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ACHIEVING THE REQUIRED MACHINING ACCURACY BY CORRECTING ERRORS USING VARIABLES OF PARAMETRIC FUNCTIONS

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Abstract. Nowadays, the machine-building complex is actively saturated with high-tech equipment, without which an enterprise cannot enter the global market or keep up with its competitors. And it's not just about using systems with artificial intelligence elements as scientific and technical solutions to improve quality and reduce production costs. It is also about reducing the time required to prepare products for production and bringing them to the consumer ahead of schedule. Today, the most preferred method in the competitive struggle is to equip CAD/CAM production with computer-aided design systems. With their help, engineering and technology services cannot only design models of new products but also generate CNC control software for manufacturing parts on CNC machines. At the same time, program frames composed in G-codes have several drawbacks, the main one being a "rigid" algorithm of action, i. e., the lack of variability for final solutions when the required accuracy is achieved by correcting the numerical values of the coordinates of the points of formation of individual surfaces in the PC. In this case, the operator largely intuitively corrects individual program frames based on his or her own experience, which is almost impossible without appropriate calculations for controllers with linear-circular and angular motions. In addition, after some such changes, the program loses its geometric adequacy to the part drawing, and by correcting one element of the shaped profile, we invariably violate the laws of contact with neighboring elements specified in the drawing. The paper considers the analytical geometry apparatus that allows a line on a double curvature surface, the theoretical trajectory of tool movement, to be represented not as a set of scalar points but in a vector representation, considering its possible torsion. This approach is ensured by parametric programming with computational frames of point coordinates and logical transitions, determining the angles of inclination of the cutter axis relative to the normal to the surface in the case of multi-axis machining. However, the main advantage of this method is the ability to correct processing errors not by local changes in the numerical values of the coordinates, but by introducing correction coefficients into the equation of the shape formation trajectory – reactors for the appearance of errors in the shape or location of surfaces, arising, for example, from elastic movements. The value of the coefficients per group of personnel can be set in the process of research and industrial production and change depending on the properties of the blanks. For example, according to the current standards, variations in hardness of up to 10–12 % were allowed for the blanks of rolling mill rolls. The article presents the experimental data of the research of the correction task in a parametric form and the results of their application for machining parts with radius cutters in real production.

Key words: multi-axis CNC machines; parametric functions; linear-circular and angular correction; forming errors; CNC control software.

Introduction

The world market offers a wide range of software for automated production preparation, including CAM [1], a system for calculating control programs installed on a computer or built directly into a CNC machine. CAM systems, in addition to constant cycles of machining standard part elements, contain a set of strategies for calculating trajectories based on the principle of 3D modeling of the contact between the initial tool surface and the workpiece surface. This ideal, mathematically speaking, construction of a machining path is a necessary but far from sufficient condition for ensuring the specified accuracy and surface roughness of the workpiece because it does not take into account the disturbing effects of the cutting process. At the same time, the approach of “forming a technology according to the chosen strategy” is a very controversial formulation of the task – the technology should be primary, which often contains individual methods for solving the issues of forming. Many micro and macro geometry errors affect the accuracy of machining parts on CNC machines. At the same time, the research task is to reduce the percentage of random errors – to systematize and establish patterns of their occurrence, that is, to create conditions for their transition to systematic ones.

There is a significant increase in interest in machining parts from a single setup on multi-axis machines due to the reduction in the cost of 5-axis CNC machines, the development of the mathematical apparatus of CAD/CAM systems, and market requirements for reducing production preparation time. At the same time, while systems of this class can be said to have closed the issue of rough machining by optimizing it according to the criterion of maximum productivity, there are still several unresolved problems for the formation of the final profile, especially for surfaces of complex shape. First of all, these are the issues of leveling the effects of disturbing effects from cutting forces, the maximum height of the residual “comb” between the cutter passes on surfaces of different shapes, determining the technological stop points (commands M00, M01) for measurements and adjustments of the CNC machine due to tool wear, etc.

The relevance of this problem is evidenced by the fact that CSoft specialists have developed UniGraphics NX postprocessors [2] for Heidenhain 430/530 [3] and Siemens Sinumerik 840D [4] control systems that implement the possibility of applying 3D correction during five-axis machining.

The main technological method for shaping surfaces of double curvature is multi-axis milling, which is performed on CNC machines with end radius (spherical) cutters. In the process of technological debugging, static trajectory corrections are determined for the operation: for the length of the cutter, its overhang T_L and radius R_F , and, if necessary, the machine zero offsets. The input 3D model, as the basis for the entire technological process of manufacturing a part, is built by a CAD system. The calculated toolpaths for multi-axis machining are created according to the adopted strategy in CLDATA format using CAM systems. To obtain control for a particular CNC, it is necessary to convert CLDATA preprocessing information into G, M codes or functions built in a specialized language (for example, Heidenhain Dialog Language), in which the syntax differs significantly from ISO-7 language standards. In some cases, the technologist-programmer has to supplement the 3D model with surfaces to account for tool plunging and changes in dynamic cutting angles. In addition, post-processing must take into account the kinematics of the machine tool, as well as whether the workpiece zero (G54) is shifted when the working bodies move or whether the axes of the workpiece coordinate system rotate along with the rotary table (for example, SprutCAM, MasterCAM). The result of the calculations can be hundreds or thousands of NC frames containing G-functions of linear and circular movements. Suppose control measurements have shown the presence of surface deviations from the specified part profile, for example, due to elastic deformations of the technological system. In that case, the task arises of finding the control frames that form these surfaces and error correction functions for this interval, which, by the way, are not automatically generated by the CAM system.

The correction vector in CNC control software is a vector that sets the trajectory of the machine tool's working bodies differently from the calculated trajectory laid down in the control. In the case of 2D machining, when the tool trajectory lies in a plane, it is assumed that the correction vector lies in the same

plane. Strictly speaking, this is not entirely correct, for example, in the case of compensation for elastic movements. For multi-axis 3D machining, the situation is much more complicated, especially when it is possible to control the angle of the spindle axis. While for turning with 2D correction ($G41$, $G42$), several pages of the user manual describe the algorithms for constructing equidistant trajectories (a line defined in mathematics as a hypocycloid), for machines with 3D correction, the algorithms for its development are not documented, which increases the likelihood of trajectory intersection and the occurrence of emergencies.

Because of the above, we can gratefully recall parametric programming for CNC machines or, for example, GTL functions by Olivetty, which are now unfortunately no longer widely used. Currently, the parametric approach to control design is especially interesting when the surface of a complex profile is given by an equation or its sections are represented as a piecewise continuous function.

The purpose of this paper is to theoretically solve the problem of calculating the parametric functions of the forming trajectory and their ability to correct in local areas of the product while maintaining the laws of contact of the elements of the machining surfaces specified in the drawing. At the same time, the task is to build an algorithm for the action of the correction module based on the calculation and experimental data as a factor for leveling disturbing factors in cutting processes.

Theoretical basis for parametric correction of machining errors for CNC machines

To accomplish this task, let's consider the analytical calculation of the tool trajectory during five-contour machining from the point of view of differential geometry. The surface of double curvature (Fig. 1) is described in the part coordinate system (PCS) X_D , Y_D , Z_D by the function $f(x, y, z)$ – smooth, piecewise continuous, having a derivative up to and including the second order. For the surface of this geometry, it is possible to replace the canonical Cartesian coordinates with other independent variables t and v functionally related to them, which uniquely determine the positions of all its points by the parametric equation $F(t, v)$ (1). At an arbitrary point $M_i(Mx(t_i, v_i), My(t_i, v_i), Mz(t_i, v_i))$ of the design curve $L(t, v)$ of the trajectory of a tool lying on a surface with the specified properties and which may have torsion, there are always three mutually perpendicular planes: the normal η , the contacting plane ψ and the tangent plane τ , which passes through the binormal and coincides with the guiding plane of the spatial curve. Together, the planes form a Fresnel trihedron that defines a trio of orthogonal vectors. The line of intersection of the planes η and ψ corresponds to the principal normal vector \bar{N} at this point of the surface with the tilt angles q^X, q^Y, q^Z formed with the positive directions of the DSC axes X_D , Y_D , Z_D , respectively. The intersection of the planes η and τ will determine the contour feed vector \bar{F} , directed tangentially to the curve $L(t, v)$ at the current point of the tool movement trajectory M_i (3). When calculating the control, it should be borne in mind that the vector \bar{F} , according to the laws of analytical geometry, will always be directed in the direction of increasing arc coordinates, and the programmed feed refers to the tool datum.

In a particular case, the calculated tool path can be defined as the line of intersection of the surface $F(t, v)$ with the plane perpendicular to the coordinate plane X_D , Y_D , for example, $v = tg(\beta) \cdot t$ or $v = const$. This assumption is fully consistent with the most common scheme for constructing passes when machining surfaces of this type – straight line segments. The presence of such a construction makes it possible to determine the trajectory of movement of $L(t)$ analytically (2) and in the vector representation (3) as a function of one variable $\bar{M}(t)$.

$$F(t, v) = \begin{cases} X(t, v) \\ Y(t, v) \\ Z(t, v) \end{cases} \quad (1)$$

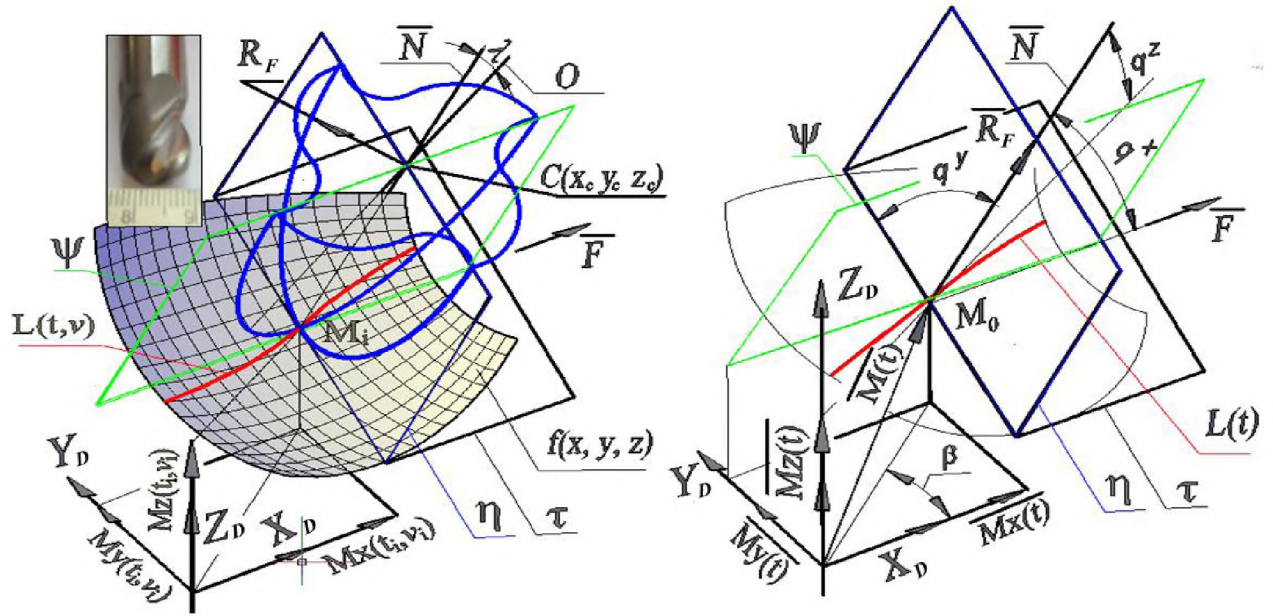


Fig. 1. $F(x, y, z)$ is a surface of double curvature in the surface of double curvature in the reference system: $\{X_D, Y_D, Z_D; M_i\}$ is an arbitrary point of the calculated trajectory $L(t)$, where \bar{N} is the vector of the main normal to the surface with inclination angles q^x, q^y, q^z ; three mutually perpendicular planes: η is the normal plane, ψ is the contacting plane, and τ is the tangent plane; \bar{R}_F is the vector of the specified position of the center of the cutter $C(x_C, y_C, z_C)$ relative to the point of the trajectory M_i ; O is the axis of the radius cutter R_F at an angle λ to the normal plane η ; \bar{F} is the feed vector

$$L(t) = \begin{cases} L_x(t, v(t)) \\ L_y(t, v(t)) \\ L_z(t, v(t)) \end{cases} = \begin{cases} L_x(t) \\ L_y(t) \\ L_z(t) \end{cases}, \quad (2)$$

$$\bar{M}(t) = \begin{cases} M_x(t) \\ M_y(t) \\ M_z(t) \end{cases}, \quad (3)$$

$$\bar{R}(t, R_F) = \begin{cases} R_F \cdot \cos(q^x) \\ R_F \cdot \cos(q^y) \\ R_F \cdot \cos(q^z) \end{cases}. \quad (4)$$

Spatial line curves are called equidistant to a given curve if the principal normal at their points coincide in direction, and the distance between the corresponding points of the curves measured in the direction of the principal normal remains constant. Curves that allow for the construction of equidistant curves within a certain range of displacements are called Bertrand curves.

In multi-axis machining with spherical cutters of radius R_F , the CNC control software can be built based on commands for positioning the center $C(x_C, y_C, z_C)$ of its spherical part – Tool Center Point Management (TCPM) mode and commands for controlling the orientation of the spindle axis. In this case, we speak of equidistant programming with an offset to the vector \bar{R}_F , which is collinear to the principal normal vector \bar{N} at a given point in the trajectory and is determined through its projection ($R_F \cdot \cos(q)$) onto

the coordinate axes. Then the equidistant trajectory of movement $\overline{(R(t, R)_F)}$ (4) of the center of the cutter $C(x_C, y_C, y_C)$ will ideally be equal to the sum of the two vectors:

$$\overline{C(t, R_F)} = \overline{M(t)} + \overline{R(t, R_F)}. \quad (5)$$

When machining on CNC machines, the main tool for achieving accuracy is “correctors” that allow you to level the effect of various disturbances that accompany the cutting process. The importance of working with correctors is evidenced by the following opinion in production: those who know how to correctly set up and use correction commands in the program have become a specialist technologist. Unfortunately, there are no standardized approaches to the algorithms of the correctors’ operation. This is especially true for the angular movements of five-axis machines, for which, in most cases, the description of the correction action is limited to the fact that they are present. For example, for the HEIDENHAIN TNC 640 CNC, the movement in the control is determined by the X, Y, Z coordinates, and the spindle position by projections of the normalizing vector $\overline{TX}, \overline{TY}, \overline{TZ}$ or by specifying its tilt angles. At the same time, the answer to the question of how the action of the correctors will change when the coordinate system is transformed, for example, its tilt or rotation, can be obtained only during experimental processing.

Therefore, with the current computing capabilities of CNC machines, the development of user-developed correction subroutines is expected. Consider an example.

To calculate the angular values q^X, q^Y, q^Z of the normal vector \overline{N} and the conditions for possible adjustment of the angular position of the spindle relative to it, dependencies (6) are determined through the private derivatives $L_x(t), L_y(t), L_z(t)$ of the function $L(t)$ (2):

$$\left\{ \begin{array}{l} L_d = \sqrt{\left(\frac{d}{dt}L_x(t)\right)^2 + \left(\frac{d}{dt}L_y(t)\right)^2 + \left(\frac{d}{dt}L_z(t)\right)^2}; \\ q^X = \arccos \left(\frac{\frac{d}{dt}L_x(t)}{L_d} \right), \\ q^Y = \arccos \left(\frac{\frac{d}{dt}L_y(t)}{L_d} \right), \\ q^Z = \arccos \left(\frac{\frac{d}{dt}L_z(t)}{L_d} \right) \end{array} \right. \quad (6)$$

It should be noted that if the CNC control software contains a command to control the angle of inclination of the spindle axis, then when it is implemented, modern CNC automatically compensates for the displacement of the tool datum by correcting the program path along two coordinates in the rotation plane.

Thus, the frames of the parametric NC can consist of the usual module of coordinate displacements – the point $\overline{M(t)}$ on the surface of the part along $L(t)$ and the projections of the radius vector of the cutter $\overline{R_F}$, with a cyclic appeal to the calculation module of corrections MC to generate them (Fig. 2). This task is realized by a structure that generates the programmatic movement of the cutter center $C(x_C, y_C, y_C)$ with the possibility of changing the angular position of the cutter axis q relative to the normal to the machined surface \overline{N} (Fig. 1). The structure includes “input data” that can be changed by the user, “output data”, and “correction data”, as well:

- $\overline{R_F \pm \Delta}$ is the radius vector, with the ability to adjust $\pm \Delta$ the “depth” of cut on the passes: if you specify $(R_F - \Delta)$ less than the actual R_F , the cutter center $C(x_C, y_C, z_C)$ will approach the surface of the part, and with $(R_F + \Delta)$ it will move away;
- $\{k^X, k^Y, k^Z\}$ are the correction factors for angular deviations from the cutter axis normal vector.

In general, value Δ can be constant or change $\Delta(\eta, \mu, \dots)$ according to a certain law, for example, depending on the pass number or the topology of local areas of the machined surface

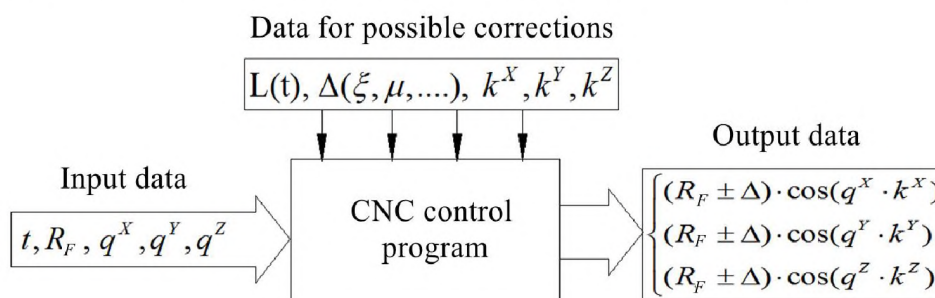


Fig. 2. Block diagram of the correction module (CP): t is the angular coordinates; R_ϕ is the radius of the cutter; q is the angular inclinations of the spindle axis and their correction factors k ; Δ is the correction value of the module cutter vector $\overline{R_\phi \pm \Delta}$

According to statistics, more than half of the surfaces of complex profiles are machined with radius cutters, the spherical cutting part of which introduces certain features into the construction of the technology for forming parts of this type. Let's consider the geometry of a 3D model of a carbide 4-tooth cutter *R6-75-4T-B* (Fig. 1) with a spherical end of radius *R6* mm (Fig. 3).

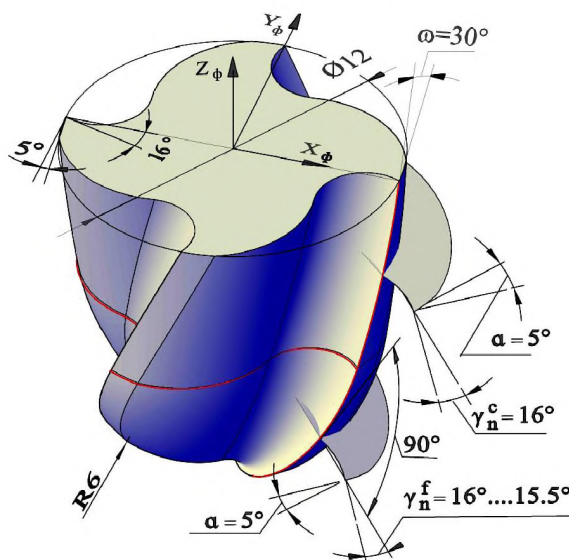


Fig. 3. Measurements on a 3D model of a four-edges cutter mill with the radius $R_F = 6$ mm ($\varnothing 12$ mm) with the rake (γ) and relief (α) angles in normal sections for the tool coordinate system X_F, Y_F, Z_F

Developing the model of the mill cutter is not an easy task with different algorithms for its solution. In this case, we chose the method of solid modeling in the tool coordinate system $\{X_F, Y_F, Z_F\}$ along the radial sections of the cutter with their calculated diametric scaling and rotation along a helical line with a

rise angle $\omega=30^\circ$ on the sphere and on the cylindrical part of the cutter $\varnothing 12$ mm. In the sections parallel to the plane $\{X_F, Y_F\}$ of the cylindrical part of the cutter, the static angles are: relief $\alpha=5^\circ$ and rake $\gamma_n^c = 16^\circ$. In the sections normal to the cutting edge on the spherical part of the cutter of radius R , the relief angle $\alpha=5^\circ$ along the cutter belt remained unchanged, which corresponds to the scheme of sharpening the tool along the back surface. The rake angle in normal sections with a decrease in the diameter of its spherical part slightly decreases $\gamma_n^f = 16^\circ \dots 15.5^\circ$ within acceptable limits from the point of view of cutting theory. When working with radiused spherical cutters, the critical zone of the cutting edge is formed around the axis point at the end of the cutter, where the cutting speed is close to zero. To eliminate this negative property, machining is performed with the spindle axis tilted in the direction of the feed vector \overline{F} by an angle of λ (Fig. 1) relative to the normal vector \overline{N} of the machined surface at this point. One of the advantages of equidistant programming is the fact that the rotation about the axis of the spherical part of the cutter does not give an error in terms of the mathematical laws of the theory of shape formation. Sometimes, in order to simplify the prediction of the spindle position, which is important to avoid emergencies, the control of the spindle axis tilt is left only in the direction of the feed vector \overline{F} , i. e., the torsion of the trajectory line is assumed to be zero. However, in this case, the accuracy and roughness can be negatively affected, because according to the studies conducted, the quality characteristics of surfaces of complex profiles largely depend on the angles of inclination of the cutter in the longitudinal and transverse directions.

Thus, the angular position of the spindle q^X, q^Y, q^Z , during machining is closely related to the geometry of the machined surface, but is limited by the parameters of the machine drive, the inclination of the spindle axis λ in the direction of the feed vector \overline{F} and the design features of the part. The latter is the most difficult to take into account both when working with CAM systems and when a technologist is programming. In the following example, let's consider the correction of the shape error from elastic deformations due to cutting forces.

For experimental machining, a sample part (Fig. 4, *a*) with a cylindrical surface of radius $R_C=39.5$ mm and a central angle of $2 \times 60^\circ$ was previously prepared. The workpiece for milling is a high-strength aluminum alloy B95, which is well processed by cutting, with a low-roughness surface due to its fine-grained structure. The machining was carried out with a radius cutter $R_F=6$ mm ($\varnothing 12$ mm) in-line, along a linear guide $L = 168$ mm, with an axial feed $\overline{F}_X = 80$ mm/min, with the angle of inclination of the cutter axis in the direction of the feed vector (Fig. 1) $\lambda = 13^\circ$. The surface was milled with a discrete rotation (Fig. 4, *a*) of the coordinate system of the cutter Y_F, Z_F around the X -axis by 3° , at each of $i=1, 20$ passes ($3^\circ, 3^\circ \times i, 60^\circ$). The machining was performed with constant cutting modes on the passes and tool contact conditions with the part: speed $V_P=230$ m/min. and depth of cut $a_e = 0.5$ mm, calculated effective diameter $d_F=5.1$ mm, height of the “comb” between the passes $h = 0.04$ mm and axial contact angle of the cutter $\psi_F = 12^\circ$.

Using the control and measuring system “Renishaw” (PH10M series with a TP7M sensor), in the reference system of the workpiece $\{X_D, Y_D, Z_D\}$, the shape “deviation from cylindricity” (Fig. 4, *b*) was controlled as the greatest distance in planes parallel to Y_D, Z_D from the points of the obtained surface to the points of the required geometry of the nominally specified cylinder $R_D=40$ mm, within the normalized area $L=168$ mm.

As a result of the measurements, the error value of the radius surface along L on the passes was obtained depending on the angle ($3^\circ \cdot i$) of the cutter axis inclination $\Delta R_p^i(3^\circ \cdot i) = 0 \dots 0.18$ mm. The reason for such deviations from the nominal value may be a change in the pattern of force action on the cutter console, when with each pass, with an increase in the angle of inclination of the cutter axis, the bending moment from the radial cutting force increases.

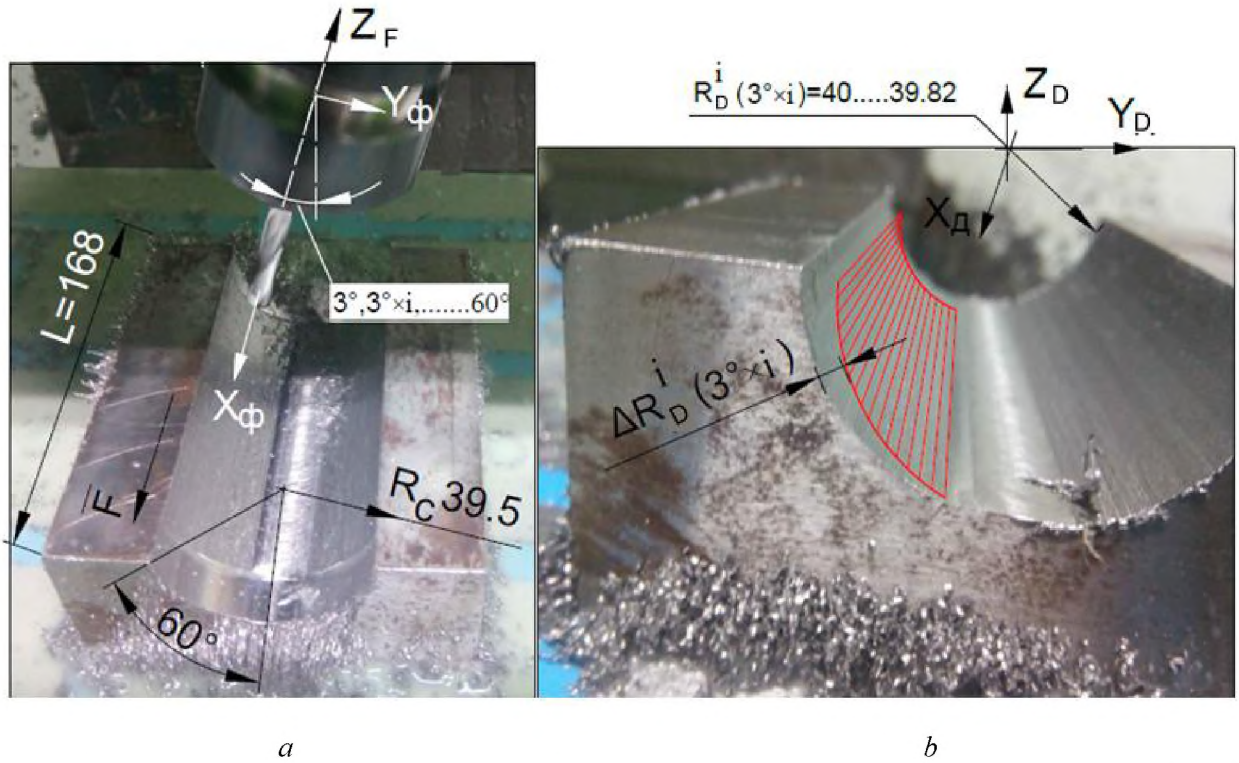


Fig. 4. Experimental milling of the workpiece (a) and measurement in the coordinate system X_D, Y_D, Z_D of the deviation from cylindricity (b)

The deviations of surface dimensions from the nominal are leveled by means of axial corrections on the passes, the values of which are obtained by the calculation module MC as a projection of the error $\Delta R_p^i(3^\circ \times i)$ obtained experimentally. When the sample was re-milled with the calculated correction, the maximum error decreased to about 36 %.

In the manufacture of a gearbox (Mariupol, OJSC “Magma”) for machining a copy ring (Fig. 5, b) fixed to the end of a gear (Fig. 5, a), a parameterized CNC control software with the possibility of 3D correction of the program trajectory was developed. The technological difficulty of manufacturing this part with a finite radius cutter $R_F=6$ mm (Fig. 1), (Fig. 2) (Fig. 5, c) was that, in addition to its low rigidity, there is a running-in surface of double curvature, with high requirements for its accuracy and roughness.

The workpiece is a ring (Fig. 5, b) with an outer surface of radius $R_n=235$ mm and an inner surface $R_p=190$ mm with a concave surface $R_k=100$ mm of a shaped profile, which is described by the following parametric equation:

$$F(t, n) = \begin{cases} X(t, n) = (R_p + \partial_R \cdot n) \cdot \cos(t) \\ Y(t, n) = (R_p + \partial_R \cdot n) \cdot \sin(t) \\ Z(t, n) = 13 \cdot \cos(7 \cdot t) + R_k - \sqrt{R_k^2 - ((R_n - R_p) - \partial_R \cdot n)^2} \end{cases} \quad (8)$$

where t is the angular coordinate $0 < t < 2 \cdot \pi$, n is the integer variable that determines the width of the machined surface; $\partial_R \cdot n = 45$ mm through the distance between passes ∂_R . The outer surface of the ring has a radius $R_n = R_p + \partial_R \cdot n$. At the i -th pass, the radius of circular interpolation in the control for moving the cutter is equal to $r_i = \partial_R \cdot i$, and the calculated trajectory is transformed into a curve belonging to the surface (8) (Fig. 5, b). To obtain equivalent values concerning surface (8), the MC module calculates the displacement along the coordinates in the direction of the normal by the value R_F with the possibility of its correction by varying the error values Δ and the coefficients of angular deviations k (Fig. 2). In the calcu-

lations, it should be borne in mind that the normal vector is always directed towards the concavity of the curve, which must be taken into account for the direction of reference of the angular value q .

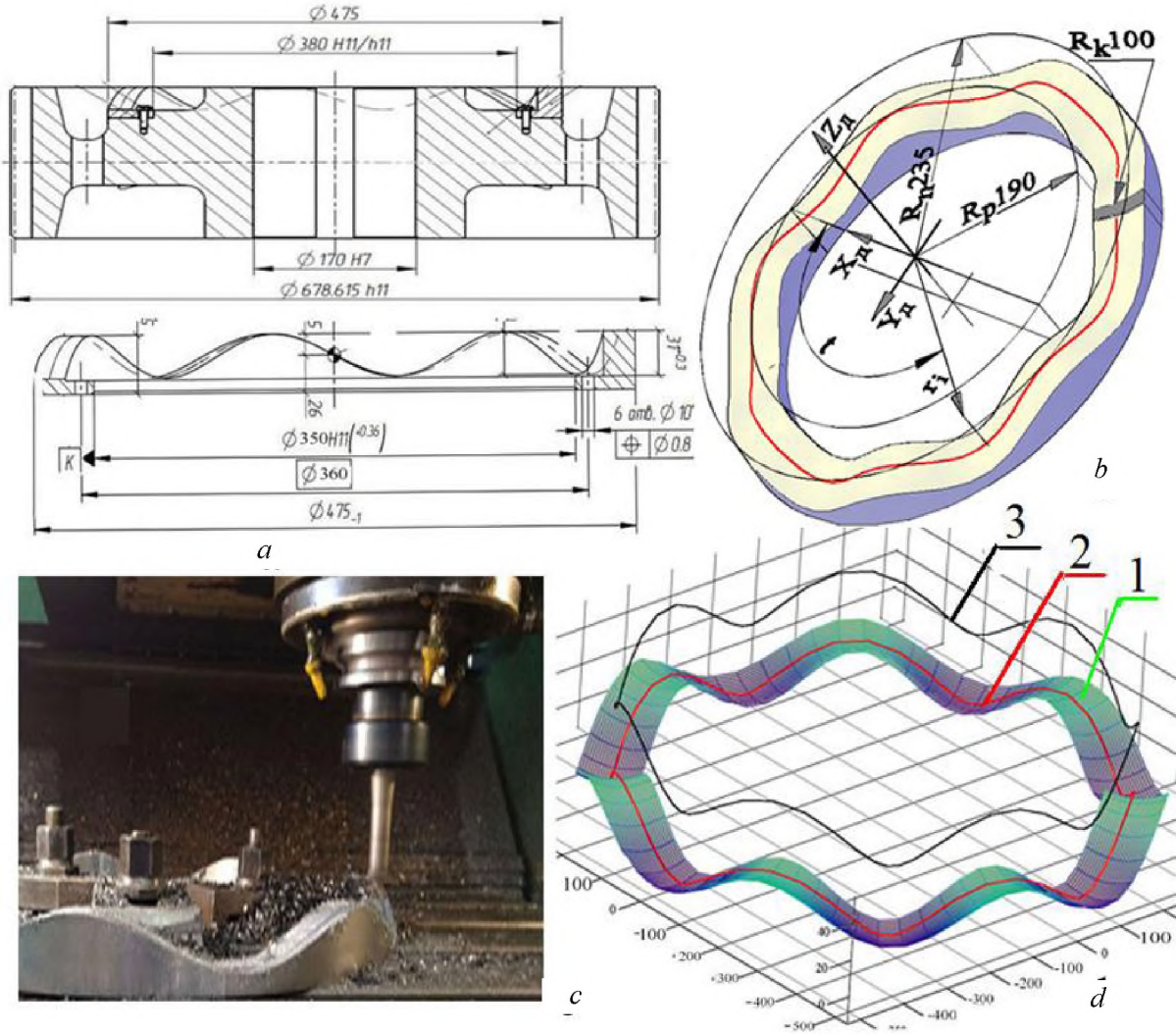


Fig. 5. Modelling a 3D correction for machining a copy ring: wheel assembly with a copy ring (a); 3D model of a copy ring (b); machining on a machine with spindle angle control (c); representation of surfaces and trajectories in MathCAD: 1 is the surface model, 2 is the calculated trajectory of the i -th pass of the cutter and 3 is the its equidistant (d)

The calculated values were checked (Fig. 5, *d*) in the MathCAD view on surface 1, and an equidistant trajectory 3 was generated for the i -th pass 2.

The final machining of the ring was carried out on a 5-axis Doosan DNM 200/5AX machining center with the FANUC 0i-MF CNC, using the method of circular interpolation on each pass with a radius of $r_i = R_p + \Delta_R \cdot i$. The part was monitored directly on the machine (Fig. 6, *a*) by the measuring head of the FARO Gage system, which was connected to a computer and adapted to work with measurement (Fig. 6, *b*) without unfastening the part, with the measurement coordinates being tied to the system in which the processing was performed to $\{X_D, Y_D, Z_D\}$ origins.

By superposition of the theoretical ring profile and the real surface model built from the measurement points, the following were monitored: deviation of the surface shape R100 in radial sections Y_D, Z_D its alignment with the base diameter $\varnothing(2 \cdot R_p)$ and possible ovality. The measurements were performed every 10^0 by the actions adopted for CMM, only in manual mode with access to the position of the points of the

circle of radius r_i relative to the machine display. While the alignment error was corrected simply by eliminating the “zero” of the DCD, the ovality was corrected by preventing the trajectory of the $\overline{\Delta_x^i(t)}, \overline{\Delta_y^i(t)}$ function from the angular coordinate t . The leveling of the shape deviation in the process of reworking was performed on each pass by correcting for the radius of the cutter, similar to how it was done for the experimental sample (Fig. 4).

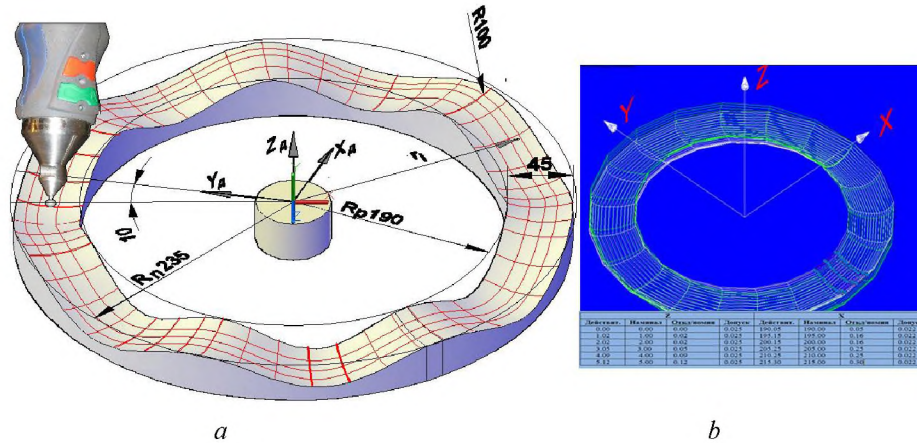


Fig. 6. Measurement of the copyrone ring (a) and formation of the control protocol (b) of its shape

Conclusions

In production, sometimes a situation occurs when a complex surface for which the control prepared by the system itself is obtained with an error. And then the question arises: what to correct, in which frame of the control, in one or more, and how? If the part is small, it can be sent to a laboratory where the best technology and control that matches it will be found through trial and error. But what about in one-off production, for example, when processing dies or in heavy engineering – editing individual frames or program frame groups? However this will lead to a violation of the geometric relationships between the two surface areas, and editing with splines, as provided for the Sinumerik 840D, is likely to affect the accuracy of the shape. Even if a “council” of experienced production specialists suggests a way to adjust the machining technique to correct the error, it is not always clear what changes are required in the initial data for the CAM system to implement these suggestions in the CNC control software. To summarize, we can say with certainty that several such manual “corrections” in the control will very soon lead to a complete loss of the logic of controllability of the machining process. And then what? Who will pay for the resulting rejects? Certainly not the system itself.

Without in any way diminishing the importance of CAM systems (they occupy a deserved place in production preparation), it should be noted that they are most actively used at those enterprises where adjusting control parameters in production shops, i. e. after laboratory tests, is not only unacceptable, but also administratively punishable.

This paper presents a theoretically grounded method for constructing a CNC control software when the trajectory task is determined by the program displacement vectors and correction vectors, while the latter are available to the user in a functional form, which ensures the inviolability of the laws of combination of trajectory elements specified in the drawing. The peculiarity of the presented method is the construction of parametric programs with a “transparent” algorithm for the implementation of equidistant trajectories of shape formation, and, more importantly, the ability to introduce corrections with a user-friendly action. In addition, the technologist has the opportunity to use the 5-axis CNC system to build a surface treatment of a complex profile along a curve, taking into account its possible torsion, i. e., with the analysis of its full curvature, which makes it possible to control the spindle angles.

Of course, creating a correction tool based on the functional principle is a non-trivial task, but it is quite feasible, given the computing capabilities of modern CNC machines that meet the conditions of pa-

rametric programming and also have the ability to use condition and branching operators to create control structures for managing the quality indicators of the machining process. It is also worth noting a common problem today, when the capabilities of modern CNCs are used only by 10–15 %, at a cost of up to \$10 thousand. And here a dilemma arises: to leave the CNC machine only the functions of a controller that receives from the control network the systems developed by CAM and transmits them to the machine or to “load” it with, for example, the above tasks. The first way will be effective for batch production, but for one-off production, its application is very problematic.

The modular principle of building controllers, which is especially effective in the field of group technology, will be restored by all these features. Furthermore, this approach facilitates the creation of a library of correction modules (CMs) of diverse types over time, thereby significantly expediting and reducing the expense of constructing new controllers. The geometric characteristics of the machined surface and the values of the kinematic parameters of the cutting modes can be created by control parameterization.

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