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DESIGN OF PARAMETRIC HOLE MILLING CYCLES ON CNC MACHINES

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Abstract: The paper describes the stages of designing a technological cycle, which implements milling the holes with an end mill. We also present the developed CONICALINT software, which generates a G-code with an argument list for calling a technological cycle from the CNC system memory. The developed algorithm for the technological cycle of milling holes with an end mill has a branched structure, since there is a choice between two methods for calculating the internal parameters of the cycle and two milling methods: down cutting or up cutting. The calculation of the internal parameters of the technological cycle consists of calculating the coordinates of the points necessary to construct the helical path of the cutting tool, as well as calculating the value of the maximum permissible value of the helical pitch within a given set of input parameters. The initial data for the calculation are represented by thirteen parameters characterizing the geometry of the cutting tool, the geometry of the desired machined surface, as well as parameters defining the milling method, the calculation method, the cutting mode and the starting points of the cutting tool path. There are eight boundary conditions that determine the acceptable values of the input parameters. Based on these conditions, a system of inequalities is designed with a set of error messages to the user in case of incorrect input of the value of any input parameter. The developed G-code of the technological cycle subroutine for a CNC machine makes it possible to calculate the tool motion, both along helical and conical helical paths, depending on the input parameters. So, you can use it when programming milling of cylindrical and conical holes. The developed CONICALINT software is a visual addition to the developed technological cycle of milling holes that allow you to generate a control G-code with a list of twelve arguments.

Keywords: *parametric milling cycle, G-code, end milling, CNC machine*

Introduction

Currently, in conditions of piece-work and small-batch production, there is a need for a quick changeover of a CNC machine and, accordingly, rapid writing of control programs for part processing [3]. Using cycles for processing typical surfaces built into the CNC system [9], as well as due to the possible lack of other optional tools (Manual Guide i interactive programming software, Conical/Helical Interpolation function, etc.) [6, 8, 12,15], it is not always possible to solve assigned problems when developing control programs without the use of CAM modules, other computer software, or labor-intensive calculations of cutting tool paths [14]. This leads to problems that require theoretical and/or practical solutions. The following main problems have been identified on the topic under analysis. The performance of the process of designing a control program to execute the same operating step on different CNC machines differs. This is due to the presence or absence of desired tools of the system [10,11]. There is no possibility to use the same control program to perform some routine operating steps on different CNC machines [7, 13]. Preparing control programs for processing surfaces of complex profiles is the most labor-intensive process [1, 2, 4, 5].

Thus, the relevance of the topic is associated with the need to develop and implement into the CNC system a technological cycle for milling holes with an end mill, taking into account all the requirements for the geometric parameters of the machined surfaces a rational processing strategy, and cutting modes, and not linked to a specific series and model of this systems.

Stages of technological cycle development

Definition of initial data

The initial parameters of the cutting tool and the required parameters of the machined surface, necessary for calculating the path of the cutting tool within the developed technological cycle for milling holes with an end mill, are visually presented in Figure 1. Table 1 provides a description of these parameters.

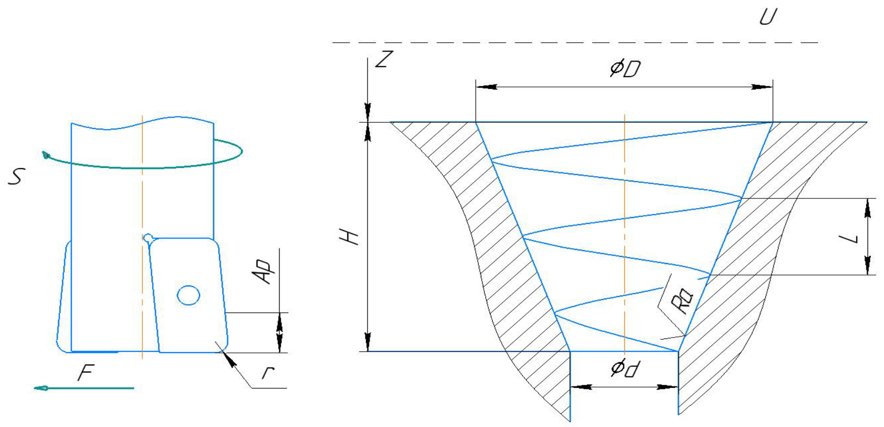


Figure. 1. Initial parameters of the cutting tool and required parameters of the machined surface

Table 1 Description of initial parameters

Parameter	Description
r	End mill wedge radius
H	Required hole depth
D	Initial hole diameter
d	Final hole diameter
Ra	Required roughness of the machined surface
L	Helical pitch value
Z	Z-axis coordinate of the hole origin plane
U	Z-axis coordinate of the clearance plane
S	Spindle rpm
F	Feed
Ap	Maximum axial depth of cut

It is necessary to select the milling method (up or down milling) and specify the calculation method (use the value of the required roughness or a fixed value of the helical pitch to calculate the internal parameters of the technological cycle).

Designation of boundary conditions that determine acceptable values of input parameters

Let us define a set of conditions, the failure of which makes it impossible or incorrect to calculate the tool path within the developed technological cycle, and the CNC machine system generates the corresponding error:

–the value of the initial hole diameter must be greater than the value of the final diameter or equal to it, $D \geq d$;

–the value of the Z-axis coordinate of the clearance plane must be greater than the value of the Z-axis coordinate of the hole origin plane or equal to it, $U \geq Z$;

–the value of the spindle rpm must be positive, $S > 0$;

–the value of the end mill wedge radius must be positive, $r > 0$;

–the value of the required roughness of the machined surface must be positive, $Ra > 0$;

–the value of the initial hole diameter must be positive, $D > 0$;

–the value of the final hole diameter must be positive, $d > 0$;

–the value of the hole depth must be positive, $H > 0$.

Thus, a set of boundary conditions has been determined, the failure of which leads to the operation shutdown of the developed technological cycle, and the CNC machine system issues a corresponding message indicating the incorrectly specified parameter.

Development of a technological cycle algorithm

Let us develop a conditional algorithm for the technological cycle of milling holes with an end mill and depict it in Figure 2. This algorithm has three logical blocks, the decisions on which are made depending on the values of the initial data.

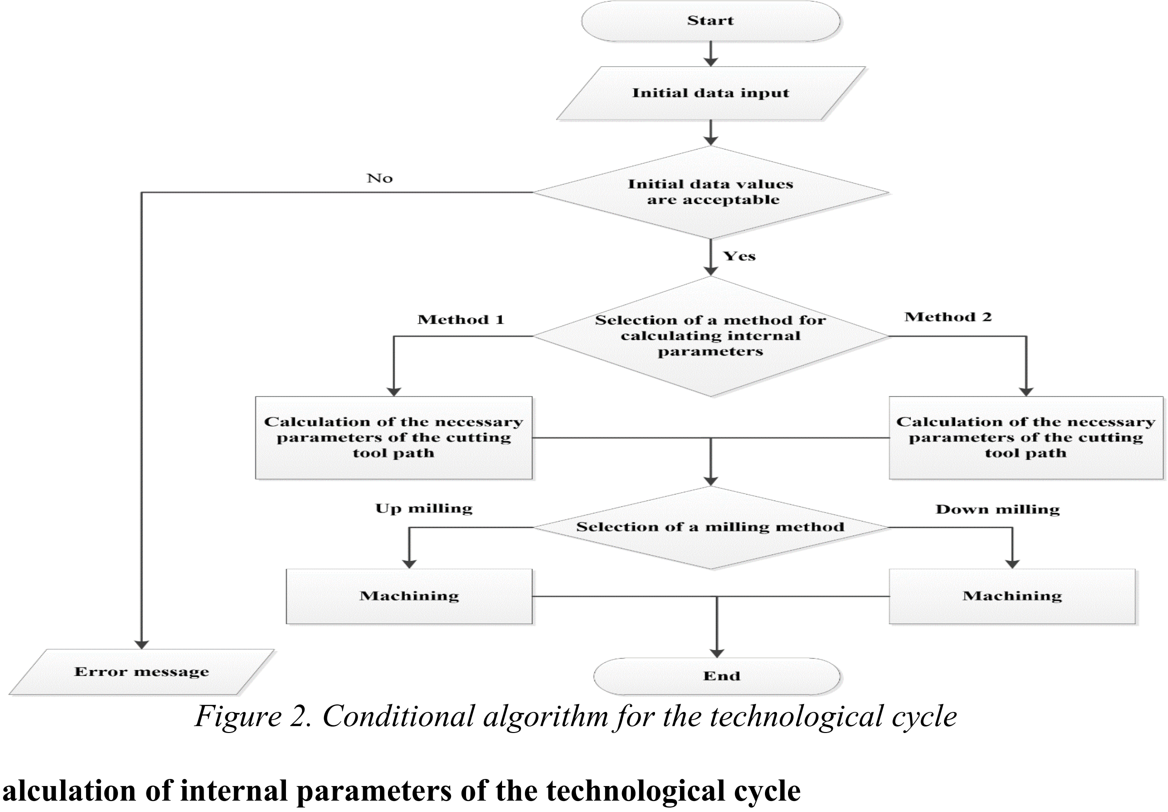


Figure 2. Conditional algorithm for the technological cycle

Calculation of internal parameters of the technological cycle

Using the formula for calculating the deviation of the actual profile of the machined surface from the required one, we recalculate the values of the initial and final diameters of the hole (D_{calc} and d_{calc}, respectively) using formulas (1) and (2):

$$D_{calc} = D + 2 \cdot (r - r \cdot \cos(\omega) + r - r \cdot \sin(\omega) \cdot tg(\omega)) \quad (1)$$

$$d_{calc} = d + 2 \cdot \left(r - r \cdot \cos(\omega) + r - r \cdot \sin(\omega) \cdot tg(\omega)\right) \tag{2}$$

The inclination angle of the machined surface ω is calculated using formula (3). The value of the inclination angle is necessary to calculate the change in the radius of the hole after each full turn of the helical path of the cutting tool, as well as to calculate the maximum permissible value of the helical pitch L, at which the required roughness of the machined surface will be maintained.

$$\omega = arctg\left(\frac{\left(D_{calc} - d_{calc}\right)/2}{H}\right) \tag{3}$$

For a cylindrical hole, the value of ω will be zero, since the initial and final diameters will have the same value. The value of this angle cannot be negative.

If a path calculation method is chosen that takes into account the required roughness of the machined surface, then we calculate the maximum permissible helical pitch L using formula (4):

$$L = \cos(\omega) \cdot \sqrt{8 \cdot r \cdot Ra} \tag{4}$$

If the calculated value of L is greater than the maximum axial depth of cut Ap, the value of L is taken equal to Ap.

The number K of complete turns of the helical path of the cutting tool is calculated as H/L and rounded to the smallest integer (6). The quotient W of H/L (5) is also necessary to calculate the final coordinate $(X;\ Y;\ Z)$ of the last turn, since if the H/L ratio is not an integer, then the helical motion path will end with an incomplete turn in order to withstand the required hole depth. Therefore,

$$W = \frac{H}{L} \tag{5}$$

$$K = FIX(W) \tag{6}$$

where FIX is the rounding to the smallest integer function used by the CNC system. If the value of W is less than one, then there is no need to calculate the value of the number of complete turns K.

Since the CNC system does not have an arithmetic function for obtaining the remainder of division, we calculate the remainder V from dividing the value of the required hole depth by the number of turns using formula (7):

$$V = H - KL \tag{7}$$

The value V characterizes the depth of the last incomplete turn (if any) in a plane perpendicular to the axis of the rotating cutting tool. Next, the final coordinates of the last incomplete turn (if any) of the path are calculated (Fig. 3).

To do this, we first find the angle β from the X axis in the XY working plane (plane G17 of the CNC system, perpendicular to the axis of the rotating cutting tool), upon reaching which the path of the last incomplete turn (8) will be completed:

$$\beta = 360° \cdot V / L \tag{8}$$

Angle β can take values from 0 to 360, not inclusive. Then, the radius is calculated relative to the center of the hole at which the path of the last full turn ended according to formula (9):

$$I = D/2 - KLtg(\omega) \tag{9}$$

Next, the coordinates $(X; Y; Z)$ are calculated using formulas 10–12:

$$X = \cos(\beta) \cdot \frac{d}{2} \tag{10}$$

$$Y = \sin(\beta) \cdot \frac{d}{2} \tag{11}$$

$$Z = -H \tag{12}$$

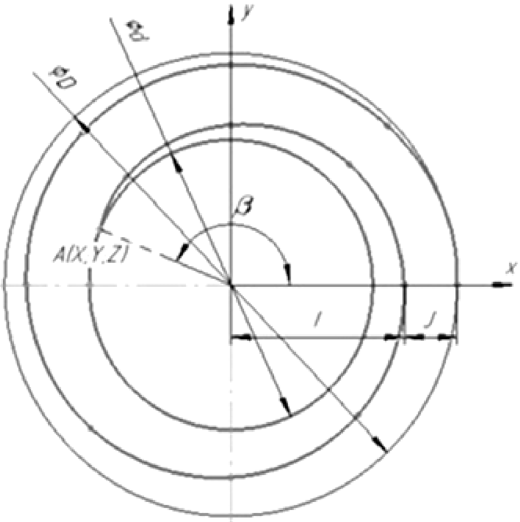


Figure 3. Calculation diagram of the final coordinates of the path

The value by which the radius of the hole changes after each complete turn (13) is calculated last:

$$J = L \cdot tg(\omega) \tag{13}$$

Thus, the missing parameters necessary for the cutting tool path drawing within the framework of the technological cycle being developed for milling conical and cylindrical holes with an end mill are calculated.

Development of a subroutine for a CNC system that implements the technological cycle

When calling a subroutine using G-code, the data (argument values) entered by the programmer is passed to the subroutine. When an argument is defined, the values are assigned to the corresponding local variables. The addresses G, L, N, O, and P cannot be used in arguments. It is also possible to skip addresses that are not required. Local variables corresponding to missing addresses are set to zero.

Table 2 Addresses of arguments and corresponding local variables

Address	Variable number
A	#1
B	#2
C	#3
D	#7
E	#8
F	#9
H	#11

Address	Variable number
I	#4
J	#5
K	#6
M	#13
Q	#17
R	#18
S	#19

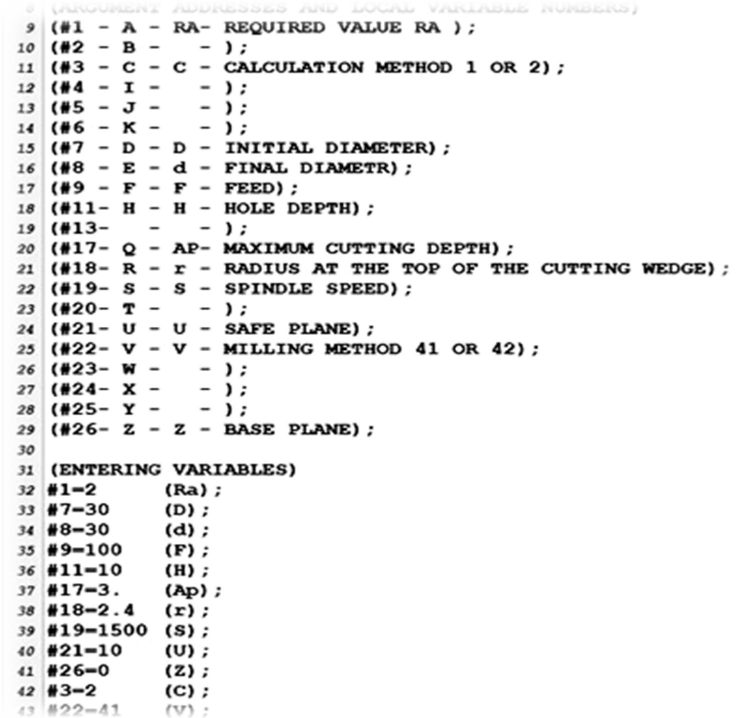
Address	Variable number
T	#20
U	#21
V	#22
W	#23
X	#24
Y	#25
Z	#26

Next, we need to assign the available argument addresses used to set the values of the local variables of the cycle being developed to the set of input parameters. We summarize the data in Table 3.

Table 3 Argument addresses used

Parameter	Argument address	Local variable
r	R	#18
ω	C	#3
H	H	#11
D	D	#7
d	E	#8
Ra	A	#1
Z	Z	#26
U	U	#21
S	S	#19
F	F	#9
Ap	Q	#17

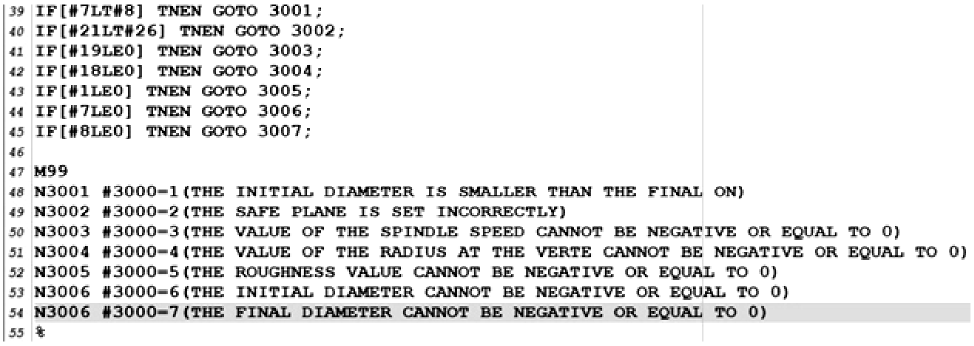
Let's develop a subroutine that implements the technological cycle in the educational version of the CIMCO Edit software editor for CNC machines. Having assigned values to the input parameters, we show the result in Figure 4.



```
(ARGUMENT ADDRESSES AND LOCAL VARIABLE NUMBERS)
(#1 - A - RA- REQUIRED VALUE RA );
(#2 - B -    - );
(#3 - C - C - CALCULATION METHOD 1 OR 2);
(#4 - I -    - );
(#5 - J -    - );
(#6 - K -    - );
(#7 - D - D - INITIAL DIAMETER);
(#8 - E - d - FINAL DIAMETR);
(#9 - F - F - FEED);
(#11- H - H - HOLE DEPTH);
(#13-     -    - );
(#17- Q - AP- MAXIMUM CUTTING DEPTH);
(#18- R - r - RADIUS AT THE TOP OF THE CUTTING WEDGE);
(#19- S - S - SPINDLE SPEED);
(#20- T -    - );
(#21- U - U - SAFE PLANE);
(#22- V - V - MILLING METHOD 41 OR 42);
(#23- W -    - );
(#24- X -    - );
(#25- Y -    - );
(#26- Z - Z - BASE PLANE);

(ENTERING VARIABLES)
#1=2      (Ra);
#7=30     (D);
#8=30     (d);
#9=100    (F);
#11=10    (H);
#17=3.    (Ap);
#18=2.4   (r);
#19=1500  (S);
#21=10    (U);
#26=0     (Z);
#3=2      (C);
#22=41    (V);
```

Figure 4. Assigning values to local variables of the cycle

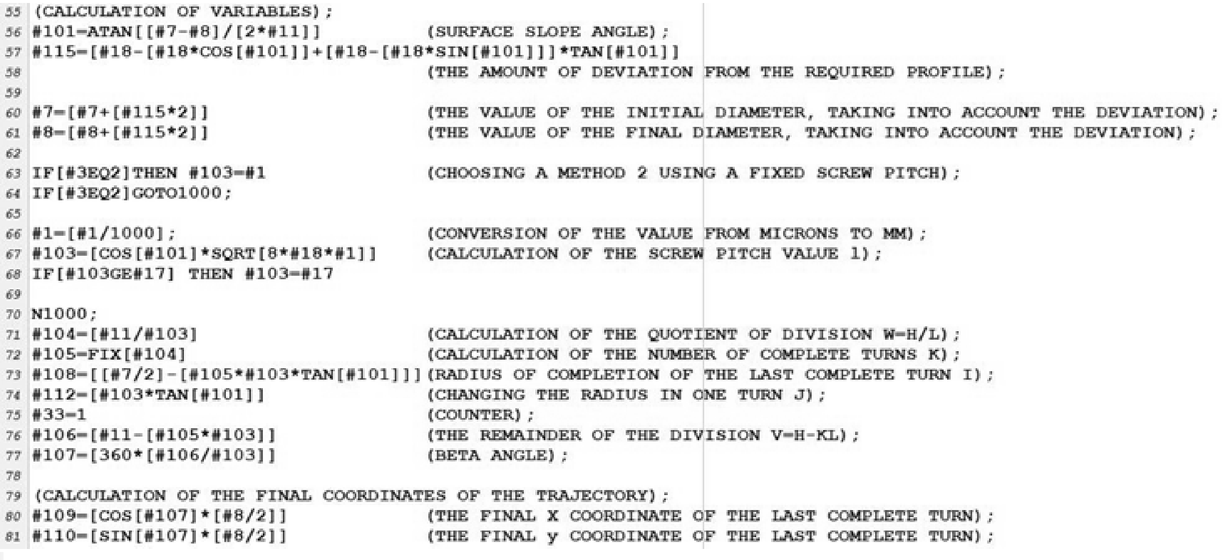
Using the conditional operator “IF” we check the boundary conditions. The result is shown in Figure 5.



```
IF[#7LT#8] TNEN GOTO 3001;
IF[#21LT#26] TNEN GOTO 3002;
IF[#19LE0] TNEN GOTO 3003;
IF[#18LE0] TNEN GOTO 3004;
IF[#1LE0] TNEN GOTO 3005;
IF[#7LE0] TNEN GOTO 3006;
IF[#8LE0] TNEN GOTO 3007;

M99
N3001 #3000=1(THE INITIAL DIAMETER IS SMALLER THAN THE FINAL ON)
N3002 #3000=2(THE SAFE PLANE IS SET INCORRECTLY)
N3003 #3000=3(THE VALUE OF THE SPINDLE SPEED CANNOT BE NEGATIVE OR EQUAL TO 0)
N3004 #3000=4(THE VALUE OF THE RADIUS AT THE VERTE CANNOT BE NEGATIVE OR EQUAL TO 0)
N3005 #3000=5(THE ROUGHNESS VALUE CANNOT BE NEGATIVE OR EQUAL TO 0)
N3006 #3000=6(THE INITIAL DIAMETER CANNOT BE NEGATIVE OR EQUAL TO 0)
N3006 #3000=7(THE FINAL DIAMETER CANNOT BE NEGATIVE OR EQUAL TO 0)
%
```

Figure 5. Checking boundary conditions

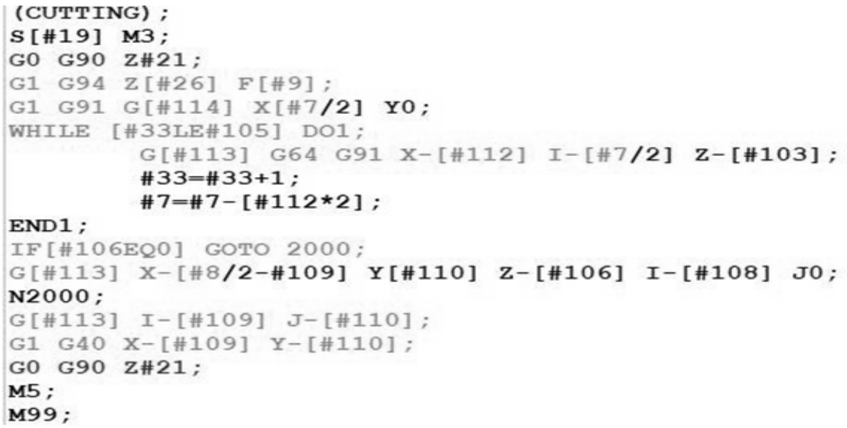
Let's introduce additional local variables of the technological cycle and calculate their values using formulas (1–13), depending on the chosen calculation method. The result is shown in Figure 6.



```
(CALCULATION OF VARIABLES);
#101=ATAN[[#7-#8]/[2*#11]]          (SURFACE SLOPE ANGLE);
#115=[#18-[#18*COS[#101]]+[#18-[#18*SIN[#101]]]*TAN[#101]]
                                    (THE AMOUNT OF DEVIATION FROM THE REQUIRED PROFILE);

#7=[#7+[#115*2]]                    (THE VALUE OF THE INITIAL DIAMETER, TAKING INTO ACCOUNT THE DEVIATION);
#8=[#8+[#115*2]]                    (THE VALUE OF THE FINAL DIAMETER, TAKING INTO ACCOUNT THE DEVIATION);

IF[#3EQ2]THEN #103=#1               (CHOOSING A METHOD 2 USING A FIXED SCREW PITCH);
IF[#3EQ2]GOTO1000;

#1=[#1/1000];                       (CONVERSION OF THE VALUE FROM MICRONS TO MM);
#103=[COS[#101]*SQRT[8*#18*#1]]     (CALCULATION OF THE SCREW PITCH VALUE 1);
IF[#103GE#17] THEN #103=#17

N1000;
#104=[#11/#103]                     (CALCULATION OF THE QUOTIENT OF DIVISION W=H/L);
#105=FIX[#104]                      (CALCULATION OF THE NUMBER OF COMPLETE TURNS K);
#108=[[#7/2]-[#105*#103*TAN[#101]]] (RADIUS OF COMPLETION OF THE LAST COMPLETE TURN I);
#112=[#103*TAN[#101]]               (CHANGING THE RADIUS IN ONE TURN J);
#33=1                               (COUNTER);
#106=[#11-[#105*#103]]              (THE REMAINDER OF THE DIVISION V=H-KL);
#107=[360*[#106/#103]]              (BETA ANGLE);

(CALCULATION OF THE FINAL COORDINATES OF THE TRAJECTORY);
#109=[COS[#107]*[#8/2]]             (THE FINAL X COORDINATE OF THE LAST COMPLETE TURN);
#110=[SIN[#107]*[#8/2]]             (THE FINAL y COORDINATE OF THE LAST COMPLETE TURN);
```

Figure 6. Calculating values of local variables of the cycle

Next, using variables and conditional transition operators “IF” and “WHILE” and choosing the method of up or down milling, we describe the tool path using calculated local variables. Figure 7 shows the result.



```
(CUTTING);
S[#19] M3;
G0 G90 Z#21;
G1 G94 Z[#26] F[#9];
G1 G91 G[#114] X[#7/2] Y0;
WHILE [#33LE#105] DO1;
        G[#113] G64 G91 X-[#112] I-[#7/2] Z-[#103];
        #33=#33+1;
        #7=#7-[#112*2];
END1;
IF[#106EQ0] GOTO 2000;
G[#113] X-[#8/2-#109] Y[#110] Z-[#106] I-[#108] J0;
N2000;
G[#113] I-[#109] J-[#110];
G1 G40 X-[#109] Y-[#110];
G0 G90 Z#21;
M5;
M99;
```

Figure 7. Tool path calculation

Thus, a subprogram for the CNC system has been developed that implements the technological cycle of milling holes using an end mill.

Visual modeling of the implementation of the developed technological cycle

Using the path drawing module built into the CIMCO Edit control program editor, we perform a visual simulation of the execution of the developed G-code cycle for milling holes with an end mill. To do this, we need to assign values to the input parameters. Table 4 presents the set of values.

Table 4 Assigned values of variables

Parameter	Local variable	Value
r	#18	0.8
φ_2	#3	1
H	#11	20
D	#7	50
d	#8	50
Ra	#1	1.6
Z	#26	0
U	#21	10
S	#19	1500
M	#13	3
F	#9	0.3
Ap	#17	2

Since the values of the initial and final diameters are equal, the tool path, respectively, should be helical and not have a slope. Figure 8 shows the operating result of the cycle.

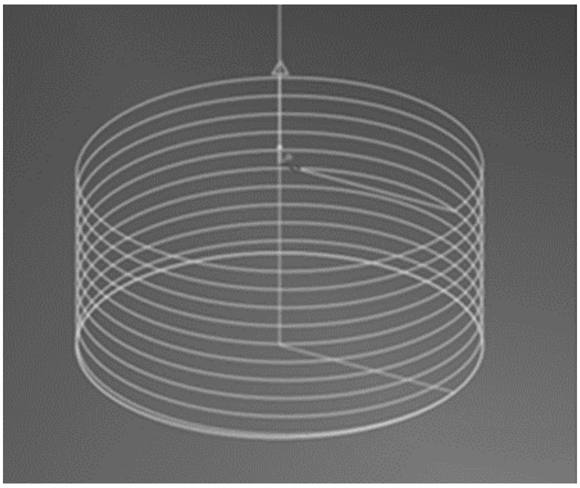


Figure 8. The operating result of the cycle with specified parameters

Next, we change the value of the local variable #8, which is responsible for the final diameter of the hole. We set its value equal to 10. With this value, the slope of the hole should be 45 °. We perform the cycle and present the drawing of the resulting path (Fig. 9).

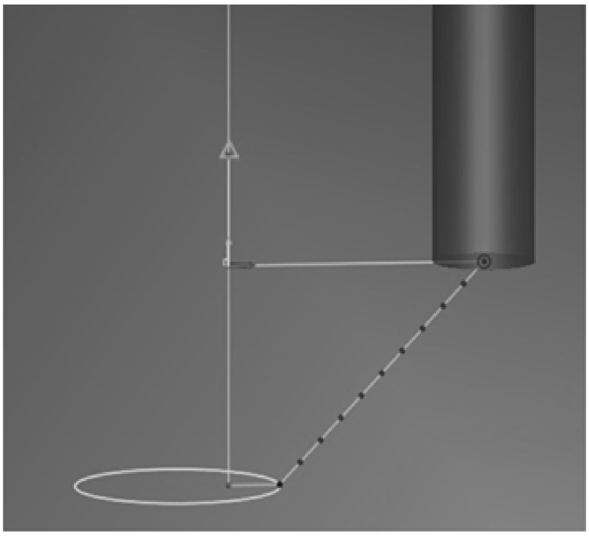
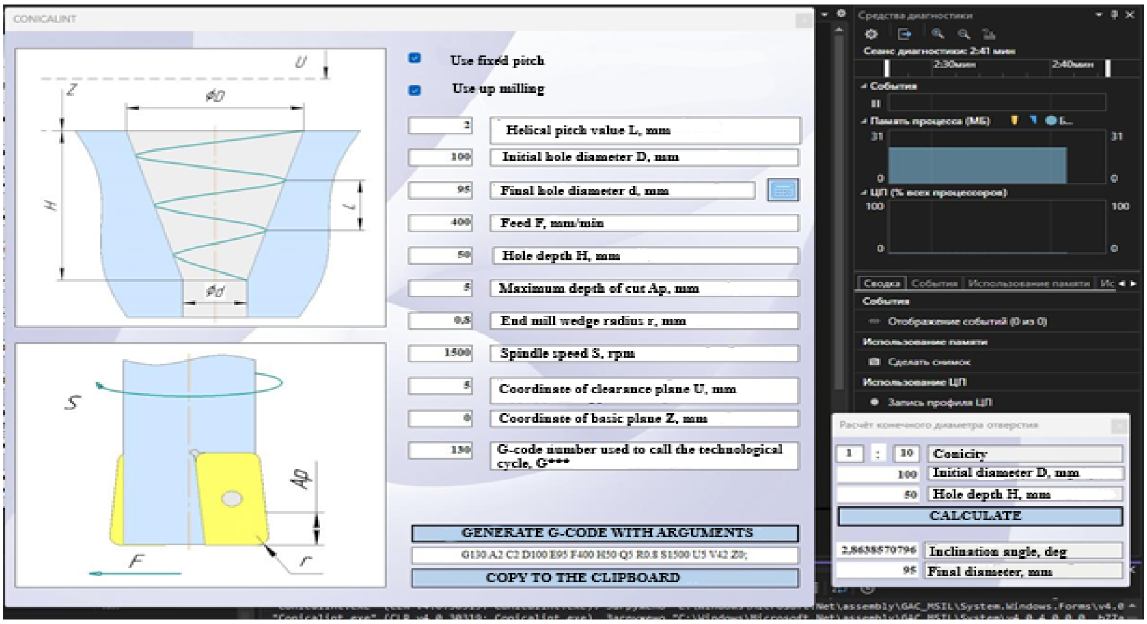


Figure 9. The operating result of the cycle with specified parameters

Figure 9 shows that the CIMCO Edit editor of the control programs does not have an algorithm for drawing a conical helical path, but, nevertheless, it displays the end point of the path that completes each of the turns.

Description of the developed CONICALINT software

Figure 10 presents the developed CONIICALINT software for the Windows operating system. The application is an instrument of graphic visualization for entering the input parameters and generating a G-code control with a set of arguments of the developed technological cycle. This application was designed on the Windows Forms platform in the Microsoft Visual Studio development environment. The application program code is written in the C# programming language.



☑ Use fixed pitch

☑ Use up milling

2 Helical pitch value L, mm

100 Initial hole diameter D, mm

95 Final hole diameter d, mm

400 Feed F, mm/min

50 Hole depth H, mm

5 Maximum depth of cut Ap, mm

0,8 End mill wedge radius r, mm

1500 Spindle speed S, rpm

5 Coordinate of clearance plane U, mm

0 Coordinate of basic plane Z, mm

130 G-code number used to call the technological cycle, G***

G130 A2 C2 D100 E95 F400 H50 Q5 R0.8 S1500 U5 V42 Z0;

1 : 10 Conicity

100 Initial diameter D, mm

50 Hole depth H, mm

2,8638570796 Inclination angle, deg

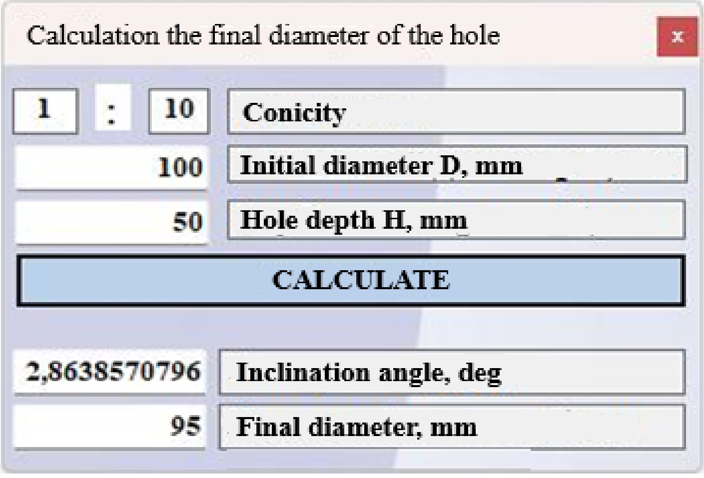
95 Final diameter, mm

Figure 10. Developed CONICALINT software

This application has the following principle of operation:

1. The user introduces the values of 11 variables, the description of which is given in the “Definition of the initial data” paragraph of this work. If the final diameter of the hole is unknown, and the cone is known, then when the button depicted in Figure 11 is pressed, the calculator window (Fig. 12) is opened to calculate the final diameter of the hole.

Figure 11. Calculator window opening button



Calculation the final diameter of the hole

1 : 10 Conicity
100 Initial diameter D, mm
50 Hole depth H, mm
2,8638570796 Inclination angle, deg
95 Final diameter, mm

Figure 12. Calculator window

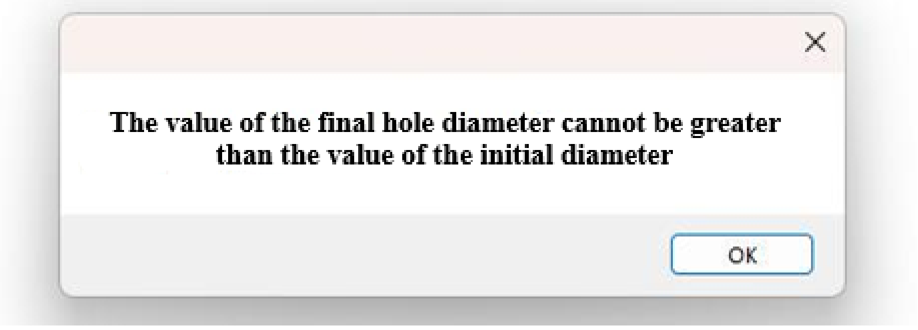
2.The user needs to indicate which of the two methods of calculating the cutting tool path is used. By default, the path calculation method is selected based on the value of the required roughness. If it is necessary to use the methodology that uses a fixed helical pitch to calculate the path, then the user needs to set the corresponding flag shown in Figure 13. It is also possible to choose a milling method in the developed technological cycle. By default, the method of down milling was chosen. We can switch to up milling by setting the corresponding flag (Fig. 13).

☑ Use fixed helical pitch

☑ Use up milling

Figure 13. Selecting the path calculation method

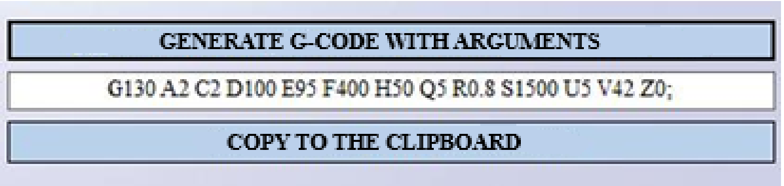
3.When clicking the “Generate G-code with arguments” button, the application checks the boundary conditions (see point 2) and the formats of the entered numbers. If an incorrect value for any parameter is entered, the corresponding error message is displayed to the user. The example is shown in Figure 14.



The value of the final hole diameter cannot be greater than the value of the initial diameter

Figure 14. Error message displayed

4.If all entered values pass the check, then the application generates a control G-code with a set of arguments (Fig. 15), through which the developed technological cycle will be called for execution from the memory of the CNC system. Also, for convenience, there is a button for copying the control G-code to the clipboard.



```
G130 A2 C2 D100 E95 F400 H50 Q5 R0.8 S1500 U5 V42 Z0;
```

Figure 15. Generated G-code with the set of arguments

The use of CONICALINT software minimizes the risk of making an error when entering incorrect values of input parameters even at the stage of designing the control program using the developed technological cycle.

Design of control programs using the developed technological cycle

To verify the operability of the developed technological cycle for milling holes, let us design a set of control programs for executing a group of operating steps for milling conical and cylindrical holes when machining the “Plate” part, the CAD model of which in an isometric view is presented in Figure 16.

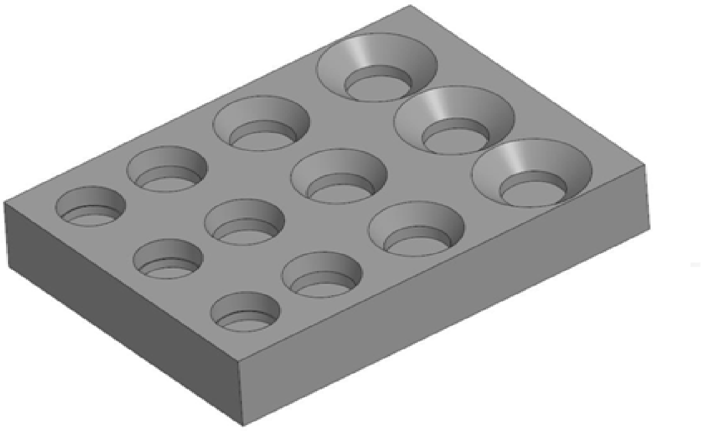


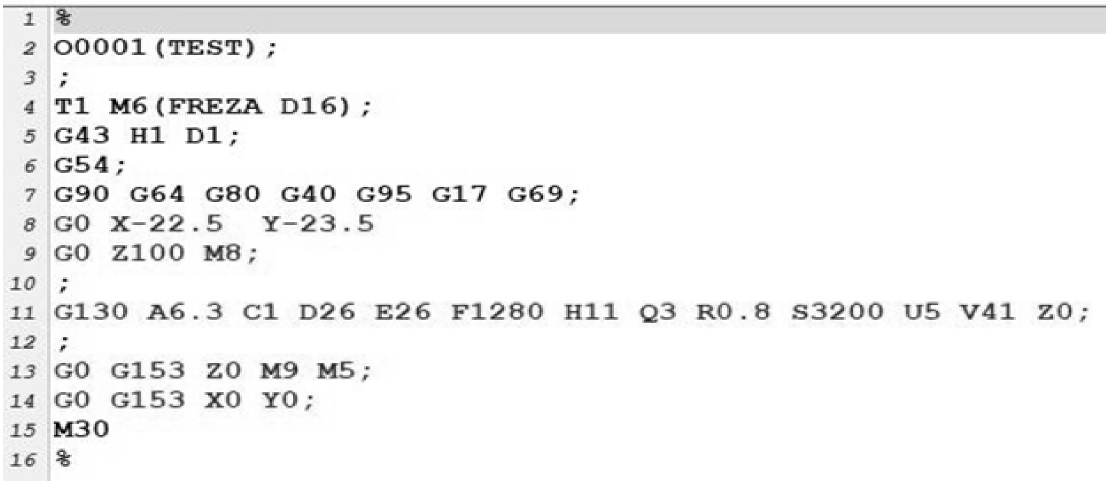
Figure 16. CAD model of the “Plate” part

Using the developed CONICALINT software and the calculator built into it, we generate a G-code with a set of arguments for making each of the twelve holes. The first row of twelve holes must be made with a roughness Ra of 6.3, the second row with a roughness Ra of 3.2, and the third with a constant helical pitch L =0.75 mm. We summarize the data in Table 4.

Table 4 Generated G-codes

Hole number	Generated G-code
1	G130 A6.3 C1 D26 E26 F1280 H11 Q3 R0.8 S3200 U5 V41 Z0;
2	G130 A6.3 C1 D30 E24.105 F1280 H11 Q3 R0.8 S3200 U5 V41 Z0;
3	G130 A6.3 C1 D36 E23.298 F1280 H11 Q3 R0.8 S3200 U5 V41 Z0;
4	G130 A6.3 C1 D45 E41 F1280 H11 Q3 R0.8 S3200 U5 V41 Z0;
5	G130 A3.2 C1 D26 E26 F1280 H11 Q3 R0.8 S3200 U5 V41 Z0;
6	G130 A3,2 C1 D30 E24.105 F1280 H11 Q3 R0.8 S3200 U5 V41 Z0;
7	G130 A3.2 C1 D36 E23.298 F1280 H11 Q3 R0.8 S3200 U5 V41 Z0;
8	G130 A3.2 C1 D45 E41 F1280 H11 Q3 R0.8 S3200 U5 V41 Z0;
9	G130 A0.75 C2 D26 E26 F1280 H11 Q3 R0.8 S3200 U5 V41 Z0;
10	G130 A0.75 C2 D30 E24.105 F1280 H11 Q3 R0.8 S3200 U5 V41 Z0;
11	G130 A0.75 C2 D36 E23.298 F1280 H11 Q3 R0.8 S3200 U5 V41 Z0;
12	G130 A0.75 C2 D45 E41 F1280 H11 Q3 R0.8 S3200 U5 V41 Z0;

Next, we design twelve control programs using the data from Table 4. An example of the text of a control program for milling the first hole using the developed technological cycle is shown in



```
%
O0001(TEST);
;
T1 M6(FREZA D16);
G43 H1 D1;
G54;
G90 G64 G80 G40 G95 G17 G69;
G0 X-22.5  Y-23.5
G0 Z100 M8;
;
G130 A6.3 C1 D26 E26 F1280 H11 Q3 R0.8 S3200 U5 V41 Z0;
;
G0 G153 Z0 M9 M5;
G0 G153 X0 Y0;
M30
%
```

Figure 17. Control program for milling the first hole

In the designed control programs, along with some G-code arguments for calling the developed technological cycle, the coordinates of the center of each hole in the XY working plane are also different.

Results:

1. The initial data is represented by thirteen parameters characterizing the geometry of the cutting tool, the geometry of the required machined surface, as well as parameters that determine the milling method, calculation method, cutting mode and starting points of the cutting tool path.

2. Eight boundary conditions are identified that determine the permissible values of the input parameters. Based on these conditions, a system of inequalities was designed with a set of error messages to the user in case of incorrect input of the value of any of the input parameters.

3. The developed algorithm for the technological cycle of milling holes with an end mill has a branched structure, since there is a choice between two methods for calculating the internal parameters of the cycle and two milling methods: down or up cutting.

4. Calculation of the internal parameters of the technological cycle consists of calculating the coordinates of the points necessary to construct the helical path of the cutting tool and calculating the value of the maximum permissible value of the helical pitch within a given set of input parameters.

5. The developed G-code of the technological cycle subroutine for a CNC machine makes it possible to calculate the tool motion, both along helical and conical helical paths, depending on the input parameters, which allows it to be used when programming milling of cylindrical and conical holes.

6. It is impossible to visually simulate the conical helical path of a cutting tool using the CIMCO Edit control program editor, which leads to the need to verify the operability of the technological cycle directly on a CNC machine.

7. The developed CONICALINT software is a visual addition to the developed technological cycle for milling holes, allowing the generation of a control G-code with a set of twelve arguments.

8. Based on the developed technological cycle for milling holes, 12 control programs with different sets of input parameters were designed. According to these control programs, a group of operating steps was carried out and quality control of the processed surfaces was performed, which showed the compliance of the results of mechanical processing with the initial requirements.

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