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PATTERNS OF CHANGES IN TECHNOLOGICAL ACCURACY OF PLANO-MILLING MACHINES DURING THE PERIOD OF THE CUTTING TOOL WEAR RESISTANCE

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ABSTRACT

Polynomial patterns of changes in the technological accuracy of the machine tool over the period of the cutting tool wear resistance were established. The software, which makes it possible to show regression models of the average value and the scattering field of the size of the manufactured parts depending on the degree of the tool wear, was developed. Based on the results of experimental studies of changes in the machining accuracy on six plano-milling machines during the wear resistance period of the cutting tool ($\rho = 5 - 50$ μm), regression models in the form of third-order polynomials were obtained. It was found that to ensure the machining accuracy within the tolerance (± 0.1 mm), the wear resistance period of the cutting tool should not exceed $\rho = 30$ μm, and the technical specification of the machine should correspond to an exceptionally high accuracy class.

Keywords: regression model, accuracy, machining, machine tool, part.

INTRODUCTION

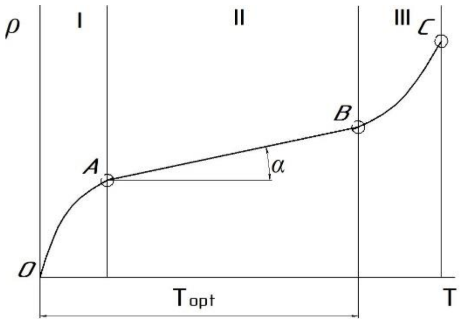
Wood blanks after machining on plano-milling machines must have the appropriate shape, size accuracy and surface roughness (Kiryk 2006). The quality of machining is affected by a number of factors: the characteristics of the material being processed, the parameters of the cutting tool and the cutting mode (Chladil *et al.*, 2019, Bendikiene and Keturakis 2017, Mazur *et al.*, 2011, Vančo *et al.*, 2020, Warcholinski and Gilewicz 2022). The determining indicator of the quality of machining on machine tools is the accuracy of the dimensions of the manufactured parts, compliance with which ensures: interchangeability of parts during the assembly of products; manufacturing accuracy of the whole product; economic efficiency of the entire production. Increased requirements for machining accuracy (±0.1 mm) primarily relate to the manufacture of bar parts on plano-milling machines. Compliance with these requirements is currently ensured by performing technological operations for calibrating individual parts or prefabricated products (window and door units), which requires additional raw materials and energy costs.

The source of errors in the dimensions of the parts produced in the cutting process is the dynamic system "machine-cutting tool-workpiece" (McTW) (Pylypchuk 2021, Vukov *et al.*, 2021), which contains a large number of factors that have both a systematic and a random nature of influence on the accuracy of machining. The main indicator of the efficiency of a woodworking machine is its technological accuracy which gradually decreases during the operation of the machine. The technological accuracy of machine tools is partially restored due to their periodic adjustment and repair, as well as timely re-sharpening of the cutting tool. That is, maintaining the required level of machining accuracy on machines requires the development of specific practical solutions to improve or restore the technological accuracy of the machine, and this, in turn, requires conducting research to find the patterns of changes in accuracy.

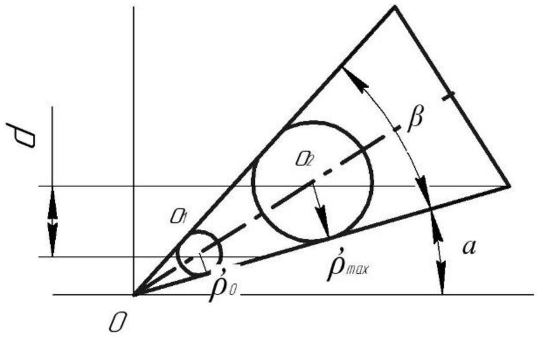
In the process of operation, the machine tools lose their initial technological accuracy and therefore require timely taking measures to prevent the appearance of defective parts. According to the manufacturers, the initial technological accuracy of plano-milling machines corresponds to a particularly high class, which ensures machining accuracy according to IT10-11 qualities (ISO 286-2). During the operation of the machine tool, various types of energy are acting, which causes the occurrence of processes in the components and parts of the machine that change the initial characteristics (Hernande and Fernando de Moura 2002, Kanarchuk *et al.*, 2003). Such processes may be reversible or irreversible. The reversible processes temporarily change the parameters of machine parts and its units within certain limits, for example, elastic and thermal deformations of machine parts and cutting tools. The irreversible processes lead to a gradual loss of machine performance and the onset of parametric failures. Some authors (Pylypchuk *et al.*, 2021) developed a parametric machine failure model based on the accuracy criterion, which makes it possible to determine the duration of the interregulating periods of machine operation.

The processes in the machines also differ in their speed (fast, medium-speed and slow), which affects the change in the initial parameters of the machine (Pylypchuk 2021). Medium-speed irreversible processes that occur during continuous operation of the machine and last for several hours include the process of gradual wear and bluntness of the cutter blade (Dobryansky and Malafieiev 2020; Zatulenko and Zaiets 2019), which is of typical character (Fig. 1a). The period of a cutting tool resistance to wear *T* is determined by the operating time before critical blunting of the cutter blade, during which three stages can be distinguished: I – running in; II – gradual wear; III – critical (emergency) wear. During roughing, the operation is conducted in zones I and II, that is, according to the criterion of maximum total stability of the cutter blade. When finishing on milling machines, the period of the cutting tool wear resistance is determined by the technological criterion – ensuring the specified quality of machining.

The authors (Kiryk and Hryhoriev 2013) note that the cutting tool after sharpening has a radius of curvature of the cutting edge of $\rho_0 = 4 - 6$ μm (Fig. 1*b*). The cutting ability of the tool is gradually lost and becomes critical when the radius of curvature of the cutting edges reaches $\rho_{max} = 50 - 60$ μm. The cutting tool period of wear resistance can range from a few minutes to 400 hours of continuous operation, depending on the material of the blade, the properties of the wood and the modes of cutting.



a



b

Fig. 1 Wear and bluntness of wood-cutting tool blades: *a* – the nature of the cutting tool blade wear during operation (Dobryansky and Malafieiev 2020); *b* – changes in the rounding radius of the blades during the cutting tool wear resistance period (Kiryk and Hryhoriev 2013).

Gradual failure of the cutting tool due to the loss of machining accuracy occurs when deviations in the size of the manufactured parts reach the tolerance field limit (Bustos *et al.*, 2010, Nadolny *et al.*, 2020, Pylypchuk 2021). The main determinant of machining accuracy on plano-milling machines is the actual location of the cutting plane passing through the center of the circle inscribed in the cutting edge of the blade (Fig. 1*b*). During the process of milling, the blades gradually wear out; accordingly, the radius of the inscribed circle increases, and its center moves along the bisector of the sharpening angle. Therefore, the machining surface is shifted by an amount of *d*:

$$d = \left(d_{max} - e_0 \cdot \rho_{max}\right) - \left(d_0 - e_0 \cdot \rho_0\right) \tag{1}$$

where: ρ_0 – the radius of rounding of the cutting edge of the initially sharpened tool;

e_0 – relative residual deformation under the cutting surface of wood.

Exceeding the average period of tool life leads to a discrepancy between the dimensions of the workpieces and the nominal sizes. In order to prevent the appearance of defective workpieces, it is necessary to use the efficient cutting tool life according to the criterion of machining accuracy, for the determination of which further research conducting is necessary.

According to the study results (Vitchev 2019, Vitchev and Gochev 2019), the surface quality of Scots pine wood samples is influenced by the rotation frequency of the cutting tool, the feed rate, and the characteristics of the milling cutter. In the work (Keturakis and Juodeikienė 2007) the influence of the blunting radius of the cutter blades as well as the feed rates and cutting speeds on the surface roughness during longitudinal milling of birch wood was investigated. It was found that the roughness of the machined surface increases as the radius of rounding of the milling cutter blades increases. In the work (Atanasov 2021), based on the results of experimental studies, determined was the dependence of the cutting force on the feed rate and the thickness of the cut chips during longitudinal milling of oak wood, tropical species – meranti, koto, as well as composite materials – medium-density fiberboard and plywood.

In order to obtain high machining accuracy during the cutting tool wear resistance period, it is necessary to prevent the occurrence of excessive vibrations of the "machine-cutting tool-workpiece" system, which is confirmed by studies (Kovatchev and Atanasov 2021) of the influence of feed rate and milling area on vibration resistance. The authors (Chunmei *et al.*, 2020) investigated the influence of different shapes of milling tool blades on cutting forces, vibration during cutting, change in chip shape at different feed rates, as well as on the roughness of the machined surface. It was found that the feed rate has a significant effect on the roughness of the machined surface, with an increase in this rate, the roughness increases, and no studies have been conducted regarding the machining accuracy. The work (Li *et al.,* 2022) also investigated the influence of the following factors on the roughness of the machined surface and the cutting power in the process of helical milling of pine wood: the helical angle of the cutter, the rotation speed of the main shaft, and the depth of milling. The influence of the input variables and the quantitative relationship between the input data and the change in the assessment indicators were clearly identified. The results obtained are useful for selecting the mode parameters of helical milling in order to improve the quality of the machined surface and save power consumption.

In the work (Djurković *et al.,* 2019), the influence of the cutting tool blade wear on cutting power and the quality of the machined surface is investigated. The tests were carried out on samples of beech wood of the same density and moisture content and without visible wood defects. It was found that the wear of the tool blades significantly affects the cutting power and the quality of the machined surface, which is important in determining the cutting mode and the period duration of the tool wear resistance. The authors (Bendikiene and Keturakis 2016) also investigated the effect of the cutting tool blade wear on the surface roughness of birch wood blanks in the planing process. It was found that after a cutting length of 3,200 m, a change in the geometry of the tool cutting edge leads to an increase in the surface roughness.

The authors (Skliarov and Prykhodai 2021) note that the introduction of automation tools and the use of robotic systems can improve the productivity and machining accuracy, but these measures cannot exclude the influence of factors such as the cutting tool wear, temperature, elastic and contact deformation of the technological machine systems on the accuracy of manufactured parts. To do this, the machines use active control systems, means of controlling the elastic movements of the machine-cutting tool-workpiece system and automatic adjustment systems, which provides an increase in machining accuracy, since they allow periodically adjusting the position of the cutting tool relative to the workpiece and can be used on milling machines. In order to obtain the required productivity, product quality, and energy saving, the authors (Rudenko et al. 2012) proposed using a new automated combined system for controlling the mechanisms of plano-milling machines with the introduction of regulators for the tool drive start-up process, the interaction of the main drive and the feed drive, and the regulator of roughness of the machined surface.

So, based on the analysis of the results of well-known studies on the quality indicators of the cutting process on plano-milling machines, it should be noted that in most works, the roughness of the machined surface and the effect on its value of the main operation factors: cutting speed and feed rate, wood species, area of the cut layer, as well as structural differences of the milling tool and the degree of its bluntness are considered as a quality indicator of processing. Few works are concerned with the study of changes in machining accuracy during the period of the cutting tool wear resistance, when due to the gradual blunting of the tool, a parametric failure according to the criterion of machining accuracy occurs, as a result of which there is a need to restore the working condition of the cutting tool. Therefore, we consider it necessary to conduct scientific research aimed at finding the patterns of changes in the technological accuracy of the machine during the period of the cutting tool wear resistance and developing measures to ensure modern requirements for machining accuracy indicators.

MATERIAL AND METHODS

During the process of machining a batch of parts on a woodworking machine, the dimensions of the manufactured parts are scattered, which is described by a field of scattering of machining errors ω (Pylypchuk and Burdjak 2009). The scattering field does not remain constant during the production time of a batch of parts, but gradually changes in magnitude and, accordingly, its average value changes. The basis of the *methodology for studying changes in the technological accuracy* of the machine during the period of manufacturing a batch of parts, which is equal to the period of the cutting tool wear resistance, is the *method of instantaneous sampling* (Pylypchuk 2010). It was preliminarily found out that ten instantaneous samples of parts in a group, $n = N_n / 10$, characterize quite accurately the batch of manufactured parts.

The dimensional inaccuracy of the manufactured batch of parts is characterized by the parameters of the scattering field ω and dimensional setting X (Fig. 2). In most woodworking machines, the machining accuracy is gradually reduced during the production time of a batch of parts. Based on the results of studies on changes in sawing accuracy during the period of the cutting tool wear resistance on circular saws (Pylypchuk 2020), it can be argued that it is necessary to apply a polynomial model that takes the form:

$$Y_n(x) = C_n \cdot x^n + C_{(n-1)} \cdot x^{(n-1)} + \ldots + C_1 \cdot x + C_0 \qquad (2)$$

where: C_0 – the coefficient characterizing the initial value of the evaluation parameter;

$C_1 \ldots C_n$ – coefficients that characterize the nature of changes in the parameter during the period of the cutting tool wear resistance.

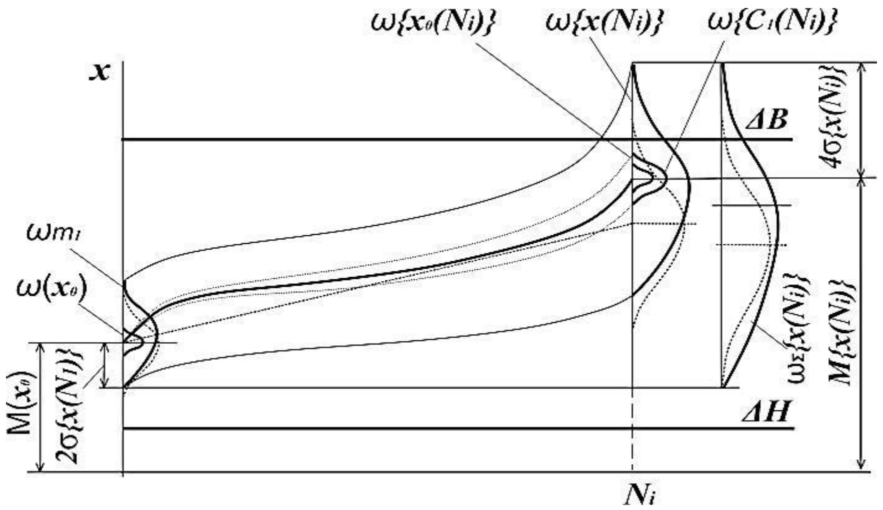


Fig. 2 Model of the polynomial pattern of changing the technological accuracy of the machine during the period of the cutting tool wear resistance.

Taking into account the polynomial model (2), the changes in the average size X_j and the scattering field ω_j are described by the equations:

$$X_j(t) = B_n \cdot t^n + B_{(n-1)} \cdot t^{(n-1)} + \ldots + B_1 \cdot t + X_0 \qquad (3)$$

$$\omega_j(t) = C_n \cdot t^n + C_{(n-1)} \cdot t^{(n-1)} + \ldots + C_1 \cdot t + \omega_0 \qquad (4)$$

where: X_0, ω_0 – the initial values of the average size and the scattering field of the part sizes;

t – the time of production of a batch of parts during the period of the cutting tool wear resistance;

$B_1 ... B_n, C_1 ... C_n$ –coefficients that determine the nature of changes in the average size of parts and the scattering field of part sizes during the period of the cutting-tool wear resistance.

The quantitative characteristic of the cutting tool wear is the degree of blunting of the cutter blades, which is determined by the radius of rounding of the main cutting edge (ρ µm). During the cutting process, the blunting of the blades of tool cutters is constantly increasing and according to data (Kiryk and Hryhoriev 2013), the value that describes the wear resistance period of milling knives is within ($\rho = 5 - 50$ µm).

To process experimental data from studies of changes in the technological accuracy of the machine tool, the *DynToch* program has been developed by the authors. It is used to obtain the mathematical dependencies describing the change in machining accuracy indicators over the characteristic periods of machine operation, using a regression equation – a polynomial of the n-th degree and in graphical form.

The program provides the following steps in a logical sequence: input data; calculation of statistical indicators and indicators of changes in the average value and scattering field; obtaining a regression equation based on linear and polynomial models and constructing graphical dependencies of changes in the average value and the scattering field of the machining error. The input data table allows processing arrays of ten samples, each of which contains ten measurements of the parts. All the samples are entered into the program in the sequence of their obtaining during the experimental studies. Calculations are performed automatically at all stages of the program, and all calculation results and their graphical representation are also automatically recalculated when each of the input data values is changed. The value of statistical indicators is also determined automatically for each of the samples after entering the input data.

The determined pattern makes it possible to analyze and predict changes in the accuracy of parts machining on any machine. In addition, by knowing the pattern, the state of technological accuracy of woodworking machines during a certain period of their operation can be monitored and the appearance of defective parts can be prevented. The developed technique can be used both to establish the pattern of changes in the technological accuracy of various types of woodworking machine structures, and to predict the machining accuracy on woodworking machines under production conditions over the period of the cutting tool wear resistance.

Determination of the actual technological accuracy of four-side plano-milling machines

The actual technological accuracy of four-side plano-milling machines was determined on the basis of experimental studies of machining accuracy in the case of eight types of machines operated in woodworking enterprises in Ukraine: Unimat 500, Profimat 23, Unimat 23 EL, Hydromat 1000, Hydromat 2000 from the Weinig company; QMB 620 GH from the Quality Greation Maker company; RMM 623 from the Reignmac company.

The experimental studies were carried out under the following conditions: wood – oak (Quercus); moisture content of the wood – 7–9%; feed rate – 20–25 m/min; spindle rotation speed – 6,000–8,000 min^{-1}; the number of milling cutters – 4 pcs.; the degree of the knives wear ($\rho = 45 - 50$ µm); the number of part size measurements in one sample is

100 (10 parts with 10 width and thickness measurements on each part). The results of the sample data processing and main indicators are shown in Table 1.

Tab. 1. Main indicators of the actual technological accuracy of four-side plano-milling machines

Machine brand, (year of manufacture)	The dimensions of the blanks, ($b \times h$) mm	Tolerance for blank size deviations, $\delta = \pm$ mm	Indicators of the accuracy of the dimensions of the manufactured parts		Processing quality, IT10–18, (ISO 286-2)	Machining accuracy class (1, 2, 3, 4)*
			Average size value, b / h mm	Scattering field, $\omega = \pm 2 \cdot \sigma$, b / h mm		
Machine tools of the manufacturing companies - China						
QMB 620 GH (year 2017)	53.0 × 31.0	Calibration, ± 0.2	45.4 / 23.3	± 0.23 / ± 0.37	13 /14	2 / 3
RMM 623 (year 2017)	94.0 × 22.0	Calibration, ± 0.2	90.3 / 18.4	± 0.21 / ± 0.33	13 /14	2 / 3
Weinig machine tools (Germany)						
Profimat 23 (year 2003)	68.0 × 33.0	Calibration, ± 0.2	59.4 / 31.5	± 0.22 / ± 0.24	12 / 13	2
Unimat 500 (year 2006)	44.0 × 35.0	Calibration, ± 0.2	40.0 / 27.7	± 0.21 / ± 0.23	12 / 13	2
Unimat 23 (year 2003)	46.0 × 46.0	Finishing ± 0.1	43.3 / 39.4	± 0.16 / ± 0.16	12	2
Unimat 23 EL (year 2005)	41.0 × 28.0	Finishing ± 0.1	40.5 /27.6	± 0.16 / ± 0.18	12	2
Hydromat 1000 (year 2014)	76.0 × 32.0	Finishing ± 0.1	71.2 / 28.1	± 0.17 / ± 0.19	12	2
Hydromat 2000 (year 2017)	80.0 × 30.0	Finishing ± 0.1	72.3 / 22.3	± 0.14 / ± 0.17	11 / 12	1/2

Note * 1 – particularly high; 2 – high; 3 – medium; 4 – normal.

Based on the analysis of the results obtained (Table 1), it is worth noting the following: under conditions of critical wear of milling knives ($\rho = 45 - 50$ μm), machining errors in all the machines, both in width and thickness of the parts, exceed up to two times the permissible values both during preliminary calibration of workpieces (± 0.2 mm) and during finishing (± 0.1 mm). The largest machining error was observed in the case of the machines of the Chinese manufacturers QMB 620 GH (Quality Greation Maker) and RMM 623 (Reignmac), which in terms of the thickness of the dimensions of the parts exceed the permissible values by 3.7 and 3.3 times, respectively. The highest machining accuracy (within ± 0.14–0.19 mm) was provided by the Weinig machines: Unimat 23, Unimat 23 EL, Unimat 500, Hydromat 1000 Hydromat 2000, however, all the machines did not meet the technological requirements for dimensional accuracy (± 0.1 mm), which necessitates conducting further research and development of measures to improve the accuracy of machining in these machines.

By checking the hypotheses about the law of machining error distribution, it was found that the distribution does not correspond to the normal law, and the Hnidenko-Weibull law more accurately describes this dependence. The discrepancy between various distributions (which can be used as input flows in the simulation modeling of wood machining processes) and the normal law is typical for such a natural material as wood, in particular, the work (Mysyk *et al.*, 2017) described the distributions of the length of defect-free areas for different species. To adequately describe such distributions of lengths of defect-free sections, it is more appropriate to use the Log-Logistic and Burr laws. In addition, the distribution of this error according to the Weibull law confirms the presence of a dominant factor influencing a decrease in accuracy and the shift in the average size value towards an increase. It means that there is a factor with a systematic nature of the impact, which is the blunting of the cutter blades leading to a decrease in machining accuracy and an increase in the size of the parts.

Thus, according to the results of statistical processing of the experimental studies on the technological accuracy of machines, it can be concluded that the accuracy of surface machining of workpieces using the machine tools is low (within ± 0.14–0.37 mm) and does not meet the technological requirements (± 0.1 mm), which is explained by the long-term operation of machine tools and the maximum wear of knives ($\rho_{max} = 50$ μm).

The study of changes in machining accuracy during the period of the cutting tool wear resistance

According to the developed methodology, experimental studies on the influence of the degree of knife wear on the accuracy of milling bar workpieces in production conditions on six machines were performed (Fig. 3).

Unimat 500, Weinig company

Profimat 23, Weinig company

Unimat 23, Weinig company

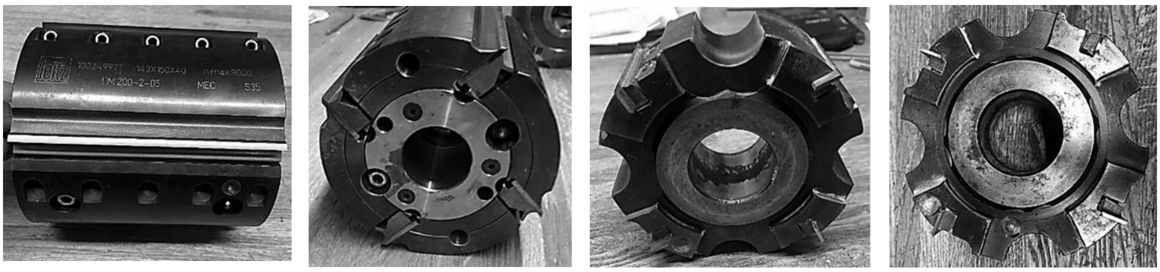
Hydromat 2000, Weinig company

QMB 620 GH, Quality Greation Maker company (China) — RMM 623, Reignmac company (China)

Fig. 3 Four-side plano-milling machines operating at woodworking enterprises of Ukraine.

The experimental studies on the technological accuracy of four-side plano-milling machines operating in woodworking enterprises in Ukraine for 5–18 years were carried out under the following conditions: wood – oak; the wood moisture content – 5–7%; workpiece dimensions: length – 730 mm; cross-section – 50 × 50 mm; feed rate – 20 m/min; period of resistance of knives to wear ($\rho = 5 - 50\,\mu$m); layer removal thickness 2.0–4.0 mm, the speed of rotation of the spindles – 6,000 min^{-1}.

The cutting tools – cylindrical assembled cutters with insert knives (Fig. 4 *a*, *b*) with a diameter of 125–260 mm, the number of milling cutter knives – 4 pcs; the permissible degree of knife wear ($\rho \leq 50\,\mu$m). Technical specifications of the milling cutters: for horizontal spindles (Fig. 4 *a*): the manufacturer – Leitz, serial number – 100249971, dimensions – 143×150×40 mm, $n_{max} = 9{,}000$ min^{-1}, HM 200-2-05, MEC S35; for vertical spindles (Fig. 4 *b*): UNIMERCO, dimensions – 145×80×40 mm, $n_{max} = 9{,}000$ min^{-1}.



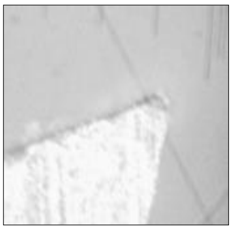
a ***b***

Fig. 4 Assembled shell-milling cutters that were used on the plano-milling machines during the experimental studies: *a* - on horizontal spindles; *b* - on vertical spindles.

The radius of rounding of the cutting edge, which was periodically measured after performing a given cutting path, was used to quantitatively assess the wear of the blade of the milling cutter. The milling cutter was removed from the machine, the top of the knife was photographed under the object-micrometer OMP No. 652295 with a division value of 0.01 mm (Fig. 5 *a, b*) and re-installed on the machine for further milling. Simultaneously with photographing the knife blade, a microline was photographed, the distance between divisions being 0.01 mm, which makes it possible to determine the dimensions of the cutter knife with an accuracy of 10 µm. The wear of the cutter knife blade was measured from the obtained photo using the AutoCad computer program.

Measurements of the dimensions of the manufactured parts on each of the machines were made by their width and thickness, and samples of 100 values were obtained (10 parts with 5 width and thickness measurements on each).

a



b

Fig. 5 Measurement of the radius of rounding of the blades of the milling cutter knives *a* – the knife of the milling cutter; *b* – the top of the experimental knife of the milling cutter under the microscope.

Indicators of machining accuracy on plano-milling machines are the average value and scattering field of the size of the manufactured parts, which is equal to $\omega = \pm 2\sigma$ mm. The criterion for evaluating the accuracy of machining is the magnitude of deviation of the actual size of the manufactured parts from the permissible value of the size error. Size tolerances of manufactured bar parts on plano-milling machines have the following values: preliminary calibration $\delta = \pm 0.2$ mm; finishing (final) machining $\delta = \pm 0.1$ mm.

On the basis of processing the results of the experiment with the help of the developed program "DynToch", the regression equations of the change in the average value and the scattering field of the thickness of the parts were obtained in the form of third-order polynomials for six machines, which take the following form:

the QMB 620 GH machine tool

$$h = 1.8 \cdot 10^{-3} \rho^3 - 2.1 \cdot 10^{-2} \rho^2 + 8.27 \cdot 10^{-2} \rho + 0.162 \quad (5)$$

$$\pm \omega = 0.4 \cdot 10^{-3} \rho^3 - 0.2 \cdot 10^{-2} \rho^2 + 1.36 \cdot 10^{-2} \rho + 0.078 \quad (6)$$

the RMM 623 machine tool

$$h = 0.9 \cdot 10^{-3} \rho^3 - 1.2 \cdot 10^{-2} \rho^2 + 5.65 \cdot 10^{-2} \rho + 0.182 \quad (7)$$

$$\pm \omega = -0.3 \cdot 10^{-3} \rho^3 + 0.84 \cdot 10^{-2} \rho^2 - 3.39 \cdot 10^{-2} \rho + 0.126 \quad (8)$$

the Profimat 23 machine tool

$$h = -0.4 \cdot 10^{-3} \rho^3 + 7.4 \cdot 10^{-3} \cdot \rho^2 - 1.65 \cdot 10^{-2} \rho + 0.103 \quad (9)$$

$$\pm \omega = 0.5 \cdot 10^{-3} \rho^3 - 0.49 \cdot 10^{-2} \rho^2 + 1.66 \cdot 10^{-2} \rho + 0.076 \quad (10)$$

the Unimat 500 machine tool

$$h = -0.2 \cdot 10^{-3} \rho^3 + 3.4 \cdot 10^{-3} \rho^2 + 2.4 \cdot 10^{-3} \rho + 0.092 \quad (11)$$

$$\pm \omega = 0.7 \cdot 10^{-3} \rho^3 - 8.7 \cdot 10^{-2} \rho^2 + 3.38 \cdot 10^{-2} \rho + 0.053 \quad (12)$$

the Unimat 23 machine tool

$$h = -0.8 \cdot 10^{-4} \rho^3 + 3.7 \cdot 10^{-3} \rho^2 - 1.32 \cdot 10^{-2} \rho + 0.1 \quad (13)$$

$$\pm \omega = -0.3 \cdot 10^{-3} \rho^3 - 3.6 \cdot 10^{-2} \rho^2 + 1.29 \cdot 10^{-2} \rho + 0.057 \quad (14)$$

the Hydromat 2000 machine tool

$$h = 0.7 \cdot 10^{-4} \rho^3 + 0.8 \cdot 10^{-3} \rho^2 - 0.21 \cdot 10^{-2} \rho + 0.09 \quad (15)$$

$$\pm \omega = 0.3 \cdot 10^{-3} \rho^3 - 0.42 \cdot 10^{-2} \rho^2 + 1.8 \cdot 10^{-2} \rho + 0.064 \quad (16)$$

All the regression equations (5-16) of the average value and the scattering field of the size of the manufactured parts describe the increasing dynamics of the growth of machining accuracy indicators during the period of the tool wear resistance. The graphs of the polynomial models of the change in the average value (Fig. 6) and the scattering field (Fig. 7) for six machines show that the empirical dependences of the change in milling accuracy during the period of the tool wear resistance are approximated with high accuracy (R^2 = 0.95–0.98) by polynomials of the third degree.

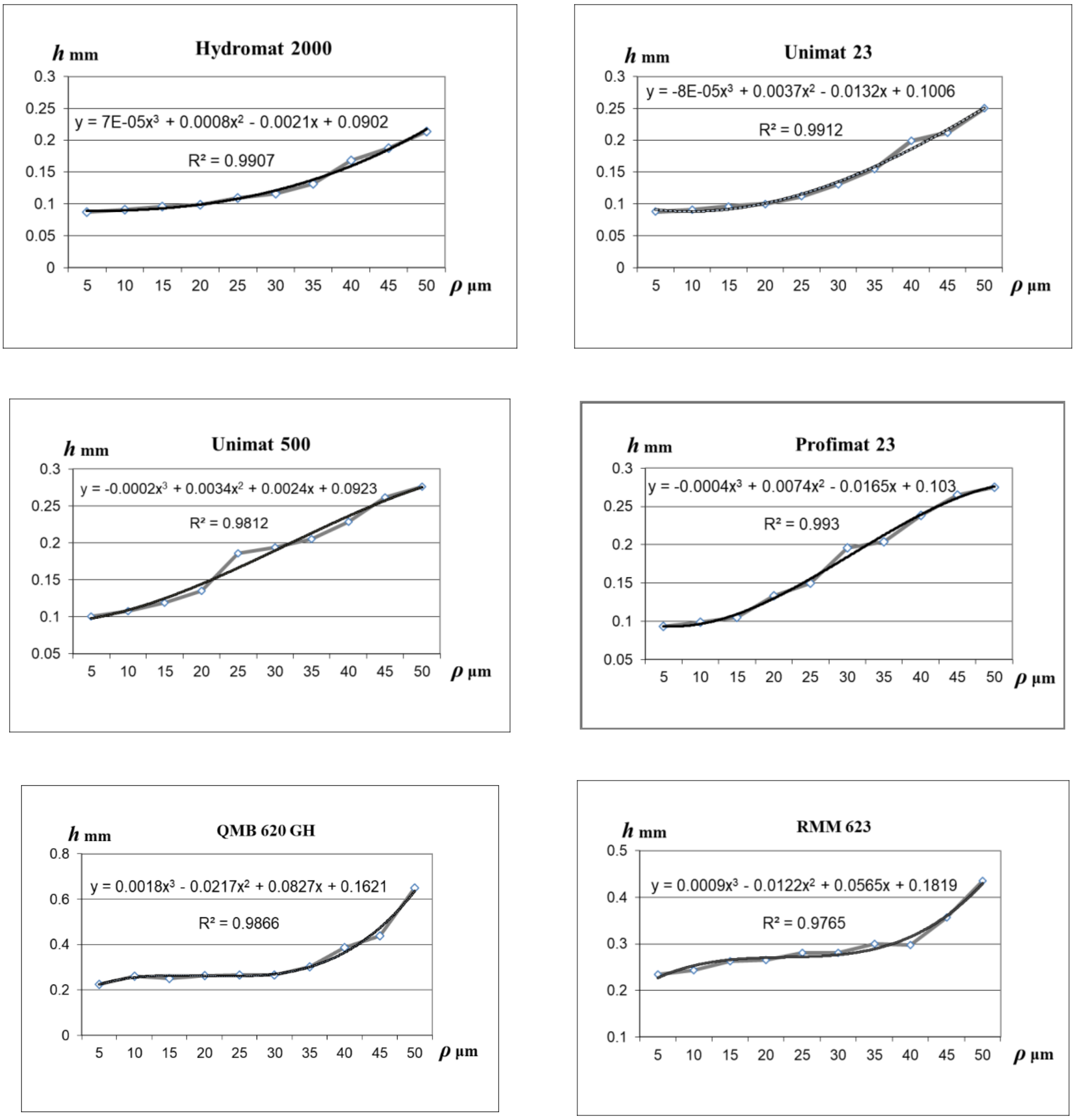


Fig. 6 Polynomial models of changes in the average size of manufactured parts on the machine tools.

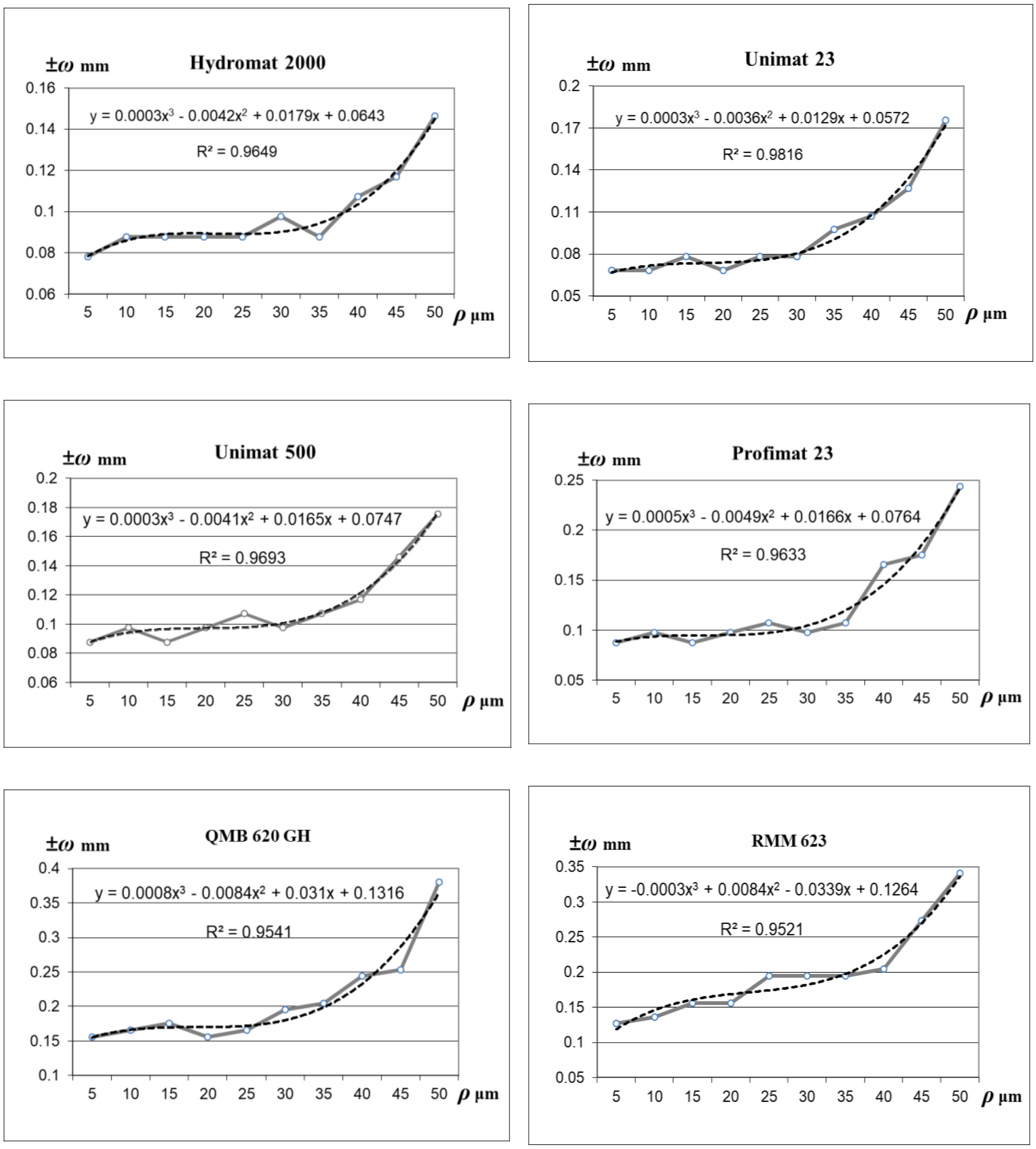


Fig. 7 Polynomial models of changes in the scattering field of the size of manufactured parts on machine tools.

Thus, the obtained regression models in the form of a polynomial of the third degree, which describe the increasing dynamics of the average value and the scattering field of the size of manufactured parts on machines of the following brands: QMB 620 GH, RMM 623, Profimat 23, Unimat 500, Unimat 23 and Hydromat 2000 during the period of knife wear resistance ($\rho = 5 - 50\,\mu$m), allow analyzing and predicting changes in the accuracy of machined parts on each of the machines and identifying the maximum duration of cutting tool wear resistance periods according to the criterion of machining accuracy

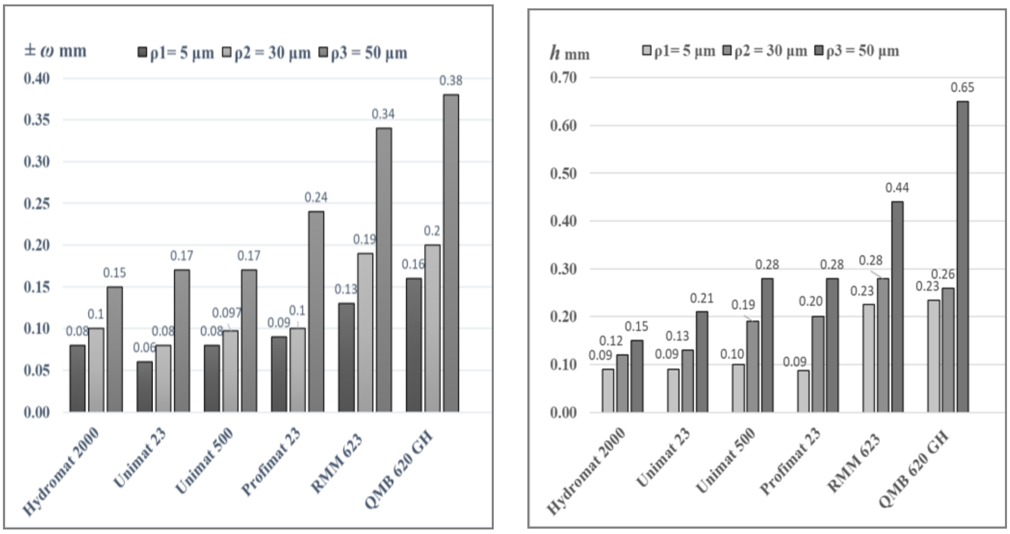
RESULTS AND DISCUSSION

On the basis of the graphs of regression models (Figs. 6–7), for each of the machines, the characteristic phases of the milling cutter knife wear resistance period were determined: initial, sharp knives ($\rho = 5\,\mu$m); medium degree of wear of knives ($\rho = 30\,\mu$m); critical, maximum wear of knives ($\rho = 50\,\mu$m). Based on this, diagrams of the magnitude of the scattering field and the average value of the size of parts for three characteristic values of the periods of the cutter knives wear resistance on each of the six machines were constructed (Figs. 8*a*, *b*).

Based on the results of the analysis of changes in machining accuracy in the case of the Unimat 500 and Profimat 23 machines (Fig. 8 *a*), it was found that the scattering field of the size of the manufactured parts increases three times ($\pm\,\omega = 0.08 - 0.24$ mm) during the entire period of knife wear resistance, and the milling accuracy within the tolerance (±0.1 mm) is provided only at the initial and middle phases of the knife wear resistance period, i.e. under the condition of $\rho \leq 30$ µm. On the Unimat 23 and Hydromat 2000 machines, the cutting accuracy during the knife wear resistance period ($\rho \leq 50\,\mu$m) is also reduced by 2.4 times ($\omega = \pm 0.07 - 0.17$ mm), but slower compared to the Unimat 500 and Profimat 23 machines. The tolerance of machining accuracy (±0.1 mm) on these machines is provided under the condition of $\rho \leq 40$ µm, which confirms the high geometric accuracy and stiffness of machine structures.

It was found that the machining error on the machines QMB 620 GH, RMM 623 of Chinese manufacturers (Fig. 8 *a*) during the period of wear resistance of the knives increases most rapidly ($\pm\,\omega = 0.13 - 0.38$ mm), that is, by 3.7 times, and the tolerance requirements (±0.1 mm) are not provided even in the initial phase of the milling period ($\pm\,\omega = 0.13 - 0.16$ mm). On these machines, during the period of knives wear resistance $\rho \leq 30$ µm, machining accuracy is ensured within ± 0.2 mm, which meets the requirements only for the preliminary calibration of the workpieces and confirms the non-compliance of the machine specification with a particularly high class of accuracy.

The average value of the size error of manufactured parts in the case of all the machines during the period of knife wear resistance (Fig. 8*b*) also increases in accordance with the increase in the scattering field of the size of the parts. On the Weinig machines, during the middle phase of the knife wear resistance period $\rho \leq 30$ µm, the average value of the part size changes within $h = 0.09 - 0.19$ mm, i.e. the thickness of the parts increases by 0.1 mm, and with the maximum wear of the knives ($\rho = 50$ µm) $h = 0.09 - 0.28$ mm, i.e. the size increases to 0.2 mm. Thus, the Unimat 500, Profimat 23, Unimat 23, and Hydromat 2000 machines will ensure machining accuracy according to two criteria during the middle phase of the knife wear resistance period ($\rho \leq 30\,\mu$m): the average value of up to 0.1 mm and the scattering field (± 0.1 mm).



a ***b***

Fig. 8 Machining accuracy for characteristic phases of the wear resistance period of the milling knives: *a* – by the scattering field; *b* – according to the average value.

On the Chinese-made QMB 620 GH, RMM 623 machines, during the period of wear resistance of the knives ($5 \le \rho \le 50$ μm), the average value of the thickness of the parts changes within the range of $h = 0.23 - 0.65$ mm, that is, the size increases by 0.42 mm. A significant increase in the size of the parts indicates insufficient rigidity of the "machine-cutting tool-workpiece" system and the need for additional dimensional adjustment of the machine before the beginning of the critical phase of wear resistance of knives ($30 \le \rho \le 50$ μm).

Based on the results of the analysis, it was found that in order to ensure machining accuracy in plano-milling machines within the tolerance (± 0.1 mm), the wear of the cutter knives should not exceed $\rho = 30$ μm, and the technical specification of the machine should correspond to a particularly high accuracy class.

CONCLUSIONS

On the basis of experimental studies in the production conditions of Ukrainian enterprises, the indicators of the actual technological accuracy of plano-milling machines of various manufacturers were determined and it was found that under the conditions of maximum wear of milling knives ($\rho = 50$ μm), the size errors of the manufactured parts in the case of all the machines exceed the permissible values (± 0.1 mm) by up to four times, which makes it necessary to establish a pattern of changes in machining accuracy during the period of the cutting tool wear resistance.

The algorithm for mathematical prediction of changes in machining accuracy in machine tools over the period of tool wear resistance was improved. Software that makes it possible to obtain regression models of the change in the average value and the scattering field of the size of manufactured parts in the form of polynomials of the n-th degree and to predict the change in the accuracy of machining on the machine during a certain period of operation was developed. Moreover, it can be used to establish the allowable duration of the period of the wear resistance of the cutting tool according to the criterion of machining accuracy and to prevent the appearance of defective parts.

According to the results of experimental studies of changes in the accuracy of machining on machine tools during the period of tool wear resistance ($\rho = 5 - 50$ µm), regression models in the form of polynomials of the third degree were obtained. These models describe the change in machining accuracy on machine tools during the period of the cutting tool wear resistance with accuracy $R^2 \geq 0.95$. It was found that in order to ensure the machining accuracy within the tolerance (±0.1 mm), the period of the cutting tool wear resistance should not exceed $\rho = 30$ µm, and the technical specification of the machine should correspond to a particularly high accuracy class.

The proposed mathematical model for predicting the change in machining accuracy during the cutting tool wear resistance period makes it possible to determine the duration of the cutting tool wear resistance period, which ensures the required accuracy of machining. The developed methodology and the obtained results are the basis for further research on the implementation of systems of active control over the size of manufactured parts and the development of systems for automatic dimensional adjustment of machine tools.

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