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CONTOUR MILLING PROGRAMMING TECHNOLOGY FOR VIRTUAL BASING ON A CNC MACHINE

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Представлена нова технологія і прикладна програма для автоматизації програмування операції фрезерування при віртуальному базування заготовки на столі верстата з ЧПУ, коли точна установка заготовки за координатним осями верстата ускладнена. Вирішення такої науково-технічної проблеми дозволяє виконувати контурне фрезерування деталей при їх довільному розташуванні на столі верстата з ЧПУ з гарантованим вирівнюванням припуску за траєкторією формоутворення.

Методика передбачає послідовне виконання трьох етапів з паралельним використанням створеної прикладної програми. На першому етапі готується електронна копія креслення деталі, яка містить виділені різними кольорами контур деталі і заготовки. Таким чином, при скануванні забезпечується автоматичне створення цифрових двомірних масивів геометричних образів, необхідних для вирішення завдання. На другому етапі в створену програму вводяться виміряні щупом на верстаті координати трьох точок заготовки. На підставі введених даних в створеній програмі вирішується завдання вирівнювання припуску методом Гаусса-Зейделя при використанні розмірності Хаусдорфа. Такий підхід дозволяє отримати кількісну оцінку подібності полігональних об'єктів, що необхідно для вирішення задачі мінімаксу розташування припуску. Задача полягає у визначенні корекції управляючої програми за двома лінійними координатами і однією кутовою навколо центра мас заготовки. На третьому етапі визначені в програмі величини корекції вводяться у стійку ЧПУ верстата і починається оброблення контуру.

Запропонована методика і створена прикладна програма були апробовані при обробленні контуру деталі на фрезерному верстаті VF-3 HAAS. Практична апробація показала ефективність методики, яка полягає в забезпеченні фрезерування гарантовано без перевантаження інструменту і скорочення часу обробки при віртуальному базування заготовки

Ключові слова: віртуальне базування, фрезерування контуру на верстаті з ЧПУ, підготовка управляючої програми

1. Introduction

It is known that the program for processing any surface of a part on a CNC machine must be tied to a specific position of the workpiece in the machining zone [1]. Typically, this problem is solved in two ways: either the workpiece is installed in a device that is pre-oriented relative to the coordinate axes of the machine, or the workpiece is installed directly on the machine table with the subsequent alignment of its actual position relative to the axis of the machine.

To implement the first method, it is necessary to ensure the presence of base surfaces of the workpiece, by which it is installed in the device, and when such conditions are met, binding the control program to the actual position of the workpiece on the machine does not cause difficulties [2]. When it is necessary to perform similar operations for large

sized parts (workpieces), for example, in aircraft manufacturing, shipbuilding, turbine construction, significant difficulties arise. First, the installation of a billet of large dimensions and mass in the desired position and its alignment takes a lot of time and effort, which leads to a significant loss of total time and does not guarantee an optimal (uniform) distribution of the allowance on the treated surfaces.

Secondly, in case of accidental installation of the workpiece, to bind its position to the control program, it is necessary to perform numerous measurements of its actual position, usually with a contact probe, which also leads to significant loss of time [3, 4].

In such cases, a promising technology is that the workpiece is installed on the machine using simple tools, such as tacks, so that it can process its surfaces in one operation, and the control program adapts to its specific position. It is important to ensure the optimal location of the future parts in the body of the workpiece, for a uniform distribution of the allowance along the entire path of the tool.

It is important to ensure the optimal location of the future parts in the body of the workpiece, for uniform distribution of the allowance along the entire path of movement of the tool. Known solutions to this problem are associated with considerable difficulties, and it still remains relevant for solving practical problems of mechanical engineering.

2. Literature review and problem statement

So, to solve this problem, it is necessary to establish the exact actual position of the workpiece on the machine. Such operations can be performed using the OMV technology (On Machine Verification), which Delcam offers [5]. It is reported about the use of «virtual basing», when the cost of OMV-measurements before the start of milling is much less than with manual basing, and the control program is corrected using special algorithms that are not disclosed [6]. It is also not indicated whether the developed algorithms provide such a distribution of processing allowance, at which the optimization problem presented in [7, 8] is solved for the case of processing large-sized cylindrical parts.

Earlier, the authors proposed an adaptive processing when programming the operations of milling the contours of parts on a CNC machine in the case of virtual basing of the workpiece, which is performed as a result of solving the minimax problem [9]. Moreover, the developed mathematical model allows you to uniquely determine the position of the workpiece on the machine table by the measured coordinates of all three of its points. When designing control programs and for modeling cutting processes in CAD/CAM systems, the solid model of the workpiece, the tool path and its geometric characteristics are mainly used [10]. The use of solid-state models for solving the problem is inexpedient, and the method of presenting the contours of the workpiece and parts in the form of the proposed digital models requires complex, time-consuming calculations, which is an obstacle to the practical application of the developed software.

Therefore, the scientific and technical problem of preparing a control program for virtually basing a workpiece of arbitrary shape in order to reduce time and ensure uniform distribution of the allowance across all surfaces processed in an operation is relevant.

3. The aim and objectives of the study

The aim of the work is to develop a technology for preparing data for programming adaptive processing by contour milling, with the solution of the optimization problem by the criterion of maximum uniformity of allowance during virtual basing of the workpiece on a CNC machine. To achieve this goal, it is necessary to solve the following tasks:

– to form an algorithm for creating models of blank contours and parts in the form of two-dimensional digital arrays and to develop an appropriate numerical procedure;

– to develop a procedure to uniquely determine the position of the workpiece on the machine table based on the measured coordinates of all three of its points;

– to develop an algorithm for finding the criterion for the similarity of the contour of the workpiece and the tool based on the Hausdorff dimensions;

– to create an algorithm of coordinate descent to solve the minimax problem of the location of the allowance along the shaping path;

– to implement all the developed procedures in the application program and test the effectiveness of the proposed technology in practice.

4. Methods and results of the study of the milling process in virtual basing on the CNC machine

4. 1. Problem statement

Automation of data preparation for the design of a CNC control program for milling involves the creation of a virtual based application program that can be easily adapted to production conditions. Therefore, the construction of the algorithm of the application program, which provides for the sequential implementation of the three stages is proposed.

At the first stage, digital arrays of geometric models of workpiece contours and parts are created, which describe flat geometric contours by two-dimensional arrays of points with a predetermined step. Moreover, this array should represent contours both in Cartesian and polar coordinate systems with a pole, for example, in the center of mass of a flat figure of a part. At the second stage, the algorithm and, accordingly, the application program must allow for the orientation of the digital array of the workpiece according to the coordinates of the three points of the real workpiece measured on the machine. And, finally, at the third stage, an automatic solution of the optimization problem is performed according to the criterion of maximum uniform distribution of the allowance. Of course, in practice, after working with the program, it is necessary, based on the results of the calculated offsets, to perform the corresponding offsets of the previously created control program, using standard G-codes.

Further, it is proposed to consider the implementation of all stages and the software of the created application program on the example of milling the bracket contour (Fig. 1).
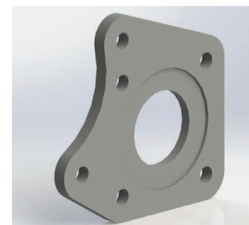

Fig. 1. Bracket

4. 2. Creating models of the contours of the workpiece and parts

As noted earlier [9], the framework representation of geometric models is successfully used for computer modeling tasks for machining parts on CNC machines. This representation describes flat geometric contours by two-dimensional digital arrays of points with a predetermined step.

To simplify the procedure of transition from the drawing of the part to the required type of digital models, a technique is proposed based on the procedure for scanning a graphic image.

The standard scanning procedure is presented in the corresponding graphic window of almost any structured object-oriented programming language, for example, Delphi. Preparation of the drawing involves some refinement, which consists in the fact that in any editor the electronic copy of the drawing is processed manually using the tools of the editor, highlighting the contour of the part to be milled with lines of the corresponding color. They also design the contour of the workpiece and make sure to put a marker line to determine the real scale of the pattern in the program. The marker line is applied using dimensional lines of the drawing. When performing such simple actions, the color of the lines should be selected using an additive color model (RGB), which will allow you to uniquely identify the corresponding image points for scanning.

A drawing prepared in this way, for example, in the standard Microsoft Word editor, must be copied to the standard Paint editor and the file in a 24-bit pattern format *.bmp must be saved.

Next, the created application is used, whose interface is shown in Fig. 2. In the window you need to write the address of the saved file and click the Download button. A drawing image appears in the graphics window with the lines highlighted earlier: part contour – blue color (RGB (0, 0, 200)), designed workpiece contour – red color (RGB (200, 0, 0)), dimension marker line – green color (RGB (0, 200, 0)).

As can be seen from the figure, the marker line is located between two dimension lines (34+34=68 mm) and the corresponding value is recorded in the program interface window. Now the corresponding scale will be applied in the graphic window of the interface and when you move the mouse, its coordinates in millimeters will be displayed in the window.

Then, when pressing the button «Scanning», the procedure of scanning the graphic window in all three colors is turned on with entering the coordinates of the corresponding points into two dimensional digital arrays: $D(x, y)$ – part contour, $Z(x, y)$ – workpiece contour. Thus, the discreteness of the representation of the contours will be one pixel of the screen, which is quite enough to solve the problem. In this case, the image of the part and workpiece contours is placed in the center of the graphics window, and the program performs recalculation of digital arrays representing the part and workpiece contours in the polar coordinate system, which is necessary for subsequent manipulations with them.

4. 3. Procedure for determining the position of the workpiece on the machine table

Windows appear in which you must enter the coordinates of the bases of the workpiece, measured directly on the machine using a standard three-axis contact probe and standard commands on the CNC machine tool stand. At the same time, to determine the position of the workpiece, coordinates of three points not only with a rectangular contour, but even with any other, open contour of the workpiece are enough. This is explained by the fact that measurements are performed on an already digitized contour and its position on the plane is uniquely determined by the coordinates of three points, conventionally represented in the form of the corresponding bases and necessarily present in the digital array.

After clicking the Apply button, these points appear in the graphics window and now you can move the contour of the workpiece in the graphics window in accordance with the bases actually measured on the machine. The movement is performed manually using the mouse (pressing the left key and moving along the X and Y coordinates) and buttons in the right corner of the graphics window to rotate the contour around the pole. It is so easy to orient the contour of the workpiece according to the actual position of the workpiece on the machine table.

4. 4. Algorithm of search for similarity criterion

When the Go button is pressed, an automatic search for such a position of the workpiece at which the maximum allowance along the entire contour will be minimal will begin. To organize a directional search that is optimal by the criterion of the minimax allowance, it is necessary to have a quantitative criterion. Analysis shows that such a task is like the problems arising in the quantitative determination of the similarity of two polygonal objects. Thus, one of the possible solutions to this problem is the use of the Hausdorff dimension, which allows one to obtain a quantitative estimate of the similarity of polygonal objects [11, 12].

Fig. 3 shows the contours of the part and the workpiece, which are represented by digital arrays containing the coordinates of two sets of points $D = \{d_0, d_1, d_2 \ldots d_n\}$ for the part and $Z = \{z_0, z_1, z_2 \ldots z_m\}$ for the workpiece. Then the Hausdorff distance is defined as:
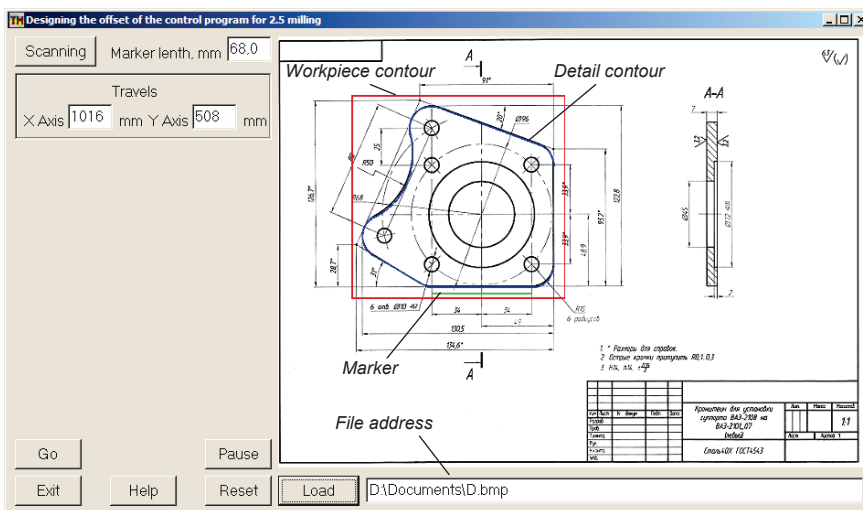

Fig. 2. Application program interface with loaded part drawing

$$H(Z, D) = \max(h(Z, D), h(D,Z)), \qquad (1)$$

where $h(Z, D)$ is the directional Hausdorf distance between Z and D; $h(D, Z)$ is the directional Hausdorf distance between D and Z.
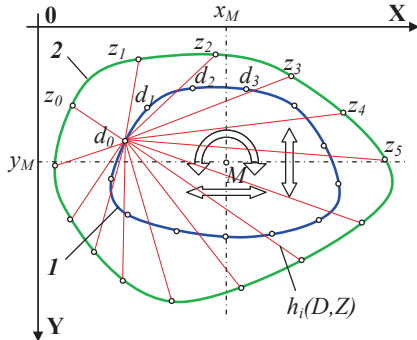

Fig. 3. To the solution of the similarity problem:
1 — part contour, 2 — workpiece contour

Some of these distances are shown in Fig. 3 by the lines for one point of the set of points of the part contour. From (1) it follows that this distance is not symmetric at all, i. e. $h(Z,D) \neq h(D,Z)$.

4. 5. Algorithm of coordinate descent

Thus, a quantitative estimate of the optimization criterion for minimizing the distribution of the milling allowance was obtained. Further operation of the program is carried out in accordance with the algorithm, the enlarged block diagram of which is shown in Fig. 4.
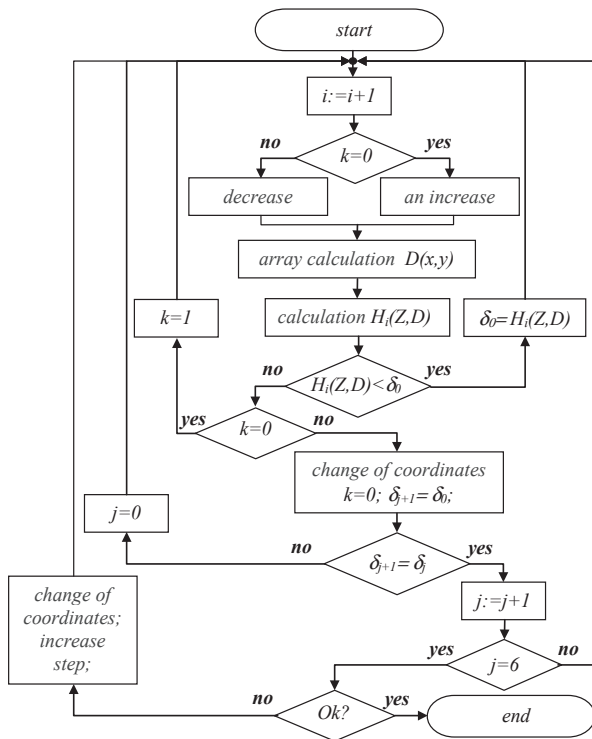

Fig. 4. Block diagram of the search for minimax allowance

At the first step ($i=1$), the initially calculated position of the part contour is changed by one step at the selected coordinate, either by the X coordinate, or by the Y coordinate, or by the angle of rotation φ. Linear movements are carried out with the pole $M(x_M, y_M)$, rotation – relative to the pole (see the arrows in Fig. 3). Further, the array of coordinates of points of the geometric model of the part contour is recalculated according to the new position $D(x, y)$ and the procedure for determining the Hausdorff distance $H_i(Z, D)$ is performed according to a separate algorithm presented in [9]. In accordance with the Gauss-Seidel extremum search method, the calculated distance is compared with the previously calculated maximum deviation δ_0. This process will be repeated until the condition $H_i(Z,D) < \delta_0$ is met. After that, when $k=0$, a step is made backward along the variable coordinate and the algorithm changes the direction of the pole movement. Now, the calculations are performed when another coordinate is changed, and the array of the part contour is recalculated again, and the maximum allowance difference is calculated. Movement in a new direction is carried out before the fulfillment of a similar condition $H_i(Z,D) < \delta_0$, and then the direction of movement changes again. Such cycles (j is the number of the cycle) are repeated until the condition $\delta_{j+1} = \delta_j$ is fulfilled 6 times, which means that the extremum is reached – the minimum of the maximum deviation of the allowance for processing (Fig. 5).
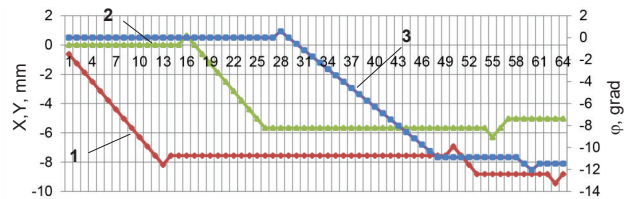

Fig. 5. Graphs of the coordinates in the search for an extremum: 1 — movement on X, 2 — movement on Y, 3 — movement on Fi

As follows from Fig. 5, the optimal values coordinates were obtained by the program in the process of automatic search for 65 iterations. Such values can be considered optimal, since they minimize the maximum value of the allowance along the shaping path.

4. 6. Simulation

Fig. 6 shows the program interface after the search for the extremum of the minimax allowance. The trajectory of a single point of the part contour is shown when the search movements are performed in all three coordinates, and displacement values appear in the interface windows that must be used to adjust the contour milling control program for such a workpiece base.

When you click the Save button, you can save all automatically made movements in the search coordinates. Using these data in Fig. 6, graphs of changes in these coordinates are plotted as a function of the step number approaching the extremum in the search process in accordance with the Fig. 4 algorithm. According to the Gauss-Seidel method of searching for an extremum, after the occurrence of the condition for changing the coordinate of motion, it changes one step back. It should be noted that there are cases of such a mutual arrangement of the contour of the part and the workpiece, for example, when crossing the contours, when the search is formally executed, but does not lead to the desired results.
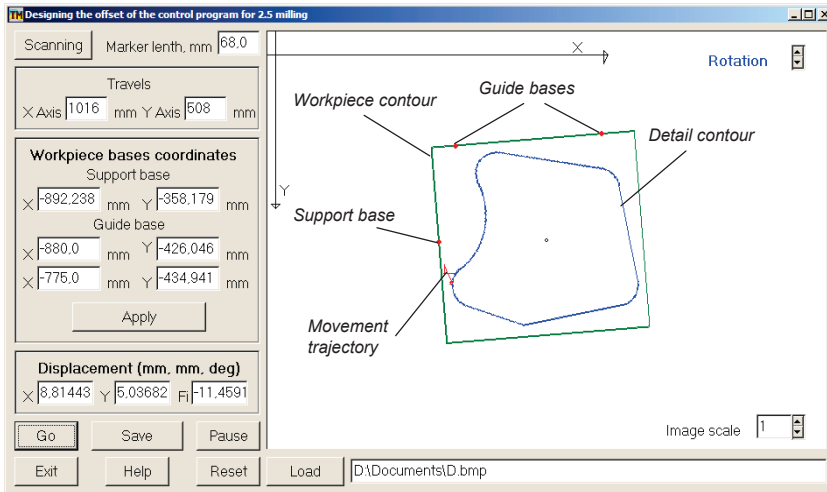
Fig. 6. Search results of contour milling control program offsets

To prevent such collisions, the search algorithm is made interactive when the final decision is taken by the process engineer. The way out of the deadlock position is carried out by the forced change of the motion coordinate with a 10 times change of the search step adopted in the algorithm.

The created program was tested with different values of the coordinates of the bases, which were entered into the corresponding interface windows. In the course of operation, there was always an optimal position of the control program with respect to the contour of the workpiece.

4. 7. Experimental study of milling in virtual basing

To illustrate the advantages of the developed methodology, modeling was carried out for milling the part contour (Fig. 1) at random basing of the workpiece using the application program created at the Manufacturing Engineering Department of the Igor Sikorsky Kyiv Polytechnic Institute. The machining of the contour of the part with the end mill $\varnothing$ 30 mm, Z6, with a feed of 0.1 mm/tooth and cutting speed of 50 m/min was simulated. For contour processing, a strategy of its circumvention along equidistant paths with a distance of 5 mm between them was adopted, and in areas where there was no cutting, an accelerated feed of

1000 mm/min was used. All these data were the same for all simulation experiments. Fig. 7, a presents the simulation results when processing a workpiece oriented along the coordinate axes of the machine. The graphical interface window shows the position of the workpiece and the trajectory of the center of the cutter, and the areas where the cutting took place are shown in green and the idle areas in red. Processing is completed in 18.5 minutes, with 8 passes around the part along equidistant paths. The same interface shows the position of the workpiece when basing in accordance with the principle of virtual basing, i. e. placing the workpiece on the table in a position that is determined by the measured coordinates of the three points, as in the above case.

Modeling of the machining, which was performed along the same paths, showed a significant excess of the specified depth of cut – in the first pass section, the cutting depth reached 12.1 mm, which in actual machining can lead to tool breakage. Reprogramming the control program in the CAM system, considering the actual location of the workpiece with the same processing strategy without changing the reference axes, excludes exceeding the depth of cut, but leads to an increase in the number of passes to 10, processing time to 22 minutes (Fig. 7, b).

For experimental verification of the developed technology on the table of the VF3 HAAS machine, a rectangular billet was installed in an arbitrary position and secured with clamps. The measured values of the coordinates of the three points, which denote the conventional bases, were recorded in the application program windows, and the correction results were used to correct the location of the control program.

So, to rotate the CNC machining program at a given angle, the G68 rotation function was used, and the offsets along the $X=8.8$ mm and $Y=4.4$ mm coordinate were added to the coordinates of the G54 working coordinate system. The milling conditions and the machined contour are fully consistent with those set (Fig. 8).
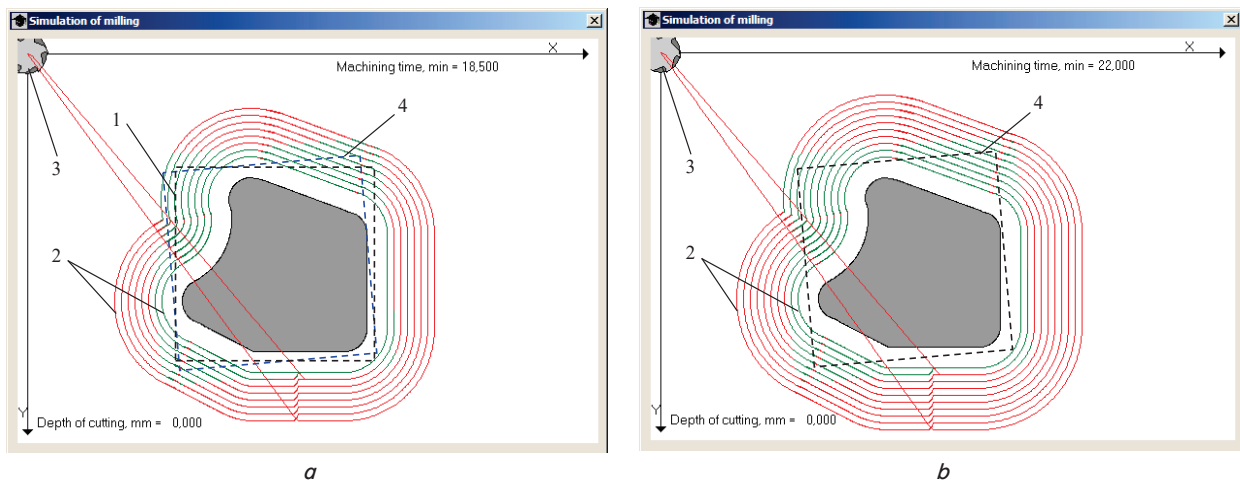

Fig. 7. Simulation results of the part contour milling: 1 — blank contour in CAM, 2 — paths, 3 — milling cutter, 4 — blank contour on a CNC machine: a — the blank is oriented along the machine axes, b — the control program is redesigned in the CAM system taking into account the actual position of the workpiece on the machine
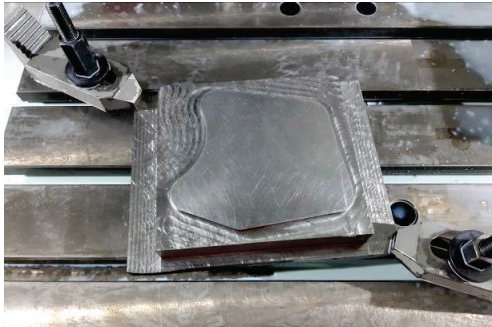
Fig. 8. Processed contour on the machine table VF3 HAAS

5. Discussion of the results of the study of milling technology in the virtual basing

To machine a part on a CNC machine, it is necessary to install the part on the machine table and, in turn, base it on the machine table. To perform the operation of basing, the workpiece must have the appropriate «mounting base» surfaces, with the help of which it is correctly oriented relative to the machine or cutting tool. Such a process requires a lot of time and effort, especially when processing large-sized parts, which often takes place in the aircraft industry.

With the improvement of CNC machines and contact measuring devices, it became possible to determine the position of the workpiece with an accuracy of up to 0.001 mm on the machine table in a matter of seconds. Due to this, it became possible to abandon the complex tooling, alignment and movement of the workpiece on the machine table.

The most important problem of creating digital arrays of blank contours and parts was solved. A similarity criterion for geometric models is found, and its numerical value is used in solving the minimax problem.

The proposed technology allows one not only to «virtually move» the control program to the actual position of the workpiece, but also to do this in such a way as to maximize the allowance for processing along the entire trajectory.

The conducted studies using the example of contour processing of relatively simple parts showed that the proposed virtual-based technology allows determining the position of the part on the machine table even in the absence of base surfaces. At the same time, there is no need to perform basing operations, which in turn reduces the time required to install the workpiece on the machine table, and also does not require special qualifications of the machine operator. In addition, the most important task of maximally aligning the allowance along the entire path of the contour processing is solved.

In the future, the developed technology will also be extended to 3D processing of complex relief surfaces of machine parts. In this case, it is possible to use the representation of a 3D object in the form of a set of 2D contours, for each of which it is possible to solve the problem according to the proposed technology and further compromise integration of such solutions.

6. Conclusions

1. A new method has been developed for preparing a control program for contour milling, which allows you to bind a control program to the actual position of the workpiece so that the maximum allowance value is as low as possible. The technique is most effective in processing large-sized parts of complex configuration, when accurate basing and alignment of the workpiece on the machine cause considerable difficulties.

2. The method involves the implementation of three stages. At the first stage, an electronic copy of the part drawing is prepared using standard Microsoft Office programs, highlighting the part contour for milling and drawing the blank contour. The file prepared in this way is loaded into the graphical window of the application program. At the second stage, the coordinates of the three base points of the workpiece installed on the machine table are measured and the results are recorded in the appropriate windows of the application program. At the third stage, the control program is shifted at the stand by the machine according to the design results and the milling operation is performed.

3. The created software is maximally adapted for practical use directly in the process of preparing an operation on a CNC machine. The developed algorithm allows you to automatically create arrays of geometric models of part and workpiece contours using the image scanning procedure, and interactively searches for an extremum when solving the task of minimizing an allowance location using the Hausdorff dimension, which allows you to quantify the similarity of polygonal objects.

4. Preliminary modeling of possible options for organizing a machining strategy on a CNC machine with virtual basing shows that without applying the developed technique, contour milling results in a significant excess of the cutting depth in some sections of the contour, which can lead to tool breakage or an increase in processing time. Approbation of the developed technique for machining the part contour on a VF3 HAAS CNC machine proves its effectiveness.

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IMPROVING EFFICIENCY OF MACHINING THE GEOMETRICALLY COMPLEX SHAPED SURFACES BY MILLING WITH A FIXED SHIFT OF THE CUTTING EDGE

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Для підвищення ефективності обробки фрезеруванням складних фасонних поверхонь (СФП), застосовуються в основному методи, пов'язані з поліпшенням властивостей інструментального матеріалу, зміною складу та властивостей поверхневого шару інструменту, нанесенням тонкоплівкових покриттів, зниженням шорсткості робочих поверхонь і поліпшенням умов експлуатації інструменту застосуванням ЗОТС.

Виходячи з вище викладеного в роботі досліджені та викладені науково обґрунтовані технічні та технологічні рішення, які полягають в розробці нового високоефективного способу обробки складних фасонних поверхонь дисковими радіусними фрезами зі зворотно-гойдальним рухом подачі. Даний метод обробки дозволяє підвищити період стійкості інструменту в 1,7 рази і продуктивність фрезерування в 1,6 рази, за рахунок постійного кінематичного зсуву ріжучої крайки відносно поверхні різання.

Запропоновано математичний апарат способу фрезерування з постійним зсувом ріжучої крайки. Аналіз даного методу за допомогою числових функцій, дозволив встановити аналітичні залежності для визначення товщини та об'єму одиничного зрізаємого шару.

Основний вплив на величину товщини зрізаного шару надає подача на зуб Sz, а на обсяг – кут υ, що визначає нормальні умови різання. Досліджено модель розподілу теплових потоків в ріжучому клині для способу фрезерування зі зворотно-гойдальним рухом подачі, що враховує амплітуду руху, що гойдає заготовки. Встановлено зниження температури до 330,2...395,5 °C, тобто на 80,6...181,6 °C для штампової сталі 9ХС і до 193,8...285 °C, тобто 56,6...120,2 °C для сталі 45, в порівнянні зі звичайним фрезеруванням. Встановлено, що загальна довжина ріжучої крайки збільшується в 2,4 рази, при цьому температура знижується в 1,5 рази

Ключові слова: фрезерування, кінематична схема різання, ріжучий інструмент, ріжуча крайка, складна фасонна поверхня, ЧПУ

1. Introduction

Kinematic schemes of surface machining, cutting tool designs and initial tool surfaces directly affect durability of the cutting tool material and, consequently, machining efficiency. For example, when 20CR13 steel is machined by means of a carbide tool, transition from kinematic schemes with a continuous cutting process (turning with a cutter)