non-linear and transient distortion, high sensitivity and low self-noise. Particular attention should be paid to improving the quality of the diagnostic signal, which consists of the sum of the spectrum of the "useful" signal and a large number of unequal noise levels coming from various objects. Spectral subtraction was used for real-time noise reduction. The most common method of denoising is spectral subtraction (Fig. 2).

The decomposition of the signal during spectral subtraction was carried out using a special weight function [22] – the *Blackman window*.

Research results

In the process of machining, a change in the properties of the *DS* is observed, which is determined by various factors. The disclosure of the features of the loss of stability of the toolpath during milling (Fig. 3) makes it possible to determine ways to improve the reliability of the operation of technological equipment (*TE*).

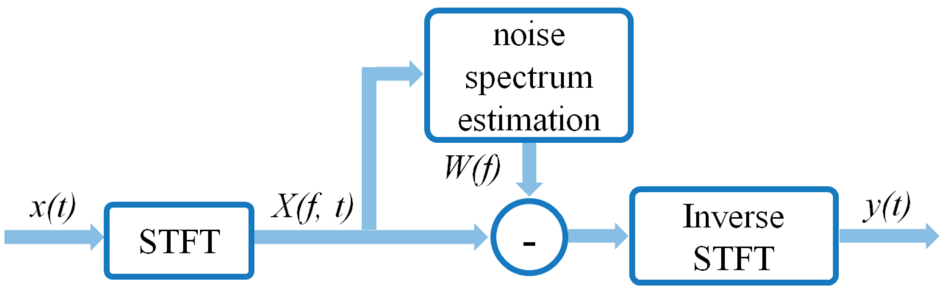
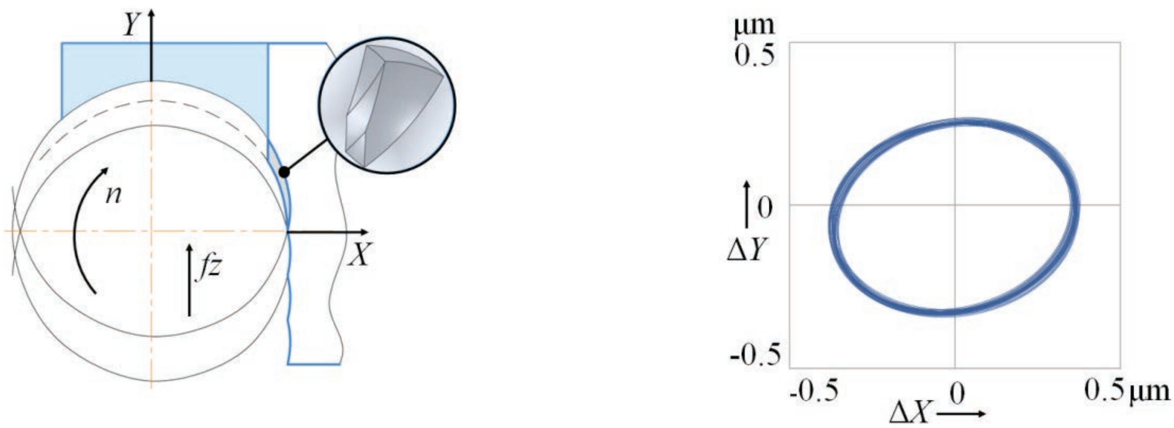


Fig. 2. The proposed spectral subtraction algorithm scheme:

x(*t*) – original signal; *STFT* – Short Time Fourier Transform; *W*(*f*) – is the function of the weighting window; *y*(*t*) – transformed signal (*Formulated by the authors*)



a *b*

Fig. 3. Pattern of the passage of the cutting edges through the processing zone:
a – the trajectory of the i^{th} tooth corresponding to the effective diameter of the tool; *b* – deviation trajectory of the front spindle support (*Formulated by the authors*)

In this study, the output parameter is roughness, and to ensure the required surface roughness, along with the establishment of processing modes, an assessment is made of the dynamics of spatial oscillations of the front spindle support (see Fig. 3, *b*). At the same time, the amplitude parameters of roughness after processing with inclined ball-end tools with a different number of teeth during climb milling are presented in Table 1. When machining with a single-edge cutting tool, a change in the angle of inclination practically does not affect the change in the amplitude parameters of roughness, i.e. for the case under consideration, the range of the *DS* stability margin is maximum. The use of a double-edge cutting tool leads to significant changes in the output parameters, the discrepancies presented are often caused by the deviation and wear of the tool, resulting in a change in the active cutting zone and an increase in the level of vibrations [6] (Fig. 4).

Analysis of the Table 1 as well as Fig. 4 allows drawing the following conclusions:

1) the greater the vibration displacement amplitude, corresponding to the cutting frequency, the higher the value of the roughness amplitude parameters;

2) the amplitude of vibration displacements does not change linearly with an increase in the angle of inclination, and a decrease in the quality of the machined surface occurs due to elastic deformations of the cutting tool, which is explained by the distribution of the cutting force components along the cutting edge [20, 23].

For the practical implementation of the principles of acoustic diagnostics, the information received on the current state of the processing process is required to be understandable and reliable. Fig. 5 shows the acoustic signal obtained during the experiment.

Table 1

Roughness parameters after machining with a ball–end tool

Number of teeth	Angle of inclination, °	Roughness parameters, µm				
		Ra	*Rq*	*Rz*	*Rt*	*Rp*
1	10	0.436	0.543	2.143	4.094	1.490
	25	0.498	0.531	2.532	4.810	1.355
	40	0.401	0.502	2.512	4.800	1.271
2	10	0.661	0.824	3.048	4.536	2.001
	25	0.620	0.793	5.104	7.599	3.079
	40	0.373	0.465	2.391	3.559	1.383

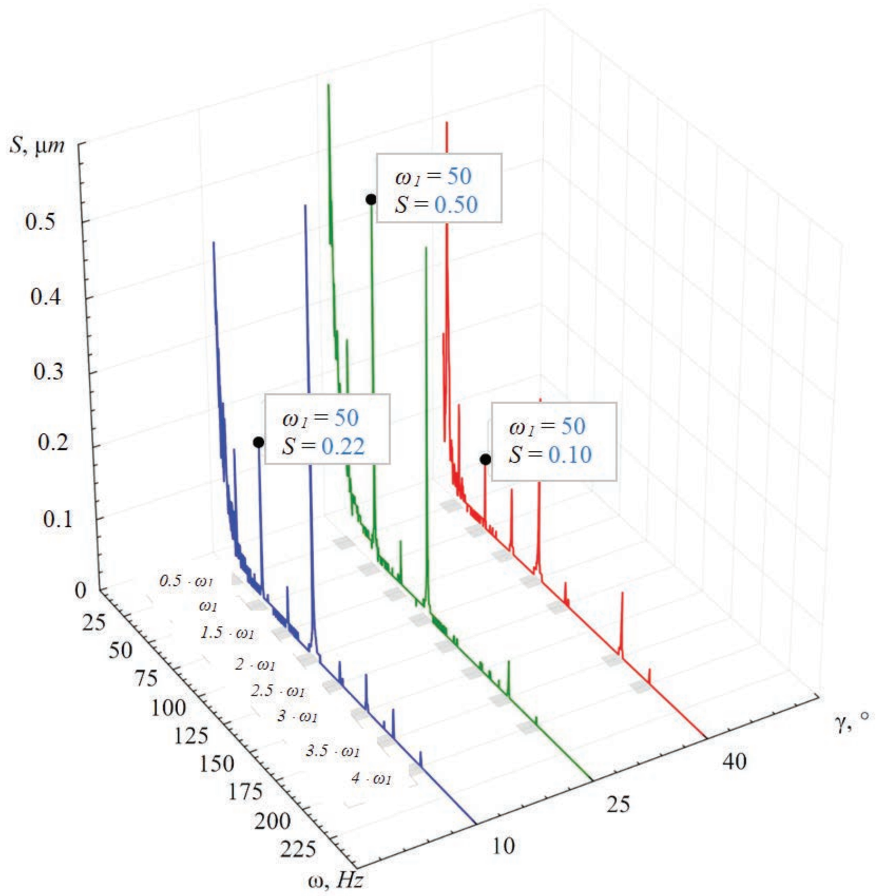
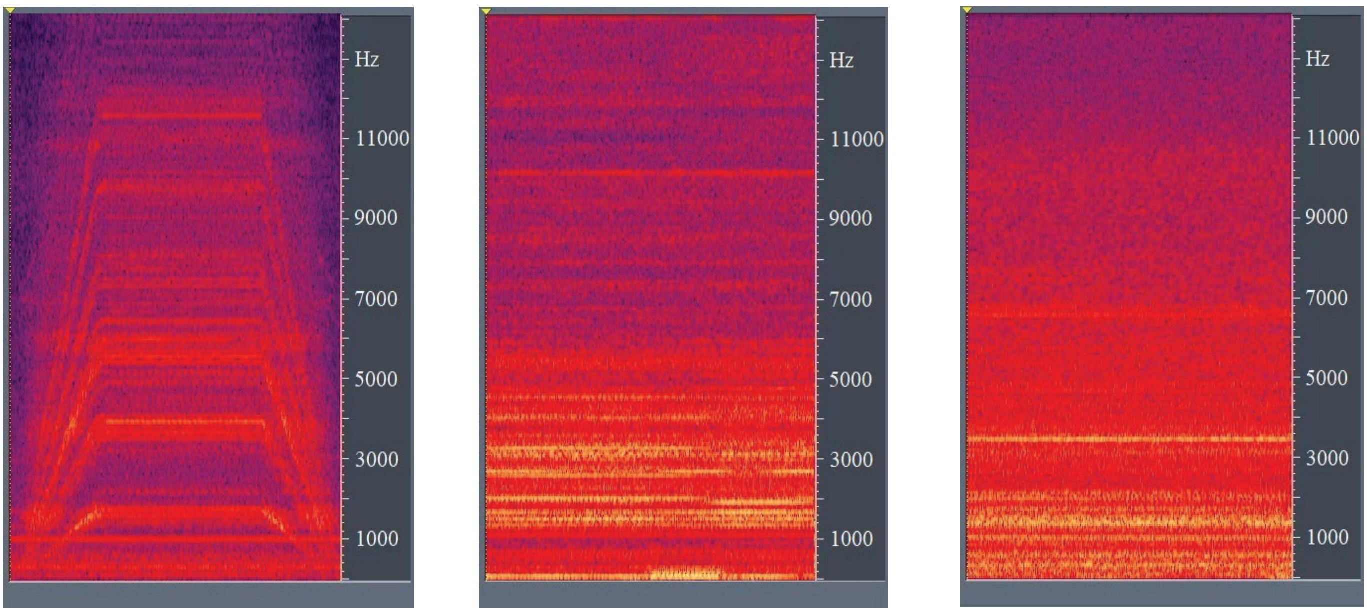


Fig. 4. Comparison of the frequency spectrum after milling with different angles of inclination, $z = 2$ (*Formulated by the authors*)



a *b* *c*

Fig. 5. Frequency spectrum of the acoustic signal:
a – spindle acceleration to 8,000 min^{-1} and stop; *b* – machining process, $z = 1$, $n = 3{,}000$ min^{-1}; *c* – machining process, $z = 2$, $n = 1{,}500$ min^{-1} (*Formulated by the authors*)

The frequency spectra considered in Fig. 5 in a detailed analysis, are consistent with the vibration diagnostics signals, however, it is advisable to analyze the acoustic signal within the cutting frequency range. To extract a narrow band of the sound wave (Fig. 6), *FFT* filter was used, which used a *fast Fourier transform* (*FFT*), the *FFT* size corresponded to a value of 4,096.

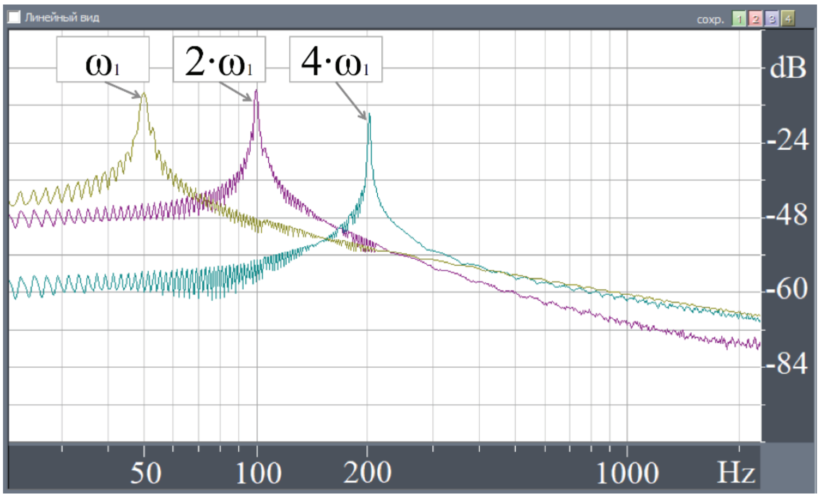


Fig. 6. Frequency response of harmonic sound waves obtained by milling with an inclination angle of 40° (*Formulated by the authors*)

The frequency ω_1 corresponds to the cutting frequency (see Fig. 6), and according to the harmonic law, the resonant frequencies are found as the product of ω_1 and an integer (ω_1 = 50 Hz, $2\omega_1$ = 100 Hz, etc.). The frequencies are calculated up to the fourth order, since with an increase in the order the intensity of the mode frequency decreases markedly and at higher orders it has practically no effect on the overall sound picture.

It can be seen from the records (Fig. 7) that the acoustic signal is modulated by the tool revolutions, and when cutting with a double-edge cutting tool, the signal amplitude changes when the tool inclination angle changes.

When studying the spectrum of acoustic diagnostic signals, a uniform phase alternation and the absence of a chaotic regime are established. After denoising, filtering and normalizing the signal amplitude, a limited number of bifurcation points are determined when the tool inclination angle is changed during machining. These facts allow concluding that the method of acoustic monitoring has informative diagnostic features.

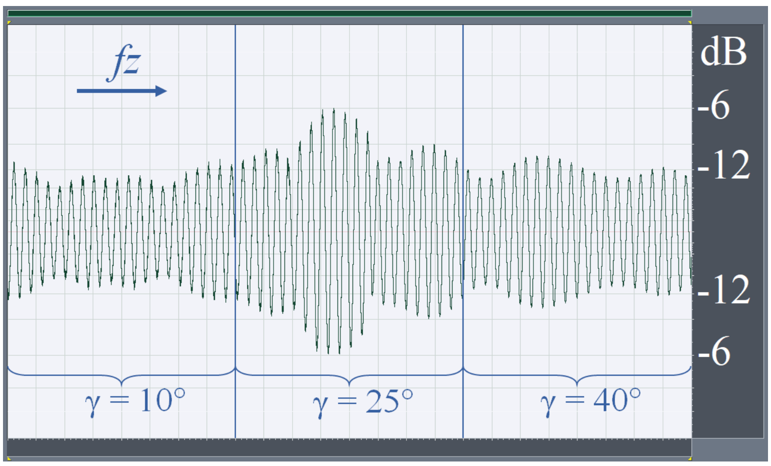


Fig. 7. Filtered acoustic signal (*Formulated by the authors*)

Given the increasing demands on the quality of parts, it is worth focusing on the predictability of roughness parameters during machining, in this study – through correlation. Identified dependencies based on the value of the pair correlation coefficient in Table 2 indicate the possibility of influencing some of the obtained parameters through changing others and the presence of technological parameters predetermining the micro-roughness of the surface.

Table 2

Calculated values of the pair correlation coefficients

Compared values		Correlation coefficient	The existence of a linear relationship	Linear connection
Φ_1 (*Ra*)	R (*Rz*)	0.91	highly probable	increases
Φ_2 (*Rq*)	R (*Rz*)	0.92	highly probable	increases
Φ_3 (*Rt*)	R (*Rz*)	0.98	highly probable	increases
Φ_4 (*Rp*)	R (*Rz*)	0.93	highly probable	increases
Φ_5 (γ)	R (*Rz*)	–0.41	very improbable	decreases
Φ_6 (*z*)	R (*Rz*)	0.40	very improbable	increases
Φ_5 (γ)	Φ_6 (*z*)	0.00	doesn't exist	–

Noted in the Table 2 correlations are significant at $p < 0.05$. It is generally accepted that a linear dependence exists if the modulus of the correlation coefficient corresponds to a value from 0.5 to 1. However, the value of the coefficient in the range of 0.3...0.5 may indicate the existence of a non-linear correlation [24, 25]. The regression graph of the parameter *Rz* (Fig. 8) indicates the confirmation of the above position.

To assess the degree of influence of the angle of inclination on the amplitude parameter of roughness *Rz*, a multivariate regression analysis is carried out. The result of the analysis is a mathematical model (1), which characterizes the relationship between the value of roughness, feed per tooth, diameter and angle of inclination of the tool, expressed by the normalized model the graphical interpretation of which is shown in Fig. 9.

$$R_z = 3 + 2.77_{f_z} - 0.55_{y} - 1.08_{D} - 0.51_{f_z\gamma} - 1_{f_zD} + 0.22_{\gamma D} + 0.2_{f_z\gamma D}. \quad (1)$$

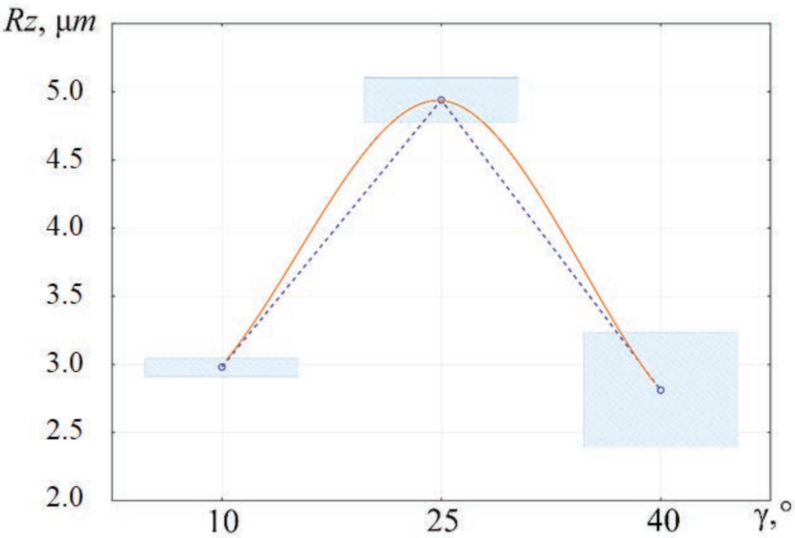
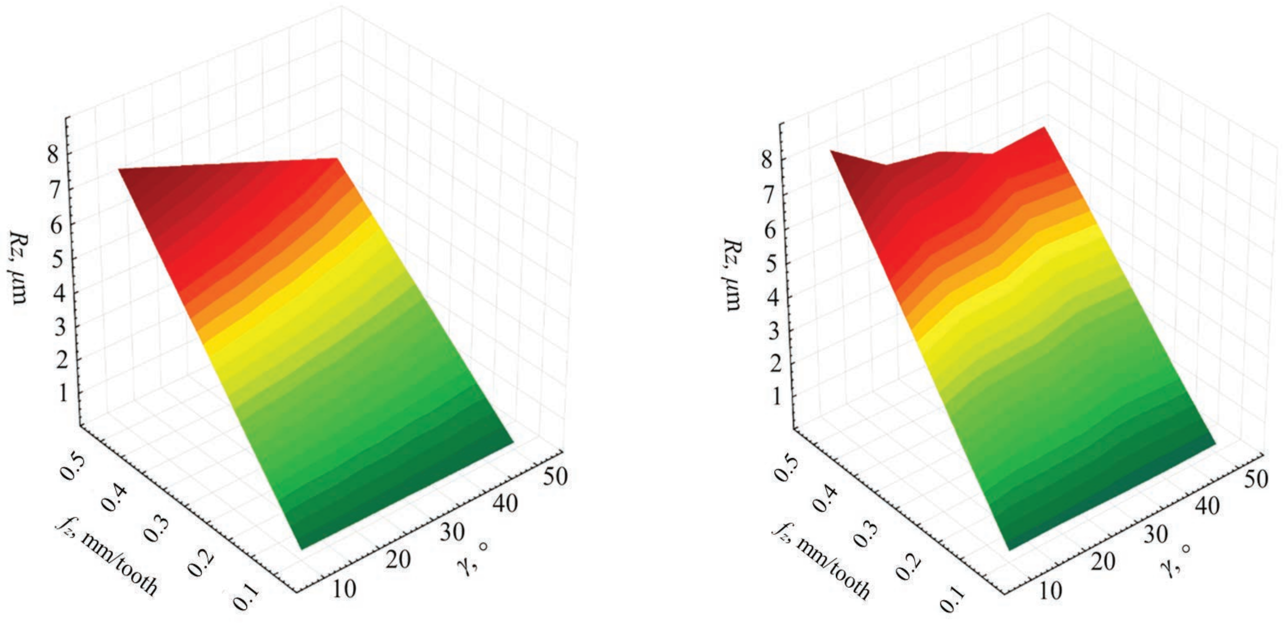


Fig. 8. Parameter *Rz* depending on the machining angle for a double-tooth cutter (*Formulated by the author*)



a *b*

Fig. 9. Dependences of the roughness *Rz* on the feed and the angle of inclination of the tool: *a* – theoretical; *b* – experimental

With a confidence coefficient $P = 0.95$, the calculated value of the *Fisher criterion* F_{calc} is less than the tabular value F_{tabl}, respectively, the hypothesis of an adequate representation of the regression model (1) is accepted.

The analysis of theoretical and experimental data on the relationship between the parameters of roughness, feed per tooth and the angle of inclination shown in Fig. 9 indicates minor differences in data presentation. At the same time, the shape of the experimental dependence differs from the theoretically calculated one by equation (1) by no more than 10 %.

Conclusions

Experimental data obtained during machining made it possible to determine that an increase in the angle of inclination of a single-edge cutting tool has practically no effect on the change in the amplitude parameters of roughness.

The values of *VA* diagnostics and roughness when using a double-edge ball-end tool show a consistent picture with the effects created by the angles of inclination and advance. At the same time, at a cutting frequency of 50 Hz, the vibration displacement magnitude for an angle of inclination 25° is, on average, 2 times greater than at 10° and 40°.

Roughness amplitude parameters R_a, R_q, R_t, R_p show a high degree of correlation with the R_z parameter. Due to the non-linear relationship between the R_z value, feed f_z, tool inclination angle γ and tool diameter D, a regression model is developed that allows predicting the roughness of the machined surface.

The obtained solutions to the problems of monitoring and analyzing the roughness parameters can significantly reduce the amount of experimental research and clarify the idea of the practical implementation of the acoustic method for controlling the cutting process in real time.

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Conflicts of Interest

The authors declare no conflict of interest.