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A CASE STUDY OF THE TOOL PATHS STRATEGIES APPLICABLE FOR MILLING COMPLEX SURFACES ON A THREE COORDINATES CNC MACHINES

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Abstract: *Milling on three-axis CNC machines is an essential method for processing materials with broad applications in various industrial domains. An important part of the milling process involves optimizing tool movements, such as positioning and retraction during the machining process, which plays a crucial role in achieving efficient machining of complex surfaces of parts. Tool movement optimization is crucial in reducing processing time, costs, and errors. Thus, a careful approach and suitable strategy are necessary to ensure precise and rapid processing of parts. In this work, we will analyze several methods and techniques that can be used for optimizing tool movements in milling complex surfaces on three-coordinate CNC machines*

Key words: *CNC milling, Tool movements optimization, Complex surfaces, Manufacturing efficiency, Three-axis machine).*

1. INTRODUCTION

The successful placing on the market of a product is totally determined by the technological process used, which is responsible for the production cycle and its quality. Thus, lately we can see a massive increase in CNC machines, which have significantly shortened the production cycle and cost, especially for manufacturing parts with complex surfaces, for example parts for aircraft, cars, and molds.

The results of previous studies allow us to understand that the reduction of machining time, quality and correctness of the technological process have been optimized through different techniques and methods of real-time monitoring of tool wear[1-2] capturing data on cutting force frequency, surface quality, tool strength and other parameters has developed new strategies to improve machining parameters. Based on these data, much research has been conducted on tool selection and engagement methods [3-6] minimizing the risk of unwanted incidents, ensuring a safer working environment for tools.

The 3-axis CNC machines typically work with linear movements between interpolation points, so complex surface curves can be misestimated. This can lead to reduced accuracy and errors, such as misalignment errors when the tool is not positioned correctly relative to the machined surface. In addition, these surfaces can often be asymmetrical or have multiple recesses and levels (Fig.1), which makes their processing more difficult. Of course, this was not possible without the implementation of advanced mathematical models in CAM software, which provide mobility to changes or new requirements in an efficient way. This implies the ability to reconfigure and modernize existing technological processes or implement new processes quickly to meet the ever-changing needs and requirements of industrial dynamics.

Unlike three-dimensional bodies with flat faces, the bodies with complex surfaces often require more advanced machining techniques because of Non-Uniform Rational B-Spline (NURBS) surfaces [7] which are characterized by a density of control points leading to the need to use a large number of parts to reproduce surfaces, which increases the complexity of the CNC program and machining time.

In general, the selection of tool movements is based on advanced mathematical models implemented in CAM software. These mathematical models are developed based on complex algorithms that take into account several parameters, such as the geometry of the part, the material from which it is made, the cutting speed, the cutting depth.

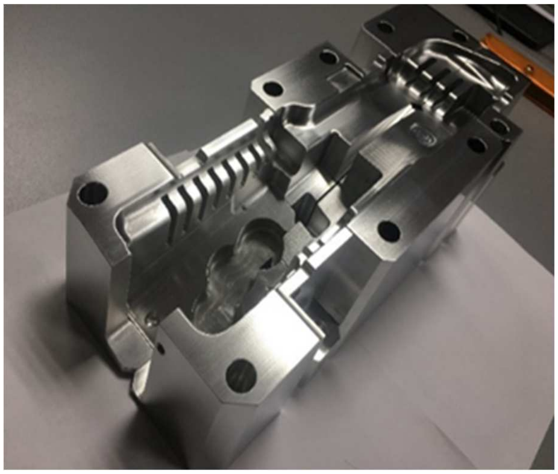

Fig.1. Complex surfaces

2. RELATED LITERATURE

Over the years, different types of path planning strategies have been defined during the processing process. The main tool path planning strategies are:

- isoparametric which involves maintaining uniform parameterization along a curve [8].
- isoplanar using curves that lie on a constant plane parallel to the tangent plane of the surface [9].
- iso-scallop [10] based on parallel planes along the surface for processing complexly shaped surfaces, each with its own advantages and limitations [11].

Park and Chung [12] attempted to address this problem based on 2D curve compensation and polygon chain intersection algorithms to avoid time-consuming 3D calculations (Fig.2), i.e. once tool paths are found in a single plane, it is much easier to post-process direction by extracting extreme points along curves. Another model that simplifies tool movements is made by Ahmet M.[13] where the algorithm is also constructed based on choice based on maximum cutting speed, taking into account machine power and tool life as restrictive factors.

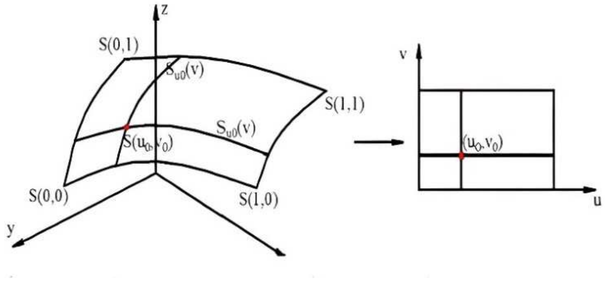

Fig.2. 3D point to 2D point

Lin and Liu [14], proposed a Z-map model for generating isoplanar tool paths from measured points. Roughing paths were generated layer by layer, while finishing paths were obtained by updating the height of the cutter at each point, taking into account tool input on the points.

Another approach to this topic was presented by Ponomarev B.B [15] who analyzes more the machining area of a single tool and proposes an algorithm that determines the minimum allowable lifting heights of spherical or conical tools to minimize tool idle movements (Fig.3).

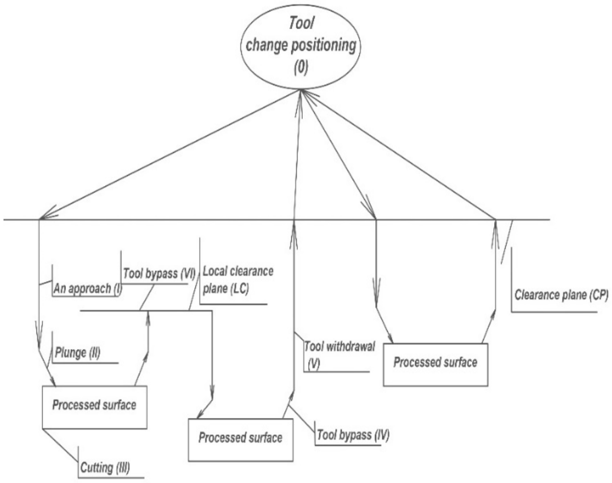

Fig.3. Motion minimization algorithm

Also, an approach to segmentation of machining areas based on measuring the geometric complexity of data points, but machining being done with multiple tools, wascarried out by Teng, Z [16]. Regions of high or low complexity are separated and machined separately using the normal vector, thus it has been observed that high machining efficiency is achieved because the tool path is significantly reduced and non-complex areas are processed by larger and more efficient milling cutters.

The geometry of the parts relative to the chosen tools determines the engagement point. Cutting tools are not an idealized geometric point and have a ball tip with a finite radius, as shown in Fig. 3, where point CC is the point of contact and point CL is the location of the milling cutter. The tool path is referred to as cutter location (CL) data, to be generated from part surface data designed and used by the CNC controller to drive the cutting tool.

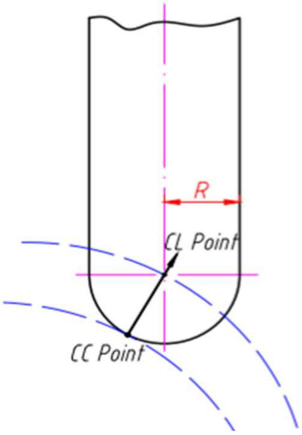

Fig.4. Tool contact point

Section 2 presents an analysis of the specialized literature for various attempts made in this direction. Section 3 will address an experimental method based on the choice of multiple strategies and the optimization of the G-code through a special tool. The results and conclusion are presented in Section 4.

3. ANALYSIS AND EXPERIMENTAL TESTING

CAM systems rely heavily on the contribution of engineers, particularly on their level of professional knowledge in making decisions related to tool selection, cutting parameters, method, and sequence of operations. Incorrect adjustment of CNC programs can lead to degradation of the technological process, long processing times, errors and defects in parts, as well as excessive tool wear. Therefore, in order to create correct and optimal programs, a case study was conducted focusing solely on the finishing operation. In this study, multiple tool paths generated automatically by SolidCam software were presented and tested.

For the experimental part, a 3D model (Fig. 5) was developed, used in ultrasonic welding installations for plastic material, with specified geometric parameters listed in Table 1. Since these types of parts are mostly unique, the semi-finished product was chosen from a 60 mm thick sheet, in accordance with what was found on the market [17].

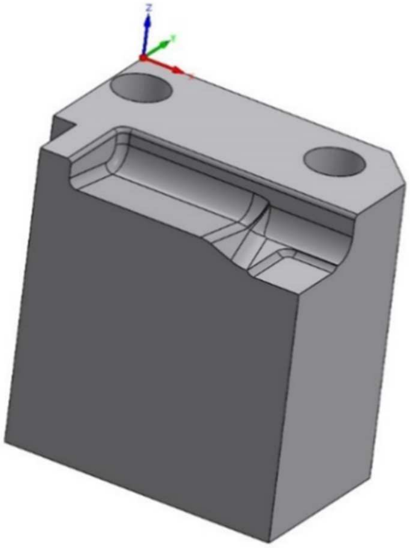

Fig.5 Experimental model

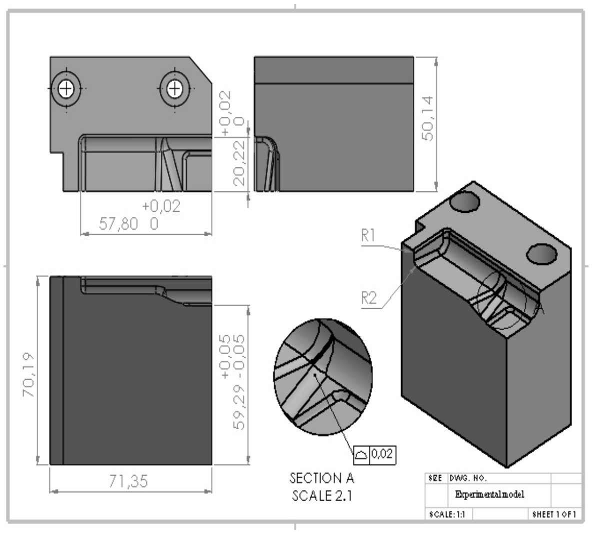

Fig.6 Technical drawing

Table 1

Characteristic of the model

Specification	Information
Material	Aluminum alloy (2017)
Dimension	71.35mm×70.19mm × 50.14mm
General Tolerance	± 0.1

The processing plan was developed for a 3-axis machining center. Four processing techniques involving high feeds to remove material were selected. These include: HSS parallel to curves, HSS parallel cutting - linear, HSS parallel cutting - hatch, and mixed method. Surface machining was performed in a single pass and under the same conditions for all techniques, using a single Ø4 mm ball nose end mill (Fig. 7), following recommended cutting parameters (Table 2).

Fig.7 Tool

Table 2

Characteristic of the tool

Specification	Information
Diameter	4 mm
Shank	4 mm
Cutter length	15 mm
Vc	160 m/min
Cutting Depth	Ap = 1/3 D
Cutting Width	Ae = 1/2 D
Single Edge Feed	Fz = 0.15 mm

HSS parallel to curves - By selecting this technique, movements along curves are automatically generated by the SolidCAM software, as shown in the first image (Fig. 8).

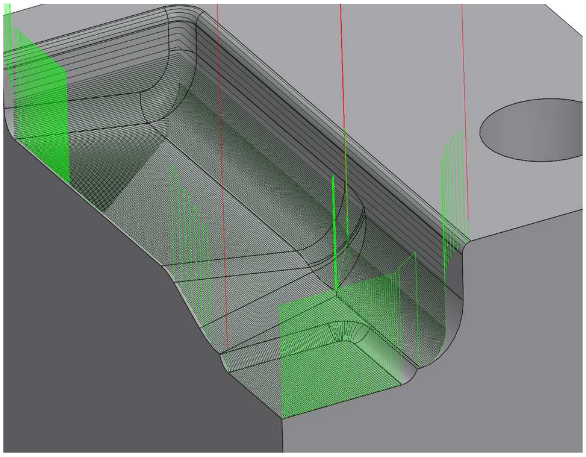

Fig.8 HSS parallel to curves

This method involves machining the surface parallel to the curves of the 3D model. The tool follows the contours of the curves (Fig. 9), removing material uniformly along the path. The entry point is set at the minimum point of the Z-axis. The cutting parameters used for this technique are as follows: Vc = 160 m/min, Fz = 0.15 mm.

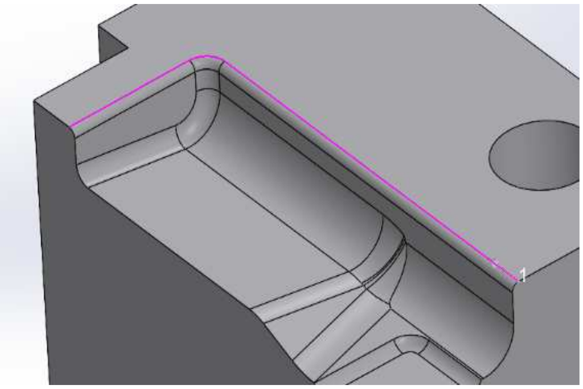

Fig.9 Contour of the curve that defines the trajectory

As a result of using this technique, a machining time of 24 minutes and 34 seconds was achieved.

HSS parallel cutting: linear - is the second technique addressed in this study. Unlike the previous technique, this method involves linear movements along the surface instead of parallel movements to the curve, as shown in Figure 10. This method increases the number of passes when the tool moves perpendicular to the curve and reduces it when it moves parallel to the curve.

The processing parameters are listed in the same order as in the previous example, Vc = 160 m/min, Fz = 0.15 mm, and the result of applying this technique was 33 minutes and 57 seconds.

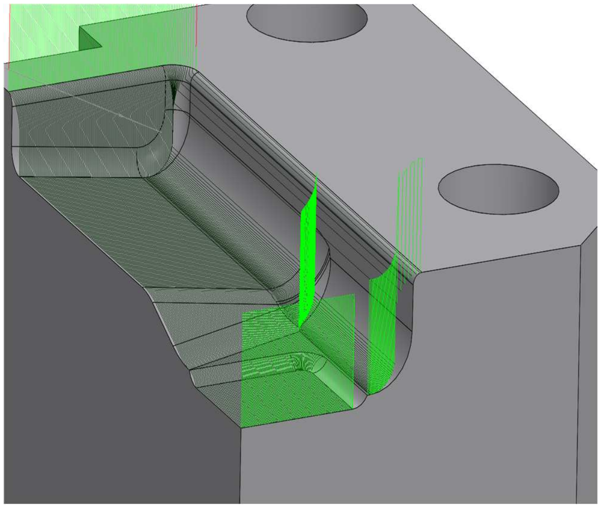

Fig.10 HSS parallel cutting – linear

In this case, the Parallel Cuts: Hatch strategy is simulated, where surfaces are approached differently, being separated and machined separately. The tool input is positioned along the curve with permanent extensions within the limits of the surfaces. The processing conditions remain the same as for the previous models.

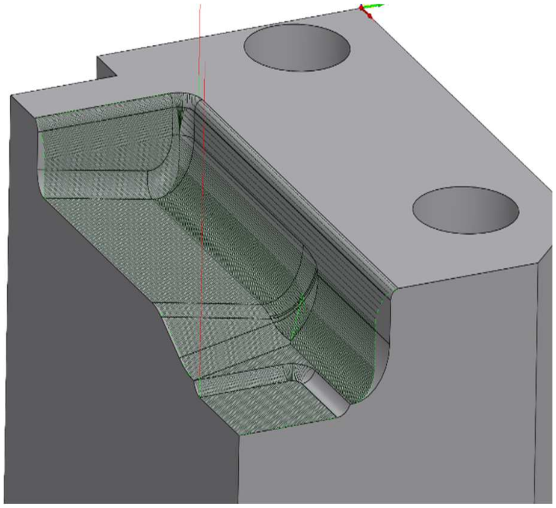

Fig.11 HSS parallel cutting – hatch

As a result of using this technique, a machining time of 25 minutes and 38 seconds was achieved.

The practical method involved manual optimization of the processing of these surfaces by independently selecting processing areas and assigning them the suitable technology.

In order to accomplish this, we divided the surface into four regions, each with its own individual strategies implemented.

The initial segment of the figure was machined using the Constant Z strategy, which involved cutting the material parallel to a fixed direction on the Z axis. This approach aided in achieving consistent machining and a satisfactory finish.

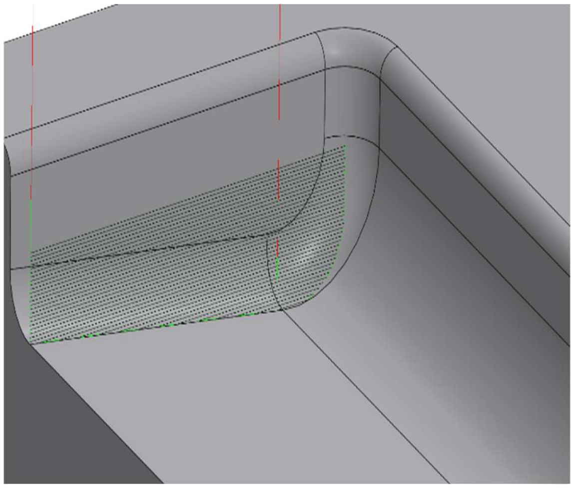

Fig.12 Constant Z

The smallest segment was processed using the hatch processing strategy, resulting in a defect-free ray model on the adjacent flat surface, which provides a good aesthetic appearance due to the uniform movements applied during the process.

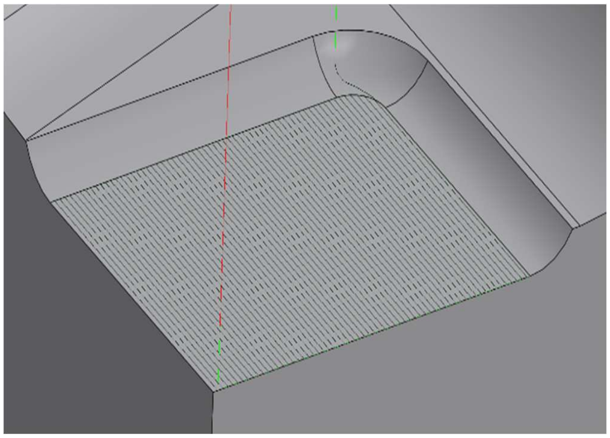

Fig.13 Hatch processing strategy

For another section of the surface, the Parallel to Curves method was employed, which involved a continuous linear movement along the curves to remove the material.

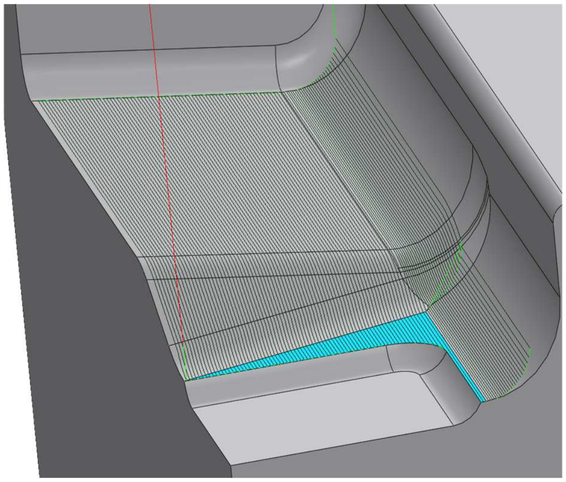

Fig.14 Parallel to Curves method

In the final segment, the linear machining method was applied to the remaining selected areas due to their profile, resulting in fast and uniform processing.

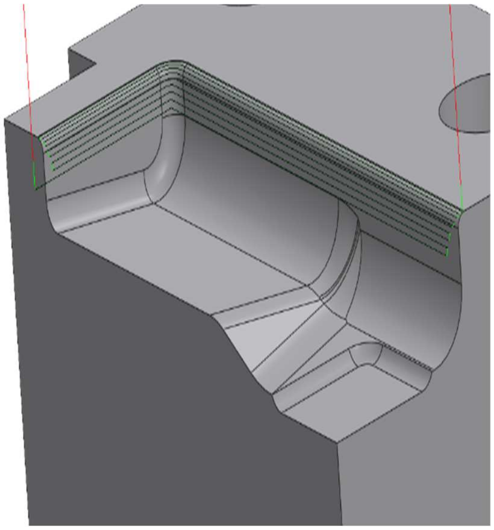

Fig.15 Linear method

To analyze and evaluate the processing methods used in this study, a table was created to compile the processing time data for the four methods employed.

The optimization of idle movements was conducted using the VERYCUT software see fig.16, which offers a 3D representation of CNC parts, machines, tools, and clamping mechanisms used in the machining process.

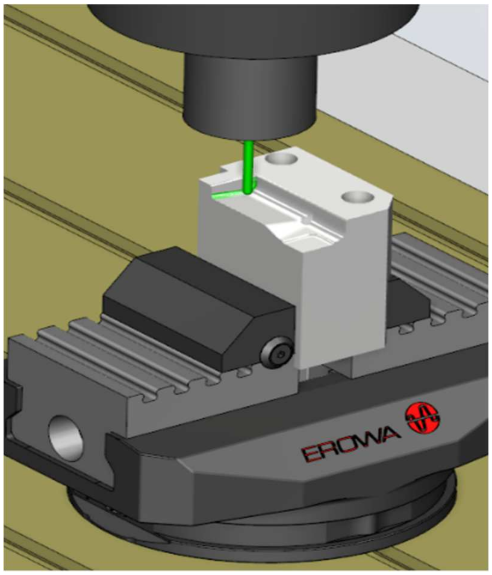

Fig.16 Simulation by Verycut

Table. 3

The times determined

Strategy types	Data without optimization (min).	Data after optimization (min).
Parallel to curves	24.38	22.20
Paralel cuts: Liniar	33.57	28.00
Paralel cuts: Hatch	25.38	23.20
Mixed method	21.38	19.55

Based on the obtained data, it is obvious that the most effective strategy for processing complex bodies is the mixed method. However, it should be noted that this method requires more time for execution and relies on the advanced knowledge of engineers.

The worst strategy automatically applied by the software in this model is the linear method, primarily because of the non-optimized route. However, we observed that successful software generation was achieved by applying the Parallel to Curves method. This method automatically generated pretty good tracks without the need for engineer intervention, showing its effectiveness. Therefore, the selected method type is always available for optimization.

After selecting the mixed technologies and optimizing the movements, the experimental model was successfully implemented as shown in the figure below.

Fig.17 The real model

4. CONCLUSIONS

The efficiency of the machining process depends mainly on the processing time of the CNC center, as well as on the type of strategy applied.

An optimization process was carried out based on an auxiliary tool VERYCUT, reducing entry and withdrawal paths in combination with different types of machining strategies.

This case study focuses specifically on parts with multiple curved and linear surfaces. The selected techniques demonstrate their efficiency in processing complex surfaces while maintaining accuracy. By optimizing the tool paths through Verycut software and by utilizing the capabilities of SolidCAM software, the processing time was significantly reduced. It is important to note that the success of these techniques largely depends on the geometry of the part.

The application of the mixed method and the optimization of movements led to the reduction of the machining time by about 7 minutes compared to the highest time automatically generated by the cam software, and about 2 minutes of the best time granted.

5. REFERENCES

[1] Fu, P., Hope, A., G. King, “Intelligent tool condition monitoring in milling operation,” Online Inf. Def. Community, p. 10, 1998.

[2] Mohanraj, T., Shankar, S., Rajasekar, R., Sakthivel, N., Pramanik, A. Tool condition monitoring techniques in milling process A review. J. Mater. Res. Technol. 2019, 9, 1032–1042.https://doi.org/10.1016/j.jmrt.2019.10.031

[3] Balasubramaniam, M. (1999), Tool Selection and Path Planning for 3-Axis Rough Machining, Master of Science Thesis, Massachusetts Institute of Technology.

[4] Dragomatz, D., Mann, S. A classified bibliography of literature on NC milling path generation, Computer-Aided Design, 29, 1997, 239-247.

[5] Tansel, I. N., & Gokler, M. I. (2018). Tool Path Optimization for CNC Milling of 2.5D Parts. Journal of Mechanical Engineering and Sciences, 12(3), 3885-3896.

[6] Soori, M., Arezoo, B., Habibi, M. Accuracy analysis of tool deflection error modellingin prediction of milled surfaces by a virtual machining system, Int. J. Comput. Appl.echnol. 55 (2017) 308–321.

[7] Lockyer, P.S. Controlling the Interpolation of NURBS Curves and Surfaces. Ph.D. Thesis, University of Birmingham, Birmingham, UK, 2007

[8] Loney, G.C., Ozsoy, T.M. NC machining of free form surfaces, Computer -Aided Design, 19(2), 1987, 85–90.

[9] Huang, Y., Oliver, J.H. Non-constant parameter NC tool path generation on sculptured surfaces, The International Journal of Advanced Manufacturing,Technology,9(5),1994,281-290.

[10] Suresh, K., Yang, D.C.H. Constant Scallop-height Machining of Free-form Surfaces, ASME Journal of Engineering for Industry, 116(2), 1994, 253–259.

[11] Dhanda M., Pande S.S. (2016) Tool path planning strategies for CNC machining of free form surfaces using surface properties. In: 6th international and 27th all India

manufacturing technology, design and research conference (AIMTDR-2016), College of Engineering, Pune, 16–18 Dec 2016

[12] Teng, Z., Feng, H.-Y., Azeem, A. Generating efficient tool paths from point cloud data via machining area segmentation, The International Journal of Advanced Manufacturing Technology 30(3–4), 2006, 254–260.https://doi.org/10.1007/s00170-005-0081-2

[13] Pinar A.M. Abdulkadir G¨ULL¨U, (2005), Minimization of CNC Part Programs in a VerticalMachining Center in Terms of Tool Path and Cutting Parameter Criteria, Turkish J. Eng. Env. Sci. , GaziUniversity, Technical Education Faculty, Ankara-TURKEY.

[14] Lin A.C., Liu H.T. Automatic generation of NC cutter path from massive data points. CAD Comput Aided Des 1998;30:77–90.

[15] Ponomarev B. B., Nam N. V. Algorithm for optimizing auxiliary movements of tools when milling complex surfaces // Bulletin of the Irkutsk State Technical University. – 2013. – no. 1 (72). - S. 33-37.

[16] Teng, Z., Feng, H.-Y.., Azeem, A., Generating efficient tool paths from point cloud data via machining area segmentation, The International Journal of Advanced Manufacturing Technology 30(3–4), 2006, 254–260.https://doi.org/10.1007/s00170-005-0081-2

[17]https://www.metancor.md/category/alyuminievyy-prokat/al-list/

Optimizarea mișcărilor sculelor la frezarea suprafețelor complexe pe mașini CNC cu trei coordonate

Frezarea pe mașini CNC cu trei axe este o metodă esențială pentru prelucrarea materialelor cu aplicații largi în diverse domenii industriale. O parte importantă a procesului de frezare implică optimizarea mișcărilor sculei, cum ar fi poziționarea și retragerea în timpul procesului de prelucrare, care joacă un rol decisiv în realizarea unei prelucrari eficiente a suprafețelor complexe ale pieselor. Optimizarea mișcării sculei este crucială în reducerea timpului de procesare, a costurilor și a erorilor. Astfel, sunt necesare o abordare atentă și o strategie adecvată pentru a asigura o prelucrare precisă și rapidă a pieselor. În această lucrare, vom analiza mai multe metode și tehnici care pot fi utilizate pentru optimizarea mișcărilor sculei în frezarea suprafețelor complexe pe mașini CNC cu trei coordonate.

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