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Correction of the Control Program for End Milling on a CNC Machine

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Abstract. *The results of experimental testing of the correction of the CNC-programs for end milling on a CNC machine are presented. The correction is performed for serial and single-piece production conditions using the method of control using a posteriori information. A posteriori information is determined during measurements directly on the CNC machine with a three-coordinate probe from Renishaw. Moreover, for serial production, the pre-machined part is measured, and for single-piece production, the machining allowance is divided into two parts and the surface machined in the first pass is measured. The correction is performed using the experimentally determined transfer function of the machining system. The effectiveness of the developed methods has been experimentally proven: after milling the first part, the average error was 0.1 mm, and after machining the second part (and subsequent ones) using the corrected control program, the error decreased to 0.012 mm, i.e. the machining accuracy is increased by more than 8 times. In the conditions of single production, when dividing the allowance into two parts and determining the correction according to the calculated transfer function, the machining error decreased by more than 6 times. The time loss for performing two passes in the conditions of single production does not exceed the machining time according to traditional technology, when to ensure the specified accuracy, it is necessary to perform several passes according to the same control program.*

Keywords: *a posteriori control method, end milling, correction of the CNC program.*

1. Introduction

End milling operations are most common in the aviation and automotive industries, in the manufacture of dies and molds, and are performed on CNC machines. The accuracy of milling depends on many factors, which are divided into random and deterministic, and for accuracy control it is recommended to use various methods [1], among which, depending on the type of production, control by a posteriori information is possible.

When using this method in serial production, the control program correction for the machining of the next part is performed based on the results of measuring the previous one. This technology involves the creation of an automatic control system that operates with a delay for the machining of one part. Control by a posteriori information during control program correction can compensate for all systematic components of the error, but it is impossible to reduce the influence of the random component. To implement control by a posteriori information, it is necessary to use a CNC machine and organize an automatic control system using control and measuring machines. In some cases, when machining on CNC machines, control can be organized directly on the machine.

When machining one part, an adjusted a posteriori information control method should be used, which consists in dividing the allowance into two parts, and the correction when removing the second part of the allowance is performed according to the results of measuring the part after removing the first part of the allowance. It is clear that such a method is advisable to use when machining complex surfaces of critical parts by contour milling, such as pump housings for nuclear power plants [2].

Thus, the problem of eliminating errors in end milling using a posteriori information control methods remains an urgent task that requires experimental testing, which will significantly increase the effectiveness of the method.

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2. Analysis of the state of the problem

The study of cutting processes, including end milling machining, has been carried out by many scientists, among whom the works of Professor Y. Altintasa [3] are characterized by the most comprehensive approach, when the process is considered taking into account dynamic phenomena based on a mechanistic model of the cutting process in a dynamic machining system. The author proposes modeling the mechanics of metal cutting, when the models include orthogonal to inclined transformation of cutting, mechanistic modeling of cutting coefficients, a field of slip lines and modeling by the finite element method. The author focused mainly on milling. The prediction of cutting force, torque, power and dimensional surface treatment for milling operations is explained. However, the developed models involve the use of a priori information about the process, which is not always possible in production in the absence of additional research to determine the necessary parameters of the machining system. Thus, predicting machining accuracy under conditions of uncertainty of many parameters of the machining system is problematic.

Recently, high-resolution virtual simulation of multi-axis machining processes has been widely used for machining process control, which plays an important role in the production of complex parts in various industries [4]. To ensure surface quality at high productivity, it is necessary to optimize process parameters such as spindle speed, feed and cutting depth using an accurate milling process model, which requires both rapid virtual prototyping of the machined part geometry to verify the tool path and accurate definition of the cutter-workpiece interaction to predict the cutting force. A three-dimensional method is also proposed here, which is based on calculating the instantaneous engagement area of the plunge angle, which is obtained by merging the intersection points between the edges of the lower-level voxels and the surface of the cutter tooth, which are then trimmed by possible contact arcs determined using the envelope theory. This approach to cutting process control relies on a priori information that is difficult to identify in real production.

To ensure the required machining accuracy, it is recommended to use the developed precision methods for CNC machine tools, which allow for separate analysis of geometric, kinematic and thermal errors [5]. However, the practical apparatus for such analysis is not specified. At the same time, the proposed method of numerical compensation of elastic deformations on CNC machine tools is an indisputable achievement. The digital twin, which is the basis, represents physical relations based on the prediction of accuracy due to error and digital methods of numerical compensation of elastic deformations. A review of these studies shows that the main thing is to create a digital twin that uses a priori information about the system.

The most difficult task is to ensure accuracy during the end milling of thin-walled parts used in the aerospace industry [6]. The main problem associated with milling thin-walled components is the static deviations of the cutter and workpiece caused by the cutting force, which manifest themselves in the form of surface errors on the finished parts. One approach to ensuring accuracy is to use conservative cutting conditions and multi-pass machining to limit the cutting forces. This approach reduces the surface error, but significantly reduces the machining productivity. It is proposed to compensate for the combined errors caused by the deviations of the tool and workpiece using a cutting force model that takes into account the change in the geometry of the process due to the deviation. The results of the location of the error along the milling width due to elastic bending of the tool are also presented.

The accuracy and productivity of the machined flexible parts depend on the deformation errors during milling [7]. Therefore, predicting and compensating for deformation errors during milling of flexible parts can be a key tool for improving the precision of parts manufacturing. This study proposes an improved virtual machining system to estimate and compensate for deformation errors caused by temperature and cutting forces during 5-axis milling of flexible parts. The improved Johnson-Cook model is used to investigate the combined effects of strain rate and temperature on yield stress during milling of a turbine blade. The finite element method is used to estimate the deformation errors caused by cutting forces and temperature on the workpiece and cutting tool. As a result, volumetric deformation error vectors are generated at each cutting location along the machining paths, which can be compensated in the new compensated machining tool paths. Thus, the deformation error caused by cutting forces and temperature on the workpiece and cutting tool is compensated by the developed prediction model. It should be noted that the calculation of the correction does not take into account the closedness of the machining system, which will negatively affect the effectiveness of the method.

To ensure the required accuracy when milling thin-walled components of parts, it is proposed to use the developed mathematical model based on the finite element method for milling thin-walled aluminum alloys of aerospace grade [8]. To model the interaction between the screw mill and the workpiece, a Lagrangian formulation with an explicit solution scheme was used. The behavior of the material at high deformation, deformation rate and temperature was determined using the Johnson-Cook constitutive material model. The damage law and the Johnson-Cook friction law were used to account for chip separation and contact interaction. Experimental work was carried out to verify the results predicted by the mathematical model. It was found that the model predicts the process performance parameters well, namely cutting forces, wall deflection and chip dimensions. The developed model predicted forces in the radial, feed and axial directions. The developed model was used to investigate the influence of process parameters on performance parameters, namely: cutting and axial forces, stress distribution, cutting temperature, part deflection and chip morphology, which is not possible with a two-dimensional orthogonal or oblique cutting model. It was found that the developed three-dimensional mathematical model provides a very useful understanding of the complex physical interaction of the helical cutting tool and the workpiece during thin-walled milling of aerospace alloys.

End milling is widely used for machining thin-film parts, which play an increasingly important role in the aerospace industry, due to the advantages of high machining accuracy and high surface quality. In [9], a systematic method for predicting and compensating for wall thickness errors in milling thin-film parts is proposed. The errors are caused by static deflections caused by the variable cutting force applied to a non-rigid part. To improve the efficiency of calculating the deformation of the part, a new finite element model (FEM) is first developed by combining the methods of substructure analysis, special mesh generation, and static stiffness modification of the structure. Then, based on the proposed FEM model, the time- and position-dependent deformations of the part are calculated to predict the wall thickness errors remaining on the finished part.

The relevance of the problem of compensation of errors from elastic deformations in end milling is evidenced by the publication [10], which states that there is currently a lack of research devoted to the manufacture of thin-walled parts with high dimensional accuracy. This article investigates the characteristics of micromilling of titanium alloy for the manufacture of thin walls. First, micromilling experiments are conducted using straight polycrystalline diamond end mills with different rake angles. A comparison of the influence of tool shape on cutting force, cutting temperature, thin-wall size error, tool wear and surface morphology is systematically analyzed, and the optimal cutting-edge shape is determined. Second, a deformation prediction model for titanium alloy micromilling is created and calibrated. It is argued that the model can be used for online compensation of thin-wall deformations.

To meet demand, particularly in small-scale production, it is necessary to increase labor productivity per worker by reducing order fulfillment times [11]. Automated generation of tool path motion is one of the means of reducing order fulfillment times. However, generating CNC programs that allow for high-precision machining requires a huge amount of time and labor, since it is necessary to modify the programs according to the results of trial cutting and review of machining conditions. One of the factors causing machining errors during cutting is considered to be the deformation of the workpiece due to clamping in the vice. Therefore, even if the dimensional tolerance measured on the machine tool is met, dimensional errors may occur when the workpiece is removed from the vice. The purpose of this study is to implement automated generation of CNC programs for high-precision pocket machining. In this study, a system is developed that predicts the elastic deformation of the workpiece due to the clamping force using the finite element method and automatically generates a machining tool path that satisfies the dimensional tolerance when the workpiece is removed from the vice. The case study confirms that the proposed system can automatically generate tool paths, which improves the machining accuracy.

In [12], a voxel-based method is developed to model the machining error caused by the elastic deformation of the tool and workpiece during end milling. The shapes of the tool and workpiece are represented by a set of cutting-edge points and a voxel model, respectively. The cutting force is calculated based on the contact state between the cutting-edge points and the workpiece voxels. The elastic deformation is analyzed based on the elastic deformation models of the tool and workpiece and the predicted cutting force. The tool deflection is predicted using a composite cantilever beam and spring model. In addition, each voxel representing the workpiece is connected to the neighboring voxels using beam elements to construct the stiffness matrix of the workpiece. The stiffness matrix and the predicted cutting force are used to predict the deflection of the workpiece. The predicted workpiece deflection is converted into tool deformation, which keeps the geometric relationship between the tool and the workpiece equivalent. Taking into account the tool deflection and the deformation corresponding to the workpiece deflection, the cutting-edge trajectory is modeled.

Thus, the lion's share of publications devoted to the correction of the control program during final milling on a CNC machine tool one way or another use the initial a priori information about the process for calculations and modeling. Such information must contain the parameters of the cutting process and the dynamic elastic machining system, which creates significant obstacles for application in production since in each case it requires determination and experimental measurements.

At the same time [13] the possibility of controlling the accuracy of contours directly on a CNC machine tool equipped with a three-coordinate contact probe has already been proven. A method for controlling the accuracy of the contours of parts is presented, which is based on measuring with a three-coordinate contact probe according to the developed control program using standard CNC commands with automatic data entry into a file [14]. The created application program performs demonstration and visualization of the results. The milling control program in the form of G-codes and a measurement data file are loaded into the application program, and all the results necessary for assessing accuracy appear in the graphic window. In addition, even for parts of complex shape, a posteriori information in the form of a digital file of the machined surface can be obtained directly on the machine using OMV technology – On Machine Verification [15].

Therefore, the method of controlling the end milling process, based on the use of a posteriori information in both serial and single production, which has significant advantages when applied in production, since it does not require complex calculations according to the developed model, remains insufficiently studied and requires experimental verification.

3. Purpose and objectives of the study

The purpose of this work is the experimental testing of the proposed technology for ensuring the accuracy of final milling on a CNC machine by compensating for errors under conditions of serial and single production using the correction design method using a posteriori information obtained from measurements of the machined surface directly on the machine.

To achieve the goal, it is necessary to:

– conduct an experimental study of the method for compensating for milling errors using the technology of a posteriori information obtained when measuring a pre-machined part;

– conduct an experimental study to determine the effectiveness of the developed correction technology when dividing the allowance into two parts based on the results of measurements of the surface machined in the first pass.

4. Materials and methods of research

The object of research is the process of final milling on a CNC machine tool. The subject of research is the accuracy of machining and compensation of error by correcting the control program in accordance with the method of control by a posteriori information.

The experiments were carried out on an OKUMA MA-600HB CNC machine using measuring equipment in the form of a Renishaw OMP60 probe using OMV (On-Machine Verification) technology [15]. To conduct experimental testing of the proposed technology, a workpiece made of Steel 20 was used, installed with an angular inclination to the coordinate axes, which allows simultaneously assessing the influence of elastic displacements along the *X* and *Y* axes. The machining was performed by mill ∅16 mm carbide cutter with four teeth.

The methodology includes:

– construction of the initial CNC-program designed based on the results of measurements of the actual position of the workpiece on the machine tool with a Renishaw probe;

– execution of the first pass and measurement of deviations of the machined surface with a probe on the CNC machine tool;

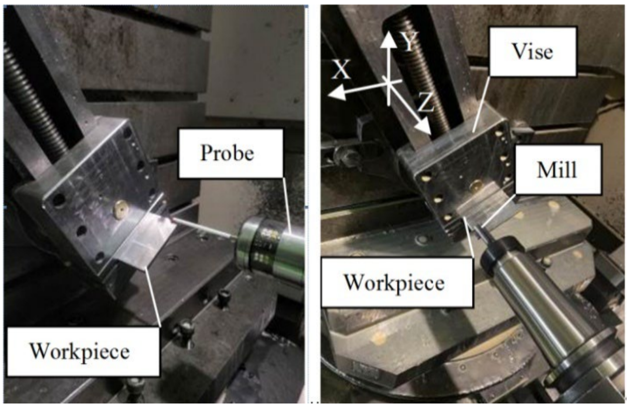
– calculation of errors and determination of the transfer function of the machining system;

– design of an adjusted trajectory taking into account elastic deformations and construction of a new adjusted control program for compensation.

The proposed approach allows creation corrective control taking into account real cutting conditions and actual behavior of the system, which increases the machining accuracy without reducing productivity.

5. Research results

For experimental research, a rectangular surface milling scheme was chosen, but for the use of two shaping coordinates, the part is located at a certain angle to the machine axes (Fig. 1). This ensures greater versatility of the experimental results obtained. The workpiece is installed on the machine table in a vice that is turned at a certain angle to the coordinate axes.

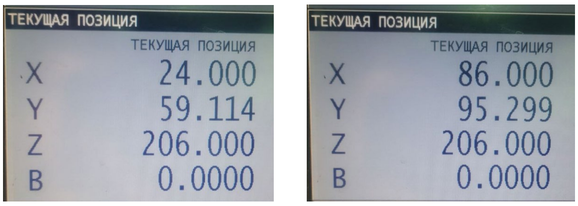


a *b*

Fig. 1. Scheme of the technological operation: *a* – coordinate measurement, *b* – surface milling

5. 1. Testing the correction technology in serial production conditions

To mill the first part, it is necessary to determine the actual angle of inclination of the part relative to the *X* axis, to do this, take measurements using a probe at the beginning and end of the part and record the coordinates at these points. The measurement results from the CNC system screen are presented in Fig. 2.



```
ТЕКУЩАЯ ПОЗИЦИЯ
     ТЕКУЩАЯ ПОЗИЦИЯ
X         24.000
Y         59.114
Z        206.000
B         0.0000
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ТЕКУЩАЯ ПОЗИЦИЯ
     ТЕКУЩАЯ ПОЗИЦИЯ
X         86.000
Y         95.299
Z        206.000
B         0.0000
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a *b*

Fig. 2. Coordinates of the beginning (*a*) and end (*b*) of the workpiece

So, according to the results of measurements with a Renishaw probe, the actual coordinates at the ends of the workpiece are: beginning (x_1 = 24 mm, y_1 = 59.114 mm), end (x_2 = 86 mm, y_2 = 95.299 mm). The actual angle of inclination of the part relative to the *X* axis is calculated by the formula: $\alpha = \arctan\left(\left(y_1 - y_2\right)/\left(x_1 - x_2\right)\right)$.

To level the milling allowance, a control program was designed taking into account the actual inclination angle ($\alpha = 30.27°$) for a cutting depth of 0.2 mm. The control CNC-program is designed taking into account the geometric relationships of the technological scheme:

$$\begin{cases} x_s = x_1 - (R_m - r)\sin\alpha - \delta y / \tan\alpha \\ y_s = y_1 + (R_m - r)\cos\alpha - \delta y \end{cases}, \quad (1)$$

where x_s, y_s – coordinates of the starting point of the CNC-program, r – radius of the Renishaw probe ball, R_m – radius of the mill, δy – distance for idle speed when cutting the mill.

To ensure a given depth H, the CNC-program cutting is designed according to the coordinates:

$$\begin{cases} x_{sCNC} = x_s + H\sin\alpha \\ y_{sCNC} = y_s - H\cos\alpha \end{cases}, \quad \begin{cases} x_{eCNC} = x_s + H\sin\alpha + L\cos\alpha \\ y_{eCNC} = y_s - H\cos\alpha + L\sin\alpha \end{cases}, \quad (2)$$

where x_{sCNC}, y_{sCNC} – start coordinates, x_{eCNC}, y_{eCNC} – end coordinates, L – workpiece length with a given-out run.

Table 1 presents the machining programs for milling to a depth of 0.2 mm and a depth of 2 mm in G-codes. The same standard cutting mode for the workpiece material and the milling cutter was used: the milling cutter spindle speed was 2580 rpm and the feed was 400 mm/min.

Table 1. CNC-program in G-code

H = 0,2 mm	H = 2 mm
T46M6 G15H5G0B0 S2580M3 G0X5Y53.582 G56H46G90Z100 G0Z3M51 G1Z-15F400 G1X105Y111.947F516 G0Z200M9M5 G30P5 M2	T46M6 G15H5G0B0 S2580M3 G0X5Y51.266 G56H46G90Z100 G0Z3M51 G1Z-15F400 G1X105Y109.631F516 G0Z200M9M5 G30P5 M2

The execution time of the entire program was 24 seconds, the milling of the surface took place in 14 seconds. After milling, the machined surface was measured directly on the machine using a length probe (x coordinate) with a step of 15 mm. The results are presented in Table 2, where y_c is the coordinate commanded by the program, y_a is the actually machined coordinate.

Table 2. Coordinate data of the machined workpiece

No.	1	2	3	4
x, mm	35	50	65	80
y_c, mm	62.987	71.741	80.496	89.25
y_a, mm	63.091	71.845	80.601	89.353
δ, mm	0.104	0.104	0.105	0.103
MSy	0.05485	0.05485	0.05541	0.05430

In table 2, for each coordinate x, the coordinate y_c of the machined surface commanded by the CNC-program is calculated using formulas (1), and the error is defined as the difference: $\delta = y_a - y_c$, where y_a is the measured actual coordinate of the machined surface. Taking into account the closedness by the loop control naturel of the machining system with respect to the coordinate y, it is possible to determine its transfer function MSy with respect to this coordinate from the measurement results. For this purpose, the process control scheme with a posteriori information can be used (Fig. 3) [2].

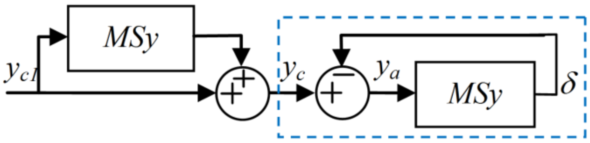

Fig. 3. Control scheme based on a posteriori information

From the scheme, where the machining system is highlighted by a dashed rectangle, according to the rules of structural diagram transformation, it is possible to determine:

$$\frac{\delta}{H} = \frac{MSy}{1 + MSy}. \quad (3)$$

On this:

$$MSy = \frac{\delta}{H - \delta}. \quad (4)$$

The transfer function values calculated by formula (4) for each coordinate x are presented in Table 2, and the average value of the transfer function is $MSy_{av} = 0{,}05485$. In accordance with the accepted practice in production, to eliminate the error that has arisen, a second pass is made using the same control program. The data measured after milling are presented in Table 3.

Table 3. Measurement results after the second pass

No.	1	2	3	4
x, mm	35	50	65	80
y_c, mm	62.987	71.741	80.496	89.25
y_a, mm	63.003	71.757	80.511	89.265
δ, mm	0.016	0.016	0.015	0.015

It can be seen that the remaining error decreased by almost 6.5 times, but the same time was spent on such a pass under the condition of a constant cutting mode.

Now, using the technology of control program correction using a posteriori information, it is possible to design an adjusted control program for machining subsequent parts, using the determined transfer function and control scheme according to Fig. 3. To maintain identical experimental conditions, preliminary milling was also performed here, which equalized the allowance along the machining length. Therefore, based on the milling program for a cutting depth of H = 0.2 mm, and the calculation of the transfer function of the MSy machining system from the first part, it is possible to design an adjusted control program for a cutting depth of H = 2 mm. The coordinates x_{sCNC} of starting and x_{eCNC} ending will remain the same as in the previous program, and the new coordinates y_{sCNC} of starting and y_{eCNC} of ending are calculated by the formula:

$$\begin{cases} y_{sCNC} = y_{sCNC(0,2)} - \dfrac{H\left(1-MSy_{av}\right)}{\cos\alpha} \\ y_{eCNC} = y_{eCNC(0,2)} - \dfrac{H\left(1-MSy_{av}\right)}{\cos\alpha} \end{cases}, \qquad (5)$$

where $y_{sCNC}(0,2)$, $y_{eCNC}(0,2)$ – coordinates of the start and end of the trajectory according to the preliminary processing with a cutting depth of 0.2 mm.

The measurement results after milling according to the program adjusted in this way to a depth of 2 mm are presented in table 4.

Table 4. Coordinate data of the processed workpiece

No.	1	2	3	4
x, mm	35	50	65	80
y_c, mm	63.714	72.463	81.212	89.961
y_a, mm	63.727	72.475	81.224	89.974
δ, mm	0.013	0.012	0.012	0.013

The results obtained show that the machining error has decreased even compared to the error remaining after the second pass. Thus, all subsequent parts of the batch can be machined according to the corrected program, without wasting time on repeated passes.

It should be noted that all measurements of the machined surface were performed directly on the machine tool using a three-coordinate probe and presenting the results on the CNC machine tool racks.

5. 2. Testing the correction technology in single-piece production conditions

According to the developed technology, in single-piece production conditions, to obtain a posteriori information about the process, it is necessary to divide the allowance into two parts, mill the first part of the allowance, carry out measurements to determine the corrective transfer function and design a milling program for the second part of the allowance.

At the beginning of the experiment, it is necessary to determine the actual angle of inclination of the part relative to the X axis, for which measurements are taken using a probe at the beginning and end of the part and record the coordinates at these points, similar to the previous experiment. To maintain identical milling conditions for both experiments, it is first necessary to perform a preliminary milling to a depth of 0.2 mm to equalize the allowance along the machining length. After appropriate measurements using formulas (2), it is possible to design control programs for the preliminary and first pass to a depth of 1 mm, the G-codes of which are presented in Table 5. The cutting mode is adopted as for the previous experiment.

Table 5. CNC-programs in G-code

H = 0,2 mm	First pass
T46M6 G15H5G0B0 S2580M3 G0X5Y54.071 G56H46G90Z100 G0Z3M51 G1Z-15F400 G1X105Y112,459F516 G0Z200M9M5 G30P5 M2	T46M6 G15H5G0B0 S2580M3 G0X5Y52.913 G56H46G90Z100 G0Z3M51 G1Z-15F400 G1X105Y111.301F516 G0Z200M9M5 G30P5 M2

After milling in accordance with the developed technology, it is necessary to measure the machined surface using a probe on the machine tool along the length with a step of 15 mm. The obtained data are presented in Table 6.

Table 6. Coordinate data of the machined workpiece

No.	1	2	3	4
x, mm	35	50	65	80
y_c, mm	64.639	73.396	82.154	90.911
y_a, mm	64.714	73.471	82.229	90.987
δ, mm	0.075	0.075	0.075	0.076
MSy	0.08108	0.08108	0.08108	0.08225

The transfer function MSy for correcting the control program when milling the second half of the allowance can be determined using formula (4). For use in designing the corrected control program for milling the second half of the allowance, it is also advisable to use the average value of this transfer function MSy_{av} = 0.08137.

Now, based on the milling program for the first half of the allowance with the cutting depth of 1 mm, and the calculation of the transfer function of the MSy machining system, it is possible to design a corrected CNC-program for milling the second half of the allowance. The coordinates x_{sCNC}, x_{eCNC} will remain the same as in the previous program, and the new coordinates y_{sCNC}, y_{eCNC} are calculated using formula (5). After calculating the new coordinates y_{sCNC}, y_{eCNC}, the results are implemented in the adjusted CNC-program for milling the second half of the allowance in fig 4.

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T46M6
G15H5G0B0
S2580M3
G0X5Y51.661
G56H46G90Z100
G0Z3M51
G1Z-15F400
G1X105Y110.049F516
G0Z200M9M5
G30P5
M2
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Fig 4. G-codes of the CNC-program for milling the second half of the allowance

To determine the results obtained, it is necessary to measure the coordinates of the machined surface with a probe on the machine tool also along the length of the part with a step of 15 mm (table 7).

Table 7. Coordinate data of the machined workpiece

No.	1	2	3	4
x, mm	35	50	65	80
y_c, mm	63.481	72.238	80.996	89.753
y_a, mm	63.492	72.249	81.008	89.764
δ, mm	0.011	0.011	0.012	0.011

The measurement results indicate a significant reduction in machining error compared to machining the workpiece in one pass (see Table 2).

6. Discussion of the results of correction by a posteriori information

The results of experimental studies presented in the article confirm the effectiveness of the method of ensuring the accuracy of final milling with control by a posteriori information. The method consists in using information about the cutting process obtained as a result of measurements of the machined surface of the part. At the same time, the possibility of compensating for errors regardless of the nature of their occurrence is ensured, since the information obtained as a result of measurements contains the integral result of the influence of all factors on the process. This is an indisputable advantage of the method in comparison with methods based on the use of a priori information, which is concentrated in the mathematical model of the process. At the same time, the developed method involves the organization of permanent measurements in the production process, that is, the creation of an automatic control system that operates with a time delay for the processing of one part.

The method is also proposed for use in the manufacture of one part. Here it is recommended to divide the machining allowance into two parts, to use information about the process (for example, in the form of a geometric size) when performing a correction for machining the second half of the allowance.

In both cases, the system should include control programs for automatic measurement using OMV technology – On Machine Verification. Such programs are included in the provision of many CNC machines, when using three-component measuring probes, for example, from Renishaw. The possibilities of such control are significantly expanded when using strain gauges [15], which are capable (together with the appropriate software) of controlling complex shapes of machined surfaces.

The conducted practical testing of control methods has fully proven their effectiveness and prepares the basis for use in ensuring the accuracy of final milling operations of complex surfaces [2].

7. Conclusions

1. For serial production conditions, an approach was implemented in which measurements and analysis of the machined surface were performed only for the first part of the series. After milling the first part, the average error was 0.1 mm, and after machining the second part (and subsequent ones) using the adjusted control program, the error decreased to 0.012 mm, i.e., the machining accuracy increased by more than 8 times.

2. According to traditional technology, accuracy is increased by repeated milling using the same program. The experiment proved that because of this, 48 seconds were spent on machining, and when milling using the adjusted CNC-program, 24 seconds were spent to obtain the same accuracy, which halves the machining time.

3. In the conditions of single production, when dividing the allowance into two parts after the first pass, the error was 0.07 mm, and after the second pass according to the adjusted control program, the error decreased to 0.011 mm, which proves the possibility of increasing the machining accuracy by correction by more than 6 times.

Conflict of interest

The authors declare that they have no conflict of interest in relation to this research, including financial, personal, authorship, or any other nature that could affect the research and its results presented in this article.

Use of artificial intelligence

The authors confirm that they did not use artificial intelligence technologies when creating the current work.

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Корекція управляючої програми кінцевого фрезерування на верстаті з ЧПК

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Анотація. *Представлені результати експериментальної апробації корекції управляючої програми кінцевого фрезерування на верстаті з ЧПК. Корекція виконується для умов серійного і одиничного виробництва за методом управління за апостеріорною інформацією. Апостеріорна інформація визначається при вимірюваннях безпосередньо на верстаті з ЧПК три координатним щупом фірми Renishaw. Причому для серійного виробництва вимірюється попередньо оброблена деталь, а для одиничного виробництва припуск на оброблення розділяється на дві частини і вимірюється оброблена на першому проході поверхня. Корекція виконується за експериментально визначеною передатною функцією обробної системи. Експериментально доведена ефективність розроблених методів: після фрезерування першої деталі середня похибка складала 0,1 мм, а після обробки другої деталі (і наступних) за скоригованою управляючою програмою похибка знизилася до 0,012 мм, тобто точність оброблення підвищена більш ніж в 8 разів. В умовах одиничного виробництва при розділенні припуску на дві частини і визначення корекції за розрахованою передатною функцією похибка оброблення знизилась більш ніж в 6 разів. Втрати часу на виконання двох проходів в умовах одиничного виробництва не перевищують часу на оброблення за традиційною технологією, коли для забезпечення заданої точності доводиться виконувати декілька проходів за тою ж самою управляючою програмою.*

Ключові слова: *метод апостеріорного управління, кінцеве фрезерування, корекція управляючої програми ЧПК.*