Prospective methods of improving productivity in mechanical processing of agricultural parts

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Abstract. The comprehensive analysis of existing literature reveals that the effective utilization of cooling and lubricating fluids plays a critical role in enhancing the efficiency of mechanical machining processes. These fluids not only facilitate the removal of chips but also significantly influence the accuracy of the surface finishes achieved. As such, they directly impact key technological parameters, including the cutting speed and feed rate, which are vital for optimizing machining operations. Research indicates that the incorporation of cooling and lubrication strategies leads to improved surface quality and dimensional accuracy of the machined components. This enhancement is accompanied by an increase in cutting capacity, which ultimately boosts productivity. Furthermore, the process of deburring is recognized as another crucial factor in refining surface quality and precision. Consequently, establishing the optimal cutting speed and feed rate emerges as a pivotal focus for process optimization, underscoring the interconnected nature of these parameters in achieving superior machining outcomes.

1 Introduction

In the world, in order to increase the quality and service life of agricultural machine parts, it is of particular importance to ensure the accuracy of the geometric parameters of the parts. At the same time, one of the important tasks is the development and research of methods of increasing productivity in mechanical processing, which takes a special place in ensuring accuracy and quality indicators, which are one of the criteria that determine the quality of parts. In this regard, the research centers of developed countries, including the USA, England, Germany, Russia, Japan, Italy and other countries, are paying special attention to improving and creating new methods of increasing productivity in the mechanical processing of parts. It is important to carry out large-scale scientific research on the creation of methods that allow the implementation of mechanical processing of parts on a global scale.

Scientific and research work is being carried out on a large scale in the field of agriculture in the world to ensure the precision indicators of parts. In this direction, it is important to create machining methods using turning, drilling and milling, to develop their design and calculation methods, and to use such methods in machines controlled by digital programs. The uniqueness of the processes of drilling and milling non-technological holes in

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agricultural parts became the basis for the acceleration of research and development in this direction, as well as new technological steps in the research of physical processes between the material and the cutting tool in the direction of milling and drilling was developed. At the same time, it is necessary to develop processing methods that can determine the quality parameters of the mechanically processed surface.

2 Materials and methods

Due to the lack of database recommendations on the choice of mechanical processing method and cutting mode, the productivity of the shaving removal process is not high, and the service life of the tools, especially the drill, is very low. During the mechanical processing of the part, the quality of the surface, due to grinding at the entry and exit points of the cutting tool, the sticking of the shaving is observed.

The most clearly indicated features are manifested in milling or drilling on non-technological surfaces of parts [1]. The most characteristic types of non-technological types for mechanical processing of details and the available methods of recommendations are shown in Table 1.

In the process of processing non-technological surfaces, the access of the cutting tool to the spherical surfaces of the part is complicated, which leads to the destruction of the working part of the cutting tool. It causes a sharp deterioration of the accuracy and quality of the surfaces, a shortening of the service life of the tool [2].

Diametrical errors (size and shape errors) of part surfaces are most clearly manifested at the tool entrance. Diameter errors at the output of the tool are usually less. The cause of this type of defects is usually additional removal of material from the walls of the hole during the drilling stage. In the process of drilling, the cutting moves from the bottom up, along the side hole of the drill. Since the material of the details made of soft metal has a low hardness, the movement of the shavings leads to separation and sticking of the walls of the hole. Often, this results in poor quality of hole shape errors.

Cracking of the hole surface and the appearance of defects are the result of the action of cutting modes. Defects in the exit of the drill from the hole lead to the process of breaking the upper part of the part. Uncut fiber is the sticking residue left on the edge of the hole by the exit of the cutting tool. Let's consider the method of drilling non-technological surfaces. With the help of two quick-release conductors, the part is fixed (Fig. 1).

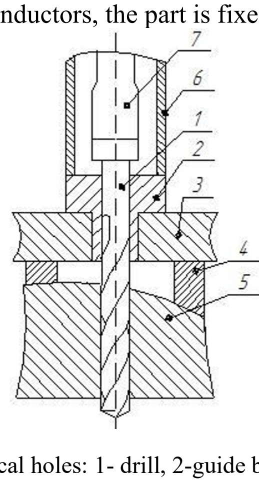


Fig. 1. Method of drilling non-technological holes: 1- drill, 2-guide bushing, 3-quick-change bushing, 4-pin, 5-part, 6-bush, 7-spindle

Currently, to carry out the process of mechanical processing of non-technological surfaces, it is necessary to manufacture special devices, use guide bushings, conduct an additional operation, which, of course, significantly increases the cost of the product.

Special devices used for mechanical processing and the methods discussed above cannot be used. In addition, there are disadvantages of certain processing methods, as well as the low quality of the processed surfaces, sticking of shavings to the cutting tool, etc. [3].

We offer a method of mechanical processing of non-technological surfaces, according to which, during processing, the input and output of the cutting tool to the surface of the part is controlled and the movement of the push is controlled. (Figure 2).

The proposed method is implemented in the following sequence. The cutting tool rotates and moves along the axis, feed rate of the cutting tool changes during the cutting tool input and output during machining. Feed rate and cutting speed are automatically adjusted according to the machining recommendations. In addition, when the cutting tool leaves the cutting area, feed rate is automatically reset [3].

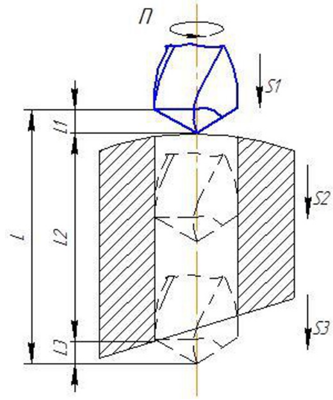


Fig. 2. The method of drilling non-technological holes with variable feed rate

The performance of the proposed machining method is evaluated by the quality of the machined surfaces and the durability of the cutting tool compared to known methods.

Research results have shown that the quality of machined surfaces increases when processing surfaces with an adjustable feed rate.

As mentioned above, the machining of parts is the most difficult task due to the processing conditions that create different requirements for cutting conditions and cutting tools.

The introduction of new methods of mechanical processing, the rational selection of cutting tools and cutting processes help to achieve the required quality of parts, reduce their cost and increase the accuracy of the prepared parts.

Based on our theoretical and experimental research, we have developed a method and methodology for selecting reasonable cutting conditions, which can improve the quality, accuracy and productivity of the machining process.

Drill is the main cutting tool for making holes. According to their construction, drills are divided into spiral drills, feather drills, center drills used for drilling center holes on work piece face surfaces, drills used for drilling deep holes, and other drills.

When drilling, the depth of cut is equal to half the diameter of the drill.

$$t = \frac{D}{2}, mm \tag{1}$$

When expanding the hole by drilling, the cutting depth is as follows.

$$t = \frac{D - d}{2}, mm \tag{2}$$

Here, D-drill diameter, mm, d-hole diameter, mm.

Feed rate (s) - displacement of the drill along its axis during one full rotation, mm/rot. Since the drill operates with two cutting edges at the same time, the feed rate applied to each cutting edge is:

$$s_z = \frac{s}{2}, mm/rot \tag{3}$$

Torque M and thrust force Py during drilling are calculated from the following formula.

$$M = C_m \cdot D^{q_m} \cdot S^{y_m} \cdot K_p \text{ , [н· м]}$$
$$P_y = 9.81 \cdot C_p \cdot D^{x_p} \cdot S^{y_p}, \text{[н]} \tag{4}$$

Here C_m and $C_p$are coefficients depending on the material to be drilled, geometry of the drill and other factors; D-drill diameter, mm; S-feed rate, mm/rot; $x_м, y_м, x_p, y_p$-exponentiation indicators.

The shear strength for drilling is defined as follows.

$$N_{cut} = \frac{M \cdot n}{975}, sq \tag{5}$$

Here M is the torque in drilling, n is the number of rotations of the spindle.

The stagnation period of drill depends on the cutting speed. Drills' stagnation is understood as the time of operation of this drill until it expires. Drills' stability is determined by the formula adopted in the tangential direction of the relation between stagnation T and cutting rate v.

$$v = \frac{A}{T^m} \tag{6}$$

In this v- cutting speed, mm/rot; T-drill stagnation, min; A-invariant size depending on the quality of the material to be drilled, the material of the drill and the conditions of drilling; m-relative index of stability (this index depends on the material to be drilled, the material of the drill and the conditions of drilling).

For drills made of high-speed steel, the value of the degree index m is equal to 0.2 when drilling steel, and 0.125 when drilling cast iron. For drills equipped with hard alloy plates, m=0.25 for steel drilling, m=0.4 for cast iron drilling. The stagnation of the drill depends on the diameter of the drill. Average values of stagnation T for drills made of high-speed steel are given in table 5.1.

The cutting speed in milling is determined as follows.

$$v = \frac{C_v \cdot D^{q_v}}{T^m \cdot t^{x_v} \cdot S^{y_v}} \cdot K_v \tag{7}$$

Here,

The stagnation period T of cutting tool.

C_v - constant coefficient depending on the material to be drilled, drill material, geometry of the working part of the drill and drilling conditions (drilling depth, cooling-non-cooling, etc.); D - drill diameter, mm; T - drill stagnation, min.; S – feed rate, mm/rot; m-relative index of stagnation; x_v, y_v - exponentiation indicators; Coefficient that takes into account the specific conditions of K - drilling:

$$K_v = K_{lv} \cdot K_{mv} \cdot K_{мv} \tag{8}$$

where K_{lv} , K_{mv} , $K_{мv}$ is the coefficient that takes into account the influence of the depth of the hole being drilled, depending on the diameter of the drill, the material of the cutting part of the drill and the use or not of the lubricating-cooling fluid.

$$v = \frac{C_v \cdot D^{q_v}}{T^m \cdot t^{x_v} \cdot S^{y_v}} \cdot K_v \tag{9}$$

When finding the cutting speed in milling, the values in the formula are taken from table 2.6.

Here

$$K_v = K_{мv} \cdot K_{иv} \cdot K_{lv} \tag{10}$$

$$K_{мv} = C_m (\frac{75}{G_B})^{n_v}; K_{иv} = 1$$

K_{Lv} - the value of the diameter and depth of the drill.

The depth of the hole to be drilled, based on the diameter of the drill

$\frac{l}{D} = \frac{120}{28} = 4.28$ according to $K_{Lv} = 0.85$

In machining, productivity is also affected by the diameter of the cutting tool and the length of the part. As the machining length increases, the probability of the cutting tool breaking also increases.

In order to prevent the sticking of shavings to cutting tool that come out and pressed during machining, we recommend stopping the feed rate of the cutting tool from time to time, which will cause the cuttings to be divided into small pieces and prevent the sticking of shavings to cutting tool and prevent the cutting tool from breaking (Figure 3).

Intermittent interruption of the thrust movement in machining consists of at least one rotation of the cutting tool or part. This stabilizes the dynamic properties of the machining process and allows improving the quality of the machined surfaces by grinding the shaving. During drilling, the cuttings are crushed along the spiral rods of the drill, which prevents accumulation of the shavings in the hole.

The performance of the proposed machining method was evaluated by the quality of the machined surfaces and the resistance of the cutting tool in comparison with the known analogues. In addition, in the process of processing the part by certain methods, it is visually determined at the exit points of the shaving from the working part of the cutting tool and on the surface.

We choose a cutting tool of the P6 brand, made of high-speed steel with a drill diameter of D=10H12 mm.

Geometric parameters of drill: $2\varphi = 118^0$, $2\varphi_0 = 70^0$, $\psi = 55^0$,
$\omega = 30^0$,

The process of drilling the hole was carried out in the following working conditions: v=8,5 m/min, s=0,3 mm/rot; v=8,5 m/min; s=0,6 mm/rot; v=14 m/min; s=0,3 mm/rot; v=14 m/mi, s=0,6 mm/rot. The degree of shaving formation and sticking was determined in the process of drilling. After finishing the drilling process, the size of the pitting of the hole surfaces was determined using a (MIM) microscope as the maximum damaged diameter relative to the nominal diameter of the holes. The size of the obtained defect was compared with the size of the hole surfaces of the conventional drilling method. The surface roughness of the hole to be processed was determined using a profilometer. Drill deflection was assessed under a microscope after drilling of all holes was completed.

Productivity can be increased when processing agricultural parts by analyzing part surfaces into technological surfaces (TS). It consists of a set of different types of surfaces that can be machined together with the continuous movement of the tool along a certain trajectory, or with a set of tools used in sequence in the implementation of the elemental machining path of the surface. Each operation of such a route, carried out on the basis of the appropriate technological method, is elementary or complex, but ensures the formation of all surfaces of the T-surface during one pass (Table 1). The design of any part can be represented by a limited set of T-surfaces oriented in the desired way in space.

A set of T-surfaces is divided into small groups, the complexes of each of which, if the necessary conditions are met, can be processed with the same type of general cutting tool used in turning-milling and drilling-milling-flaring CNC machines (Table 2). The possibility of producing several T-surfaces from a subset of them using one cutting tool of the specified type is evaluated by fulfilling the individual necessary conditions for each combination of produced T-surfaces (Table 2).

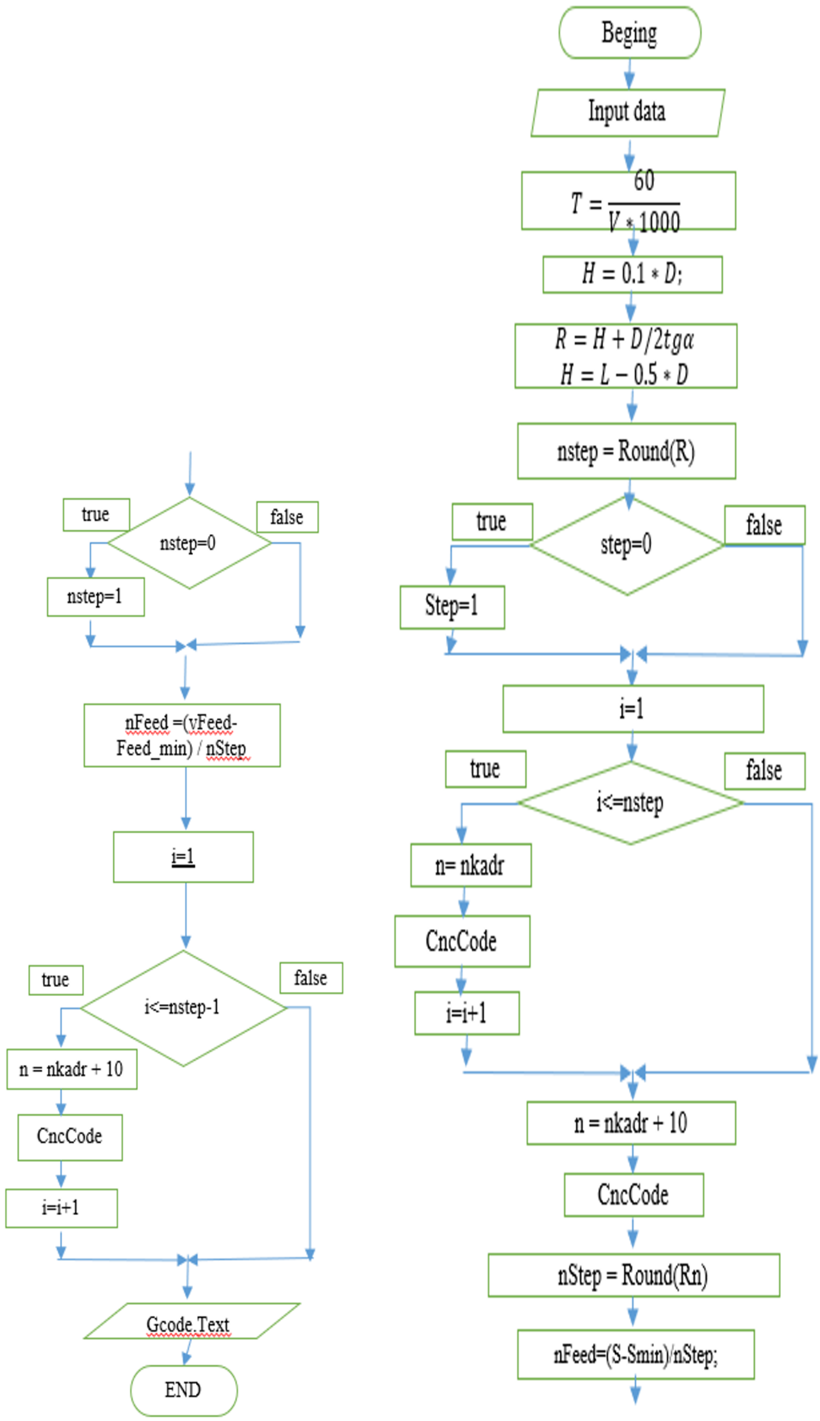


Fig. 3. The block method of drilling non-technological holes with variable feed.

Table 1. Technological surfaces and their processing methods

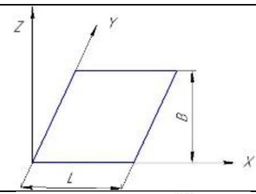
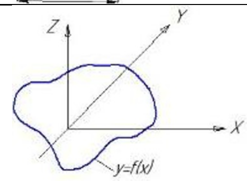
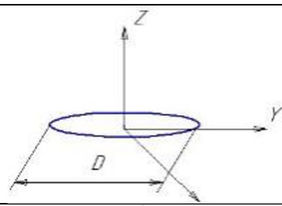
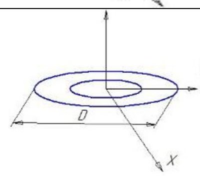
<table>
<tr><th>Designation</th><th>Sketch</th><th>Technological method</th></tr>
<tr><td rowspan="2">TS1</td><td>
</td><td rowspan="2">Milling:
- face;
- cone;
- disc</td></tr>
<tr><td>
</td></tr>
<tr><td rowspan="2">TS2</td><td>
</td><td rowspan="2">Turning-milling:
- face;
- cone;
- disc</td></tr>
<tr><td>
</td></tr>
</table>

Table 2. T-surfaces that can be made using the specified type of tool

№	Type of cutting tool	Surface preparation
1	Finger mill	TS1, TS2,
2	Disc mill	TS1, TЮ2
3	Face mill	TS1, TS2
4	Passing and cutting tool	TS2,

3 Results and discussion

Mathematical statistics is not limited to processing observations. Experimental design methods are most effective for studying complex technical systems. The main task of experiment planning is to obtain maximum data with a minimum number of experiments in the system. The nature of the experimental design allows us to simultaneously change all the factors affecting the process being studied.

Mathematical methods of experiment planning were used to study the process of drilling holes in agricultural parts. Fast corroding of the drill can cause damage to the part. In order to prevent bending of the cutting tool, it is necessary to take measures so that it does not affect the main indicators. For this, it was assumed that the position of the instrument should not change constantly in the experiment.

The first step in designing an experiment involves choosing the level of variability of the factors being studied. The degree of variability of the factors depends on the technological capabilities of the equipment and the assigned tasks. The number of levels should contribute to the complete description of the system without significantly complicating the task. Two- and three-level plans are the most common.

The three-level experimental design fully describes the actions of each factor, reveals not only linear, but also quadratic effects, which significantly improves the accuracy of the obtained models.

To obtain simple formulas for searching for regression coefficients, we use the normalized form of the factors in the plan to determine the percentage and sign of each effect on the studied response. The transition from natural values of variables to normalization is carried out with transformation formulas:

$$x_{inorm} = \frac{x_i - x_{ji}}{\Delta x_i} \tag{11}$$

where x_i is the extreme natural value of the factor level; x_{ji} - the main level of the i-th variable; Δx_i -interval of change.

In this work, we used three main factors (3-1), two main factors and one block coefficient, the number of experiments was N=10, the number of replications was N = 3 (Table 3). Using such a plфт reveals linear and quadratic effects for all 3 factors, as well as main factor interactions. The plan was created using the statistics 7 software product. The order of temperaments was randomly selected so that the experimental conditions did not distort the results due to systematic variation.

Table 3. 3 repetition factor matrix (N=10)

№	Level of factors			№	Level of factors		
	Number of holes (block factor), X_3	Feed, X_2	Cutting speed, X_1		Number of holes (block factor), X_3	Feed, X_2	Cutting speed, X_1
1	1	-1	-1	**6**	2	0	-1
2	1	0	1	**7**	2	-1	0
3	1	1	0	**8**	2	0	-1
4	1	1	0	**9**	2	-1	1
5	1	1	0	**10**	2	1	-1

Many relationships in the study of cutting processes are traditionally represented by equations of motion.

$$y = Cv^{a}S^{\beta}t^{y} \quad , \quad T = \frac{C_{M}}{V^{\frac{1}{m}} S^{y_v} t^{x_v}} \tag{12}$$

where v is the cutting speed; s - feed; t - depth of cut; C, α, β, γ are constant values.

Cutting speed and feed have a significant effect on the process of forming the machined hole and its accuracy. The depth of cut during milling is constant, so it is removed from the equation.

The process of drilling holes in parts is characterized by a very rapid wear of the cutting tool, which is proportional to the number of experiments. Thus, the factor "position of the cutting tool", given in terms of the number of holes N, is entered into the following equation:

$$Y = Cv^{\alpha}S^{\beta}t^{y} \tag{13}$$

where v is the cutting speed; s - feed; t - depth of cut; C, α, β, γ are constant values.

Using the logarithm, this equation can be expressed as:

$$lnY = lnc + lnv + \beta lnS + ylnl \tag{14}$$

Equation (3.11) can be expressed as follows:

$$\hat{y} = b_0 + b_1x_1 + b_2x_2 + b_3x_3 \quad (15)$$

where ŷ = x1, x2, x3 - coded values are factors v, s, l, respectively.
In this case, the coded value of the factor is xi

$$x_i = \frac{2(ln\ddot{x}_i - ln\ddot{x}_i)}{ln\ddot{x}_{iB} - ln\ddot{x}_{iH}} + 1 \quad (16)$$

where xi is a natural value; xiв, xiн are the natural values of the upper and lower levels, respectively.

It is convenient to use the results of multivariate experiments to estimate the coefficients of the equation. In addition, the results of the experiment for a three-level factorial plan consisting of two main factors and one block can be presented in a multifactorial form:

$$\hat{y} = b_0 + b_1x_1 + b_2x_2 + b_3x_3 + b_{12}x_1x_2 + b_{11}x_1^2 + b_{22}x_2^2 + b_{33}x_3^2 \quad (17)$$

In the classical version, the search for multivariate analysis of variance is carried out in two stages: the method of least squares and the method of maximum likelihood. In the first step of finding the regression equations, we use the least squares method. It is based on the minimization of the quadratic residuals of the model, which is calculated as follows:

$$RSS = \sum_{i=1}^{n} e_i^2 \quad (18)$$

where ei is the residual, the difference between the observed and predicted value.

As a result of the analysis of variance, we find a model consisting of significant effects and their interactions according to Fisher's criterion (F):

$$F_i = \frac{MS_i}{MSR} > F_{0,05(fms_i, fMSR)} \quad (19)$$

where MS_i is the average sum of squared effects and interactions (the ratio of the sum of squares to the number of degrees of freedom fms_i), MSR is the average sum of squared residuals (the ratio of the sum of squares to the number of degrees of freedom $fMSR$).

We check the obtained sequence for the reliability and fit of the obtained model using the statistics 7 software product.

First, we check that the modeling is not redundant (the existence of a linear relationship between the input quantities). The verification is done by changing the transformation, they must satisfy the following inequality.

$$VIF_i = \frac{1}{(1 - R_i^2)} \leq 10 \quad (20)$$

where, R_i^2 coefficient is the coefficient of determination of the i-regression element.

The second step is to validate the model using the signal-to-noise ratio. If the inequality is satisfied, the model is considered suitable.

$$\frac{\max(y) - \min(y)}{\sqrt{V(y)}} > 4, \text{ here, } V(y) = \frac{1}{n}\sum_{i=1}^{n} V(y) \quad (21)$$

where, $\max(y)$, $\min(y)$are the maximum and minimum approximate values; V(y)- average volatility.

The third step is to check the quality of the model found using the coefficient of determination.

$$R^2 = 1 - \left(\frac{RSS}{MSS + RSS}\right) \quad (22)$$

where, RSS is the sum of residuals, MSS is the regression sum of squares.

R^2 value closer to unity means that the model more closely approximates the variation in system responses.

To estimate the regression more rigorously, we calculate the adjusted estimate that should satisfy the inequality:

$$R^2_{sp.} - R^2_{for.} < 0{,}2 \tag{23}$$

$R^2_{sp.}, R^2_{for.}$ – predicted accuracy ratios [57]:

$$R^2_{sp.} = 1 - [(\frac{RSS}{df_{RSS}})/\frac{RSS+MSS}{df_{RSS}+df_{ESS}}] \quad , R^2_{for.} = 1 - [\frac{PRESS}{MSS+RSS}] \tag{24}$$

here, $PRESS$ – the residual sum of squared error per hole:

$$PRESS = \sum_{i=1}^{n}(\frac{y_i - y_i}{1-h_{ii}}) \tag{25}$$

The fourth stage is the analysis of shavings away from the regression dependence. It may be due to measurement errors, abnormal effects of any factors and other random events. Such observations significantly distort the regression model and should therefore be identified:

$$e_{ti} = \frac{y_i - y_i}{\sqrt{MSR}\sqrt{1-h_{ii}}} \tag{26}$$

where h_{ii} is the indicator of the influence of the observation on the model ("disparity");
MSR is the squared average residual

The residuals calculated for each shaving must follow the distribution law of the random variable with a distribution within the bounds of the confidence interval.

The resulting model should be modified according to the maximum likelihood method. For this we use the power-law or Box-Coxa logarithmic variable.

$$\hat{y} = \begin{Bmatrix} (\hat{y}+C_\lambda)^\lambda \\ \ln(\hat{y}+C_\lambda) \end{Bmatrix} \frac{at\ \lambda \neq 0}{at\ \lambda = 0} \tag{27}$$

where, $\hat{y} + C_\lambda$ is a real variable function, C_λ is a constant value selected by the program.

The Box-Cox variable allows us to plot the sum of squared residual versus the operator value. The best value is the value that provides the minimum function.

The variable technological parameters of the experiment are cutting speed and feed, an additional parameter (block coefficient) is the "state of the cutting tool" expressed in the accumulated cutting length. Table 4 shows the natural and normalized levels of the experimental design factors.

Table 4. Plan of factor level

Main factor level	Blocked factor level	Factors		
		Number of holes (block factor)N (X_3)	Feed rate, s mm/rot, (X_2)	Cutting speed mm/min, (X_1)
1	1	1-10	0,06	13.5
0	2	11-20	0,04	9,8
-1	3	21-30	0,03	4.9

There were no particular difficulties in determining the natural level of the feed rate factor. A feed has a defined exact discrete number.

Values not exceeding 0.06 mm/rot can be considered, taking into account the recommendations for setting cutting conditions with a range of allowable feed. The range of drilling speed levels is even wider. For a drill with a diameter of 10 mm, this range corresponds to the following range of cutting speeds.

The calculation of the natural value of the accumulated cutting length for each of the three blocks was carried out according to the sequence of experiments in the plan of experiments (Table 4.2), according to the formula below, taking into account the drilling speed and the thickness of the processed PKM material.

$$l_k = \sum_{i=1}^{k} \frac{\pi d h}{s_i}, \tag{28}$$

where d is the diameter of the tool, h is the thickness of the material, si is the feedin the i-th experiment, k is the experiment number needed to determine the accumulated cutting length.

Based on the sum of the measured diameters, the deviation of the longitudinal cross-sectional profile was calculated.

Several diameters were measured by scanning 300 points from each circle to determine the variation of the hole diameter in different radial sections, the measurement scheme is shown in Figure 4.

Experimental studies were conducted to determine the effect of the presence of cooling technological means during drilling on the accuracy of the holes and the roundness of the hole.

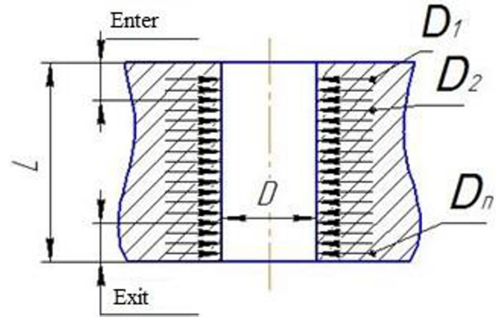


Fig. 4. Scheme for measuring hole diameters.

$$\Delta = \frac{D_{max} - D_{min}}{2} \tag{29}$$

Here Dmax and Dmin are the values of the maximum and minimum diameters $D_{1/1} - D_{1/5}$ $D_{2/1} - D_{2/5}$

The average value of the recorded roughness V was determined and used in all subsequent calculations. The contact method does not allow you to get an informative picture of the roughness in the part, because the surface of the part after processing is significantly different from the metal. The optical method of roughness measurement is devoid of these disadvantages, since there is no direct contact with the sample during measurement. PKM roughness was observed using an optical interference microscope using a Bruker ContourGT-K1 profilometer.

Regression equations make it possible to determine the change in the deviation of the longitudinal cross-sectional profile of this or that effect from the sign and value of the coefficient. The X1 2nd factor was found to be the most significant regressor, followed by X2 thrust and X1 cutting speed, with X3 2nd representing the path traveled by the cutting tool having the least influence.

The minimum value of the function corresponds to the minimum value of feed and the average value of speed. Thus, if it is necessary to increase the performance with a minimal effect on the deviation of the profile of the longitudinal section, the increase in the amount of feed should be considered first.

Profile deviation Δ helps to complete deviations of the longitudinal profile when drilling holes in the part.

$$\Delta_{det} = 3{,}31 + 0{,}6X_2 + 0{,}74X_1X_2 + 0{,}66X_3^2 \tag{30}$$

The coefficients of determination for Δ PKM are 0.52, respectively;

The analysis of the surfaces shows that the deviation of the profile of the longitudinal section gives the PKM layer.

The maximum determined value is observed when s=0.055 mm/rot and minimum speed v=6.33 m/min, as well as maximum speed v=13.1 m/min and minimum feed s= 0.031 mm/min. At the limit of the minimum defined values lies the limit of average values of velocities, for the first layer there is no feed effect, for the second it is minimal. The deflection response surface of the longitudinal section profile shows that the maximum amount of feed is s=0.055 mm/rot and the cutting speed is v=13.1 m/min, while the minimum is the cutting speed v = 13.1 m/min and the minimum feed is s = 0.031 mm/min, which is observed at the corresponding maximum speed. The most common methods of cutting the part (maximum speed, minimum feed).

The block coefficient X3 (the number of drills) almost does not change the shape of the response surfaces, but directs it to an increase in the value of the specified. To visually demonstrate the change in the shape of the hole with depth, we record the values of the diameters of the holes for all radial sections on the graph (Fig. 4.6).

It should be noted that the graphics of other holes treated during the experiment have the same shape. To compare the profile of the longitudinal section with diameters, they must be doubled, since the profile of the longitudinal section is calculated based on the radius, not the diameter.

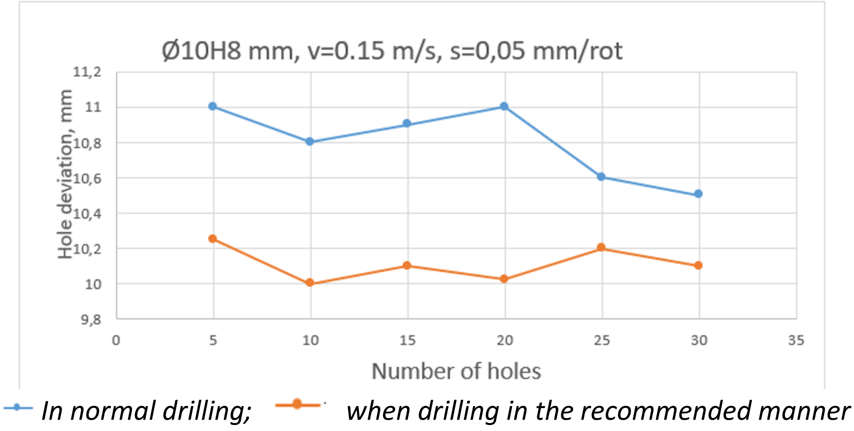


Fig. 5. The graph of the deviation of the diameter of the hole from the diameter of the drill

Due to the small size of the hole in the part diameter, the effect of the linear expansion coefficient of the PKM is almost unchanged. An increase in diameter is observed at the end of drilling.

In the process of studying the deviations from the cylinder, no statistically significant regularities were found regarding the factors of cutting speed, feed and length.

An analysis of the variation intervals shows that there are external suppliers of 42-46 μm that are not circulating. Large values of the controlled parameter are associated with the anisotropy of its properties, the presence of microcracks and uncut fibers.

Correspondence of holes to surface roughness is one of the main criteria of their quality. Roughness affects the durability, fatigue strength and corrosion resistance of parts. For metal alloys, the effect of cutting conditions on surface roughness is well understood. The microrelief of holes in PKM is difficult to study and predict because cracks and uncut fibers appear. The roughness of the holes in mixed packages is even less studied, so a number of studies are needed to identify the surfaces.

Let's look for a regression model for the most common microrelief parameters in production. The designation of the factors in the models is as follows: X1 (cutting speed), X2 (feed), X3 (number of holes).

In normalized form, the regression models for the Ra parameter are as follows:

$$R_{a_{det}} = 3{,}22 - 0{,}43\mathrm{X}_1 \tag{30}$$

The coefficients of determination for Ra PKM are 0.32, respectively. The smallest coefficient value means that PCM drilling is less predictable than metal drilling. This is related to the structural properties of the composite material and the anisotropy of its properties.

Part surface roughness Ra is very different from similar surfaces for metal. There is no feed effect for Ra, but a significant effect of cutting rate. As the cutting speed increases, the roughness decreases because the more dynamic cutting process helps to cut the part fibers cleanly. The normalized regression models for the second stiffness parameter Rz have the following form:

$$R_{det} = 31{,}86 - 3{,}18\mathrm{X}_2 - 4{,}03\mathrm{X}_1 + 4{,}79\mathrm{X}_2^2 \tag{31}$$

No statistically significant effect of speed on Rz parameter was found. An interesting relationship was found for the Rz parameter in the part layer. Here, in contrast to the Ra parameter, the flow effect appeared not only linear, but also quadratic. In the Ra parameter, the effect of speed has a minus sign. Thus, the Rz parameter in the partl layer takes minimum values at high cutting speed v=13.5 m/min and average feed speed s=0.04 mm/rot, maximum values at low cutting speed v=4.9 m/min, s=0.03 mm/rot and higher thrust s=0.06 mm/rot.

Above, we considered the main factors affecting surface roughness. Technological methods of its reduction depend on these factors.

First of all, it is necessary to use a technological machine tool and a quality cutting tool. In addition, cutting parameters can be optimally selected in terms of surface roughness. It is known that increasing the cutting speed and reducing the depth of cut and the number of feeds improves the surface roughness. In the same way, the use of cooling-lubricating fluids in the cutting process leads to an increase in surface cleanliness by facilitating the cutting process.

According to the results of the test, the use of the drilling method for better crushing and removal of cuttings from the cutting zone and reduction of the adhesion level allows to reduce the cutting speed to 0.3-0.6 mm compared to 1.05-1.3 mm with the existing method. Surface roughness decreases from Ra 7-8.5 microns to Ra 5.5-6.2 microns.

Thus, there are no disadvantages in processing with periodic stopping of the pushing movement of the drill, which ensures the improvement of the reliability of the drill and the achievement of the quality of the processed holes.

The tests consisted of successive drilling of holes at specified cutting rates (v=8.8 m/min, s=0.050 mm/rot). The diameter of the hole was measured in one central section. The graph (Fig. 4.7) shows the deviation of the diameter of the holes from the diameter of the drill.

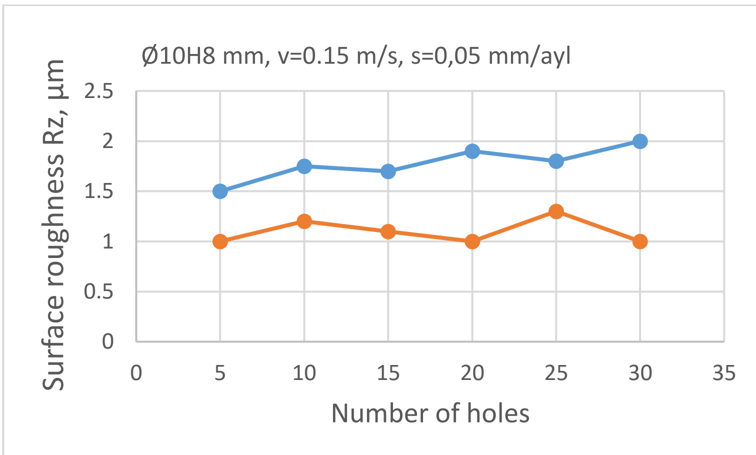
According to the results of field tests, it works with 30 hole resistance, which ensures that the diameters of the holes are below 0.27% of the defect level. The range of variation in the diameters of the holes is 26 μm, the maximum permissible value is 30 μm, which made it possible to obtain holes of the 9th level of accuracy. The proposed method of 30 holes has a diameter variation of 32 μm, which allows to obtain holes of the 10th accuracy class.

Table 5. Hole diameter statistics

Drilling	Number of drilled holes	The average deviation of the diameters of the holes, mm	Standard deviation δ, mm

Drilling in the existing method	10	D_c+0.016	0.005
	20	D_c+0.015	0.008
	30	D_c+0.014	0.0086
Drilling in the proposed method	10	D_c+0.009	0.0035
	20	D_c+0.008	0.006
	30	D_c+0.007	0.007

Using a profilometer, the Rz parameter of the hole's roughness is measured. The drawings show the roughness of the walls of the number of holes processed in the figures. Figure 3.8.



In normal drilling; when drilling in the recommended manner

Fig. 6. The roughness of the holes

By comparing the average values for the performance of different methods (10, 20, 30 holes), we evaluate the compliance of the roughness with the specified tolerance level. Hole roughness statistics are given in Table 6. After processing 30 holes, the roughness Ra does not exceed 1.31 µm, the average value is Ra 0.63-0.71 µm. The average roughness Ra is 3.64 µm with a maximum value of Ra 4.98 µm among 30 machined holes.

Table 6. Surface roughness statistics

Drilling	Number of drilled holes	R_z, µm	
		Average	Maximum
Drilling in the current method	10	3.05	4.05
	20	3.1	3.86
	30	3.96	4.68
Drilling in the proposed method	10	2.55	2.56
	20	2.6	3.38
	30	2.7	2.35

The proposed drilling method gives the best surface roughness. Successful tests of the proposed method made it possible to introduce them into production.

Table 7. Surface accuracy when drilling in the normal drilling method

Number of holes	When drilling in the normal drilling method	When drilling in the recommended method	Number of holes	When drilling in the normal drilling method	When drilling in the recommended method

	Surface accuracy Δ , mm			Surface accuracy Δ , mm	
1	0.2	0.1	16	0.15	0.15
2	0.3	0.15	17	0.15	0
3	0.4	0.15	18	0.1	0.1
4	0.3	0.1	19	0.4	0.1
5	0.25	0	20	0.3	0.15
6	0.22	0.01	21	0.25	0.15
7	0.3	0.02	22	0.22	0.1
8	-0.1	0.03	23	0.3	0.15
9	0.1	0.05	24	-0.1	0.15
10	0	0.2	25	0.3	0.1
11	0.1	0	26	-0.1	0
12	0.15	0.1	27	0.1	0.01
13	0	0.15	28	0	0.02
14	0.1	0	29	0.1	0
15	0.1	0.1	30	0.15	0.1

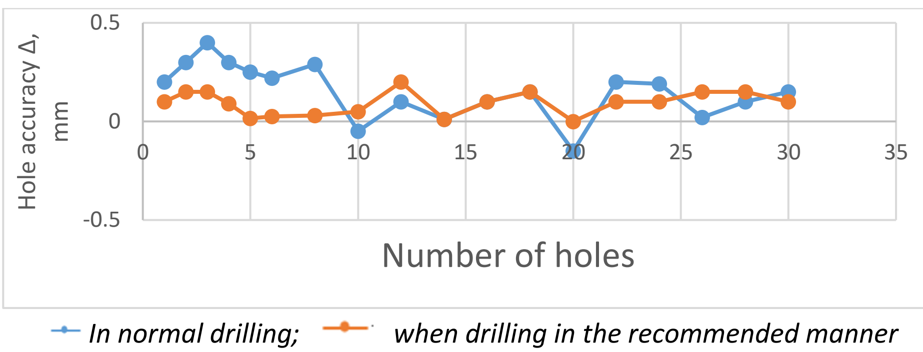


Fig. 7. Surface accuracy comparison chart

In turn, we can know that the processing accuracy is high in the proposed method.

From the above graph, the accuracy of the hole Δ is obtained. As can be seen from the graph, we can see that the accuracy of the hole in the part was higher when we processed it with 2 different recommended methods than the normal method.

4 Conclusion

1. The content and sequence of technological transitions that determine the structure of operations performed on a multi-purpose CNC machine directly affect the consumption characteristics of the main types of production resources, an original methodological approach is proposed for their determination.
2. A set of T-complexes unites intersecting subsets, the complexes of each of which, if the necessary conditions are met, can be processed by the same type of common tool.
3. The possibility of producing several T-complexes with one device of a certain type from its own set is evaluated by fulfilling the necessary conditions that are individual for each combination of produced T-complexes.
4. The technical indicators of the implemented schemes for the operation of a set of T-complexes with one tool, as well as the variable indicators of the incomplete production costs for performing the relevant operations, are reliably determined by the developed methodology, fixed codes of the complexes, technological methods and types of tools.

5. The low productivity of the cutting process during drilling has a great impact on the stability of the drill. For numerically controlled machines, a method for controlling the movement of cutting and pushing movements of shavings of predetermined length in drilling has been developed.

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