SELECTION OF OPTIMAL MACHINING STRATEGY IN THE MANUFACTURE OF ELEMENTS BOUNDED BY CURVILINEAR SURFACES

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Abstract: Increasing machining accuracy realized on CNC machine tools causes that the more frequently surfaces machined with this technique are not subject to further finishing processing and directly affects on the final quality of the product. Achieving geometric accuracy established by the constructor is the problem that modern technologists and CAD/CAM programmers have to faced with. The paper presents the influence of toolpath tolerance and machining strategy available in CAD/CAM software on the constituting process of technological surface layer for elements limited with curvilinear surfaces. The impact of the above mentioned parameters on the location and direction of geometrical deviations were also analyzed. Following article is part of research of the impact of selected technological parameters on the freeform surfaces geometric structure manufactured on CNC machines.

Key words: Toolpath Tolerance, Machining Strategy, Geometric Deviations, CAD, CAM

1. INTRODUCTION

Most of the objects used in industry consist of simple geometries such as plains, cylinders, tapers, spheres, torus or their mutual combinations. Nowadays industry forces us to use more complex shapes and this in turn determines us to use freeform surfaces. The largest share of these elements can be seen in the aerospace, optic, plastic, automotive or biomedical industry. The most recognizable objects in industries mentioned above are the turbine blades for jet engines, aircraft fuselages, car body parts, ship propellers, asymmetric lenses, housings of household appliances, etc. To produce this kind of elements sometimes it is necessary to perform specialized tools (press tools, molds, punching dies, etc.) that should be characterized by high manufacturing precision in order to use them to produce parts of high quality and repeatability.

Measurement of geometrical deviations of freeform surfaces can be achieved in two ways: direct and indirect comparison with the reference models (Saviol et al., 2007). The first one is based on a comparison of the resulting object with the real one. Indirect comparison relies on the measurement of machined surface done by such machinery and equipment such as: coordinate measuring machines with contact or noncontact heads, radars or laser interferometers, fotogrameters, optical systems based on projection and reflection of measuring fringes, profilometers (measurements with a resolution of nanometres), confocal microscopes, atomic forces microscopes, X-ray tomographs and ultrasonic measurements. As a result, we get the digital equivalent of the analyzed element, carrying the deviations arising during the manufacturing process, and then comparing the resulting cloud of control points with the nominal virtual geometric model.

The geometric accuracy of manufactured parts limited by curvilinear surfaces is a very important issue. Machine components, which curvilinear surfaces cooperate with each other and so must be in the 7, 8 accuracy class, are more common. What is more, from some of these parts also high technological quality of the surface layer to reduce the costs associated with additional technological operations is required. Machining of these objects is achieved primarily through numerically controlled machine tools, and their geometric accuracy is closely related to parameters such as: technical condition of machines (machine error) (Czerech and Kaczyński, 2013), condition and type of the machining tool, machining technology parameters (Czerech et al., 2012), or the machining strategy used to create technology programs in CAM software. We can influence through using various optimization algorithms on the last of the above-mentioned parameters (Makhanov, 2007). With their help it is possible to control adaptive interface of tool paths, which can adapt to the topography of the machined surface. However, these are complex operations requiring high skills and specialized knowledge from the person that creating a technological program.

Preparing technological programs in the CAM environment involves choosing an appropriate machining strategy from the available software library and describing its technological parameters. Thanks to that the tool trajectory is stretched on the machined surfaces of the geometric model prepared in the CAD environment. Approximating algorithms used in generating toolpaths in the CAM software, are adjusted to different types of machining strategy and choosing the wrong type of path can adversely affect on the quality of the final product (Lazoglu et al., 2009). Additionally, not properly selected and defined strategy can contribute to increase of geometric deviations and can enlarge the costs, both directly related to the time of machining and indirect, resulting from wear of the machine's working parts or cutting tools.

Toolpath is a trajectory, on which machining tool is moving. The accuracy of path is controlled by two parameters defined by the technologist / CAM programmer. The first one determines approximating algorithm of the machining strategy and it is called the longitudinal approximation. It creates a series of line segments along path and it is described by value of path tolerance. The second component of the tool trajectory accuracy is a transverse approximation, which is defined during defining the step of toolpath (the distance between the tools' pass). Parameters mentioned above determine the geometric accuracy of manufactured objects. Undervaluation the toolpath tolerance resulting in growth in number of segments thus the technological program capacity increasing and imposes high power of computing machine controller, which working at a high feed rate is forced to process large amounts of data in a very short time. Reducing the path step also increases the volume of the NC program and significantly affect the manufacturing time by increasing the number of tool passes.

In case when the machined surface must, for aesthetic or functional reasons, be subjected to additional technological operations, such as polishing (e.g. forming surfaces in molds for plastics processing), the person performing this treatment is forced to reduce these inequalities left over from previous operations. Their shape and size is defined precisely by the value of the toolpath tolerance and its step. Polishing the surface is very time consuming activity and affects negatively the geometric accuracy of produced parts. So optimally selected and defined machining strategy enables to minimize the costs associated with additional technological operations.

The process of generating tool paths for freeform surfaces is a subject of discussion for many researchers. Optimization of the distribution paths is the element that minimize the geometric deviations of freeform surface machined on numerically controlled machining centers. This process can be based on the using specialized algorithms, which control the distribution of the toolpath on approximated surface. One can distinguish here two leading solutions. Adjusting direction of the tool trajectory (Lazoglu et al., 2009) and the density of the path relatively to the local geometry of curvilinear surface (Agrawal et al., 2006; Choi and Banerjee, 2007; Lee, 2003; Vijayaraghavan et al., 2009). This allows to stabilize the level of irregularities caused by machining and to minimize forces acting during the cut. Moreover, this solution leads to the minimization of machining time (Feng and Su, 2000).

Choi and Banerjee in their work propose the implementation of the algorithms optimizing the tolerance and path step relatively local conditions which results from surface topography. They use isoparametric curves for longitudinal approximation instead of line segments, thus they gain higher accuracy of toolpath. For transverse approximation three cases of shape of inequalities arising from tool pass to identify crucial areas can be distinguished. The first case is a quasi-triangular geometry, which is described by flat base (defined by the local flatness of surface) and two sides (described by the radius of ball endmill), geometries with convex and concave base curvature are the next two cases. Algorithm proposed by Choi and Banerjee uses the two dependences mentioned above and adapts to the actual curvature of the freeform surface.

Using neural networks is not the only solution used for optimization of the trajectory tool distribution on approximated surface. Ding et al. in their paperwork (Ding et al., 2003) propose optimizing algorithm based on projecting additional tool transitions in places that require reduction of cut layer, and then combined them with the base path.

One of the biggest difficulties in process of preparing technological programs in CAM environment is to estimate which one of available strategies will be optimal (will introduce the least noise). Nowadays the production engineer have at disposal two toolpaths, which geometry is close to: parallel lines (Fig. 1a), gradually propagating outlines described by external surface boundaries (Fig. 1b), propagating along or across to ones of surface creating (Fig.1c), stretched between arbitrarily defined curves (Fig.1d) or described by morphic spiral (Fig.1e), or circular (Fig.1f), and then projected on machined surface. Choosing wrong strategy can significantly contribute to the reduction of geometric accuracy of manufactured objects (Schutzer et al., 2006; Zhang et al., 2012).

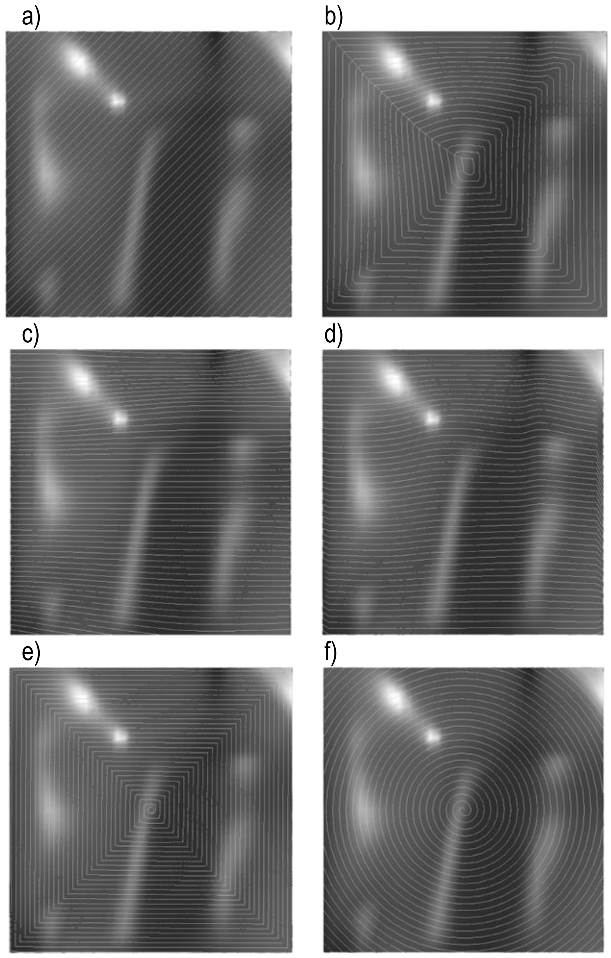

Fig. 1. Example types of machining strategies: a) parallel, b) scallop, c) flowline, d) blend, e) morphic, f) spiral

2. METHODOLOGY AND TEST STAND

The research was designed to study the estimation of geometric deviations values determined by the values of toolpath tolerance and the modeled surface topography. This process has proceeded according to the following algorithm:

1. building geometric model of the manufactured part in CAD module in MasterCAM X5 environment;
2. choosing optimal machining strategies available in CAM module library in software mentioned above;
3. describing machining strategy by defining machining technological parameters;
4. toolpath conversion to vector geometry;
5. division resulting path segments in two equal parts;
6. establishing check points at the ends of the resulting segments;

7. projecting duplicates of points on the approximate lobe of the freeform surface;
8. saving cloud of points of the path and points projected on a surface to the text file;
9. data import into a spreadsheet and inspection software;
10. analyzing the impact of toolpath tolerance on the value and the location of geometrical deviations.

To perform the study a PC computer was used, equipped with MasterCAM X5 application used for creating and editing surface and solid geometrical models and creating technological programs for numerically controlled machine tools. Furthermore, application Geomagic Qualify was used for creating distribution maps of geometric deviations which enables to compare the cloud of points with the geometrical model. Spreadsheet Excel was used as an additional tool in analyze the numerical data.

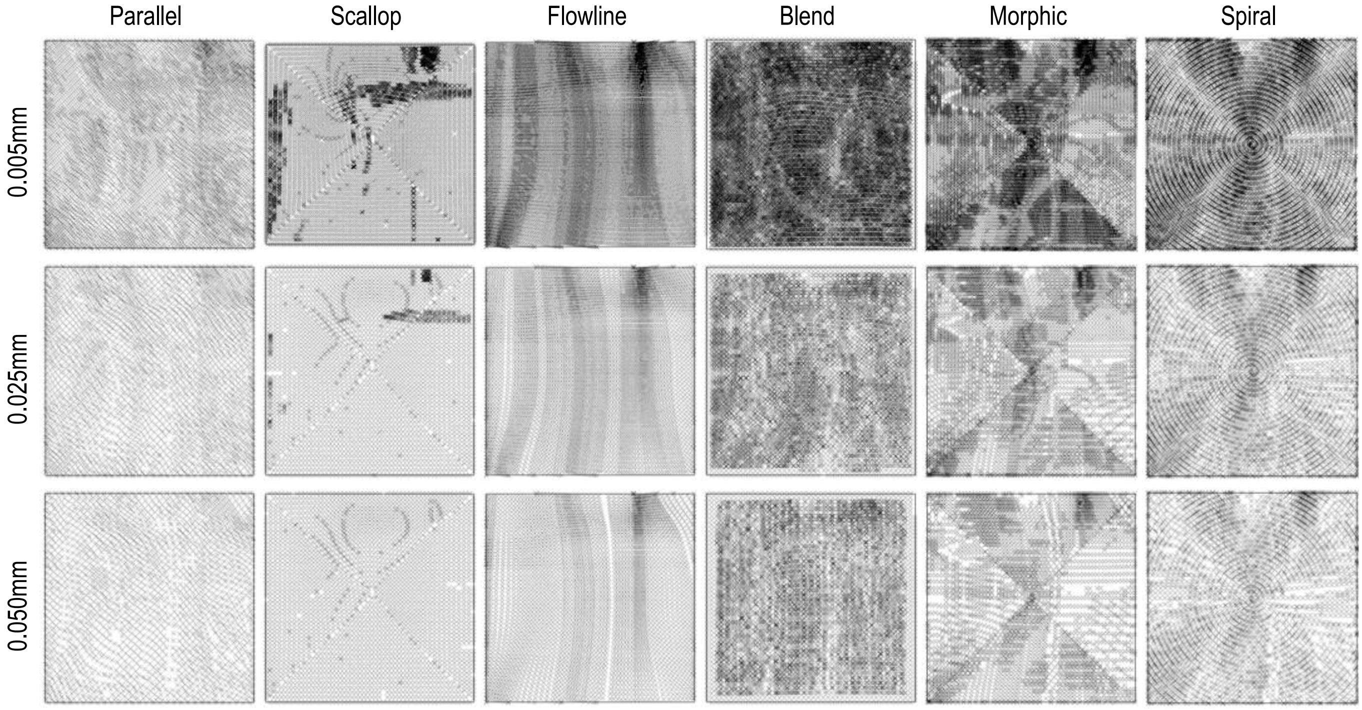

Fig. 2. Distributions of end and mid points of analyzed toolpaths segments for selected tolerance values

3. RESEARCH PROCESS

Following the algorithm mentioned above, lobe of curvilinear surface was prepared as a first. It was modeled in Design module of MasterCAM software by stretching Coons surface on splines that create the web. After carefully analyzing the topography of created geometry, six types of machining strategies were distinguished, which trajectory of the tool had been spread optimally on the machined surface.

The next step was to describe technological parameters of each strategy with unification with parameters such as: path tolerance, transverse step or tool type. After finishing all actions mentioned above, converting the tool trajectory to geometry consisting of line segments that result from the surface approximation had begin. For the study, to accurately depict the impact of tool path tolerance values on the process of constituting deviations, all segments of the path were divided into two parts. As a result, additional points were obtained, giving much greater ability to identify errors of technological programs, that arise during the development phase of machining strategies and help to increase the geometric deviations of machined surfaces.

So prepared geometrical path was a base for creating the control points at the ends of all segments (Fig. 2). Then duplicate of those points were cast on the approximated surface using a toolpath. Thanks to this operation coordinates of nominal points (collective with the surface) and real points (at the ends of path segments) were obtained.

Data, prepared in this way, were exported to a spreadsheet, which undertook further processing and analysis of results.

4. TEST RESULT ANALYZE

Statistic analysis of results obtained in the examination process has allowed to visualize statistic parameters changes determined by the type of strategy and the tolerance values of the path.

In case when the CNC technologist / programmer prepares the technological program used for machining the element limited with curvilinear surfaces, he is able to control the amount of generated segments that create the toolpath by oscillating the tolerance value and, as it turns out, the type of machining strategy (Tab. 1). Unfortunately he is limited with design assumption which define the quality of the machined surface and shape deviation values. This imposes the maximal path tolerance value, while the conversion power of the CNC machine tool driver determines the lower limit of the range. Since working at high feed rate the machine tool cannot cope with such large amounts of data to be processed, and hence will not be able to pass information to the servo drives at the right pace.

By analyzing the values that illustrate the medium values of the geometric deviations (Tab. 1) can be stated, that the largest value are generated by blend path, which is approximating the surface between two arbitrarily defined curves. Most preferably the flowline path falls here, approximating the surface after its forming. In analyzing the maximal positive and negative deviation values, flowline path is the most advantageous path as well. Unfortunately, it appears that blend, morphic and spiral strategies have very similar characteristics and generate a much larger deviation than a path tolerance value assumed in describing the strategy. It can significantly complicate the process of preparing programs controlling the machine operation. In addition, these paths tend to increase the maximal values of deviations, while reducing the tolerance of the path.

Tab. 1. Geometric deviation statistical parameters summary

	0.005	0.010	0.015	0.020	0.025	0.030	0.035	0.040	0.045	0.050
					MEDIAN					
FLOWLINE	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
PARALLEL	0.001	0.001	0.002	0.002	0.003	0.004	0.004	0.004	0.005	0.005
SPIRAL	0.001	0.001	0.002	0.002	0.003	0.004	0.004	0.005	0.005	0.006
MORPHIC	0.001	0.001	0.002	0.003	0.003	0.004	0.004	0.005	0.005	0.006
SCALLOP	0.001	0.003	0.004	0.004	0.005	0.005	0.006	0.007	0.007	0.008
BLEND	0.001	0.002	0.003	0.004	0.005	0.007	0.008	0.009	0.010	0.011
					MAXIMUM POSITIVE					
FLOWLINE	0.005	0.012	0.013	0.024	0.027	0.027	0.027	0.036	0.027	0.036
SCALLOP	0.017	0.035	0.051	0.053	0.054	0.054	0.054	0.055	0.055	0.055
PARALLEL	0.152	0.152	0.152	0.153	0.154	0.153	0.155	0.154	0.155	0.155
MORPHIC	0.838	0.658	0.345	0.179	0.053	0.105	0.105	0.062	0.049	0.049
SPIRAL	0.838	0.658	0.345	0.179	0.053	0.105	0.105	0.062	0.049	0.049
BLEND	0.844	0.662	0.346	0.179	0.081	0.105	0.105	0.083	0.084	0.109
					MAXIMUM NEGATIVE					
FLOWLINE	-0.017	-0.017	-0.017	-0.017	-0.017	-0.017	-0.017	-0.017	-0.017	-0.017
SCALLOP	-0.036	-0.040	-0.045	-0.045	-0.046	-0.046	-0.046	-0.046	-0.046	-0.046
PARALLEL	-0.098	-0.100	-0.100	-0.103	-0.104	-0.105	-0.105	-0.105	-0.105	-0.105
MORPHIC	-0.405	-0.411	-0.382	-0.384	-0.270	-0.388	-0.204	-0.108	-0.108	-0.108
SPIRAL	-0.405	-0.411	-0.382	-0.384	-0.270	-0.388	-0.204	-0.108	-0.108	-0.108
BLEND	-0.411	-0.418	-0.387	-0.389	-0.326	-0.393	-0.323	-0.328	-0.328	-0.328
					NUMBER OF POINTS					
BLEND	15346	11690	9900	8658	6635	7022	6628	6348	6065	5767
FLOWLINE	6341	4460	3550	3003	2838	2703	2666	2585	2571	2573
MORPHIC	9959	7158	5917	5048	4608	4244	3934	3720	3539	3336
PARALLEL	6783	4996	4164	3642	3341	3103	2812	2647	2545	2405
SCALLOP	11317	7834	6551	5665	5258	4832	4554	4293	4065	3758
SPIRAL	8773	6322	5081	4591	4217	3847	3632	3221	3221	3089
BLEND	15346	11690	9900	8658	6635	7022	6628	6348	6065	5767

Furthermore, an analysis of the distribution of geometric deviations in terms of the percentage of points in each interval values of deviations (Fig. 3) has been made. In this case it is also clearly seen that the flowline path best reproduces approximated surface, because even with path tolerance equaled 0.05mm all deviations in measuring points are within the limits of 0.02mm, what is determined by a small value of standard deviation. Analogously to this can be estimated, that using for creating the part of blend path would be a less favorable solution, because its nominal distribution is almost flat and illustrate occurrence of such deviation values, which are significantly bigger than implied tolerance. Path created by scallop strategy also performs poorly. Morphic, spiral and parallel strategies generate identical deviation distributions, what characterize their trajectories, which quality is far much poorer than flowline path's.

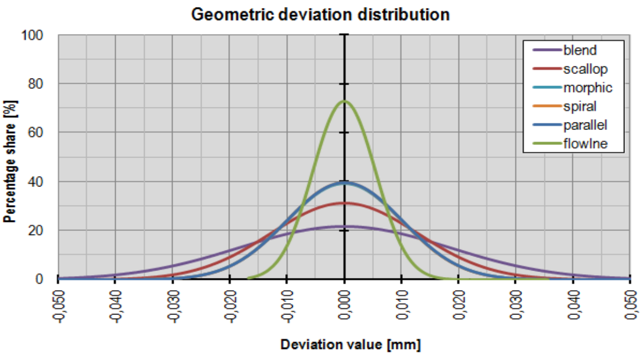

Fig. 3. Geometric deviation distribution for 0.05mm toolpath tolerance.

Brining great part of information about the process of creating geometric deviations and allowing to estimate the influence of curvilinear surfaces topography is to compare the cloud of given points with the nominal model (Fig. 4). Surface topography correlation with value and intensity of deviation occurrence is ideally illustrated here. As can be seen on their distribution maps, the biggest positive values of deviations are located in areas of cavity on analyzed surface (the material forming the surplus is not fully collected). However on bulges and their immediate vicinity deviations with the biggest negative values are located (working tool will cut through machined surface).

Analyzing all charts it can be concluded, that the path created by flowline strategy is characterized by high liquidity of approximating algorithm and generates minimal amounts or values of geometric errors. Other machining strategies are far less favorable and their usage in process of creating technological programs can contribute to significant reduction of accuracy and the manufactured object can be recognize by quality control as a fault.

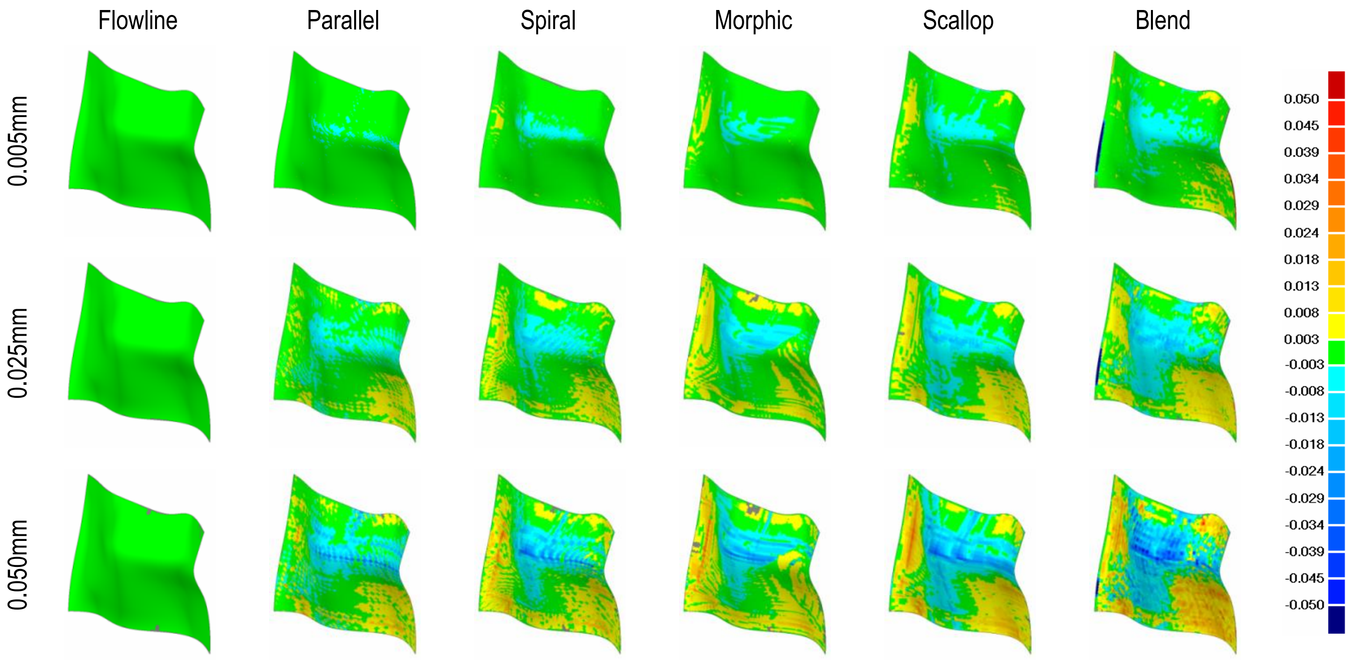

Fig. 4. Geometric deviation distribution maps for selected toolpath tolerances values

5. CONCLUSIONS

After conducting thorough research and statistical analysis the impact of toolpaths tolerance on forming geometrical deviations, the following conclusions are constituting:

a) method proposed in this paper is a fine tool that enables to estimate which machining strategy brings the smallest geometrical errors to technological programs controlling the machine tool;
b) this method also enables to estimate that influence has a path tolerance value on deviation creating process and technological program volume;
c) choosing the optimal machining strategy can increase the accuracy of manufactured parts, which is identical to the reduction of production costs;
d) mismatched machining strategy may increase the intensity of local sweeps and not completely removing the material stock, which can lead to difficulty in matching the two cooperating components;
e) undervaluation toolpath tolerance can increase geometrical deviations of produced objects, which can cause difficulties for the engineers and CNC programmers prepare NC programs.

Based on these research it will be possible to move to the next stage which will develop a method of error correction on level of creating technological programs and verifying the impact of technological parameters such as: cutting speed, feed rate of the blade or the diameter of the tool on the technological process of constituting the surface layer.

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