MACHINING ERROR COMPENSATION FOR OBJECTS BOUNDED BY CURVILINEAR SURFACES

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Abstract: The paper is devoted to topic related with machining error correction for objects bounded by curvilinear surfaces manufactured on numerically controlled milling machine. Currently it is realized by two techniques. The first of them is called on-line and requires continuous correction of toolpath during the machining process. This approach requires expanded adaptive control systems. The second method called off-line is based on correction of machining control system outside the machine (on the basis of control measurement results). This paper shows methodology of machining shape error correction with off-line technique (with no constant and direct connection to CNC machine tool). This method is based on usage of CAD/CAM systems, numerically controlled milling machine and coordinate measuring machine. Manner of procedure proposed in this paper was verified on the example of ruled surface profile described with NURBS technique. Realization of this proposed methodology of machining error correction has shown significant accuracy correction of manufactured element.

Keywords: CNC Machine Tool, CAD, CAM, Coordinate Measuring Machine, NURBS

1. INTRODUCTION

Manufacturing of elements using numerically controlled machine tools is one of the most popular techniques deployed in modern production processes. Even in case of cold, hot or casting part shaping, many of finishing technological procedures are done by machining. It is caused by noticeable tendency to shorten machining time, the possibility of eliminating other more expensive and time-consuming technological procedures, the possibility of increasing diversity of manufactured products and an increasingly significant role of flexible production. In these cases machining of solid material can be more cost-effective than preparing workpiece by using expensive press tools, dies, molds or casting dies. In many cases thanks to super-efficient tools, with increased wear resistance layers, machining can replace expensive and time-consuming electrical discharge machining (Cichosz, 2006).

Machining of geometric models containing curvilinear geometries is now used in industry for manufacturing different kinds of cams, dies, forming insert for injection moulds, electrodes for electro machining drill and other specialized tools. High accuracy is needed in manufacturing of these elements. Since elements of machines, of which curvilinear surfaces work together, are more common, so they must be in 7,8 accuracy class. Besides accuracy these elements are required of repeatability and high quality of the geometric surface structure.

Factors induced by machining itself, such as thermal and elastic deformations of some elements in kinetic shaping chain, changing the coefficient of friction on surfaces which are used by working units and other loaded with machining forces have essential influence on wrought object accuracy (Chen and Ling, 1996; Lim and Menq, 1997).

1.1. Causes of machining deviations and correction methods

All elements produced on computer controlled machining are burdened with machining errors, which can be grouped according to different genesis.

The first biggest group are geometric errors. They are treated as machining errors, which occur even without mechanical load and basically result from imperfect performance, insufficient stiffness or machining wear. They affect the components mutual compatibility during cooperation, which is their perpendicularity and parallelism. They enlarge severely with increasing machining wear. Okafor and Ertekin in their work (Okafor and Ertekin, 2000) and also Lim, Meng and Yen (Lim et al., 1997) precisely describe causes of that kind of errors.

The second equally important group are deviations resulting from thermal distortion, which can be divided into local and resulting from machine's work environment. These first can come from friction caused by cooperating element's movement, axe's servo drives, other gears and from machining process itself. Engines, bearings, hydraulic systems, ambient temperature and others can be a heat source. The most difficult is to eliminate this group of errors, because they are difficult to predict and estimate. Thermal deformations of machining units are caused by thermal expansion of construction materials which are subjected to impact of changing and different temperatures. Heat sources multiplicity and its complicated transfer mechanism cause the analytical temperature determination of the machining elements is almost impossible. Experimental methods specifying the temperature fields in machining and thermal deformations designation are widely used. These methods, however, are complicated and laborious and the results are similar. Thermal deformations reflect the workpiece as measure and shape errors. The subject of estimation and thermal deviations errors is widely described in works (Li et al., 1997; Ramesh et al., 2000).

Another very relevant source of errors is machining process itself and phenomenon accompanying. Basically these are forces acting on machining and workpiece, which mainly depend on machine working element's and workpiece weight, machining and inertial forces. This problem was widely described in Raksiria and Parnichkun's works (Raksiria and Parnichkun, 2004) and as well Yaldiz's et al. (2007).

This big quantity of systematic and random errors caused the development of research which eliminate errors components and get the machining of high accuracy. Two methods of error correcting for numerically controlled machining were results of this research. The first of them, off-line method, is based on indirect correction of NC program. The second method of machining errors compensation is on-line, which is characterized by direct correcting during machining.

Analysis of literature connected with machining error correction shows that many approaches towards increasing accuracy of manufacturing have been elaborated. One of them is designing the machining process, in which machining forces are controlled by adjustment of parameters such as feed or the width of machining layer. The result is that the tool is not bending over the specified and permissible limit (Yang and Choi, 1998). Adaptive on-line control approach is developed, which corrects the position of the tool in real time. This approach requires the machining armament with sensors to control permanent merits which have influence on machining preciseness (for example tool banding, dislocation error of machining working unit and others) (Yang and Choi, 1998). Off-line methods are widely used, which include updating of toolpath based on known machining error distribution. It requires the series of machining tests and control measurements which purpose is to appoint modified toolpath (Ryu and Chu, 2005; Lechniak et al., 1998; Lao and Hsiao, 1998).

During realization the technologic program by machine tool, the person who is operating it, has no possibility of compensation these errors, and hence has no influence on machining accuracy. The correction of measurement and the shape of workpiece machined in control program can be entered only after machining, measuring and evaluating the executed object. There are also systems allowing to compensate machining deviations in real time, but these are very complex systems mainly based on neural networks. They allow, in some extent, preliminary evaluation of some machining deviations and minimize them.

2. COMPENSATION METHODOLOGY OF MACHINING DEVIATIONS AT CURVILINEAR PROFILES

Methodology of compensation machining deviations proposed in this article base on off-line method. It can correct summary machining errors, which sources were described in chapter one.

Fig. 1 shows the algorithm of compensation methodology of machining deviation at curvilinear profiles.

This proposed methodology is based on CAD/CAM systems usage, coordinate position measuring technique and CNC milling machines. The initial element is object's geometric model created in CAD module. Based on it, the detail machining program in CAM module is created later on. After manufacturing the object in CNC milling machine, coordinate position control measurements are done. As a result of these measurements one can get information on values and the distribution of occurring machining deviations. When deviations values meet the needs of executive, the machining process is ended. Error values are corrected when they are too big. First, based on information on values and distribution of observed machining deviations, the shape modification of geometric model of manufactured object is done (CAD). An adjusted geometric model is created that way, which shape takes into account the occurring machining errors. This model is used in generating the adjusted machining program of parts (CAM). After second machining of part, control measurement are done again. Information on effectiveness in methodology of machining errors correction is gathered this way.

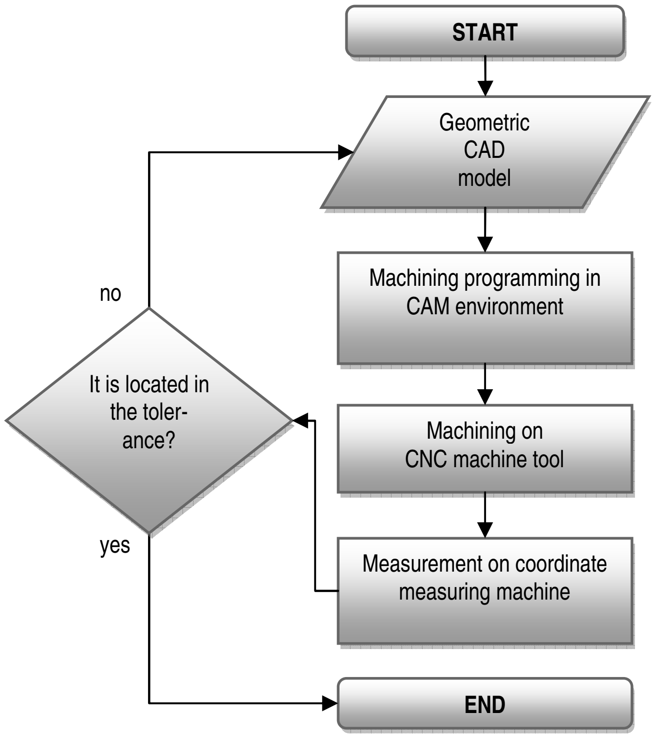

Fig. 1. Algorithm of machining deviations' compensation at curvilinear profiles

In presented methodology the relevant element is value designation and distribution of machining deviations in manufactured profile. The graphic presentation of machining deviation in flat profile is shown in Fig. 2. This is a distance form point observed during measuring to correspondent nominal point on profile (measured in normal direction to profile).

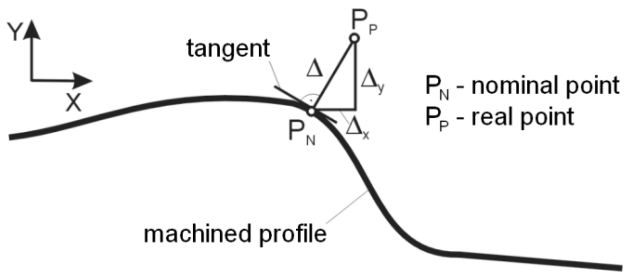

Fig. 2. Graphic interpretation of machining deviation

Deviation values are determined from the following dependence:

$$\Delta = \sqrt{(X_P - X_N)^2 + (Y_P - Y_N)^2} \tag{1}$$

where: Δ – machining deviation, X_P, Y_P – measuring points coordinates, X_N, Y_N – nominal point coordinates.

2.1. Test stand

Test stand consisting of three elements was used in research on effectiveness in compensation deviation method.

First of them was PC computer, equipped with CAD/CAM application used for creating geometric models build of ruled surfaces, which were formed from NURBS curvilinear outlines.

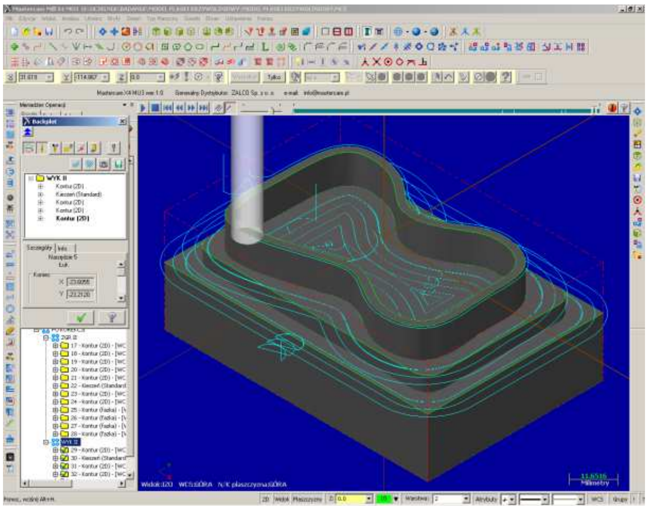

Fig. 3. MasterCAM's environment interface with created geometrical model and programmed path

Fig. 4. Vertical machining centre used to manufacturing elements containing NURBS geometries

Object's geometric modeling was done in MasterCAM X4 MU3 environment. Fig. 3 shows graphic interface of this environment with modeled surface element and programmed tool path.

The second element of this environment was numerically controlled vertical machining centre made by AVIA FOP VMC650 with HEIDENHAIN iTNC530 control system (Fig. 4). Producer declares +/- 0,005mm of positioning preciousness and repeatability.

This machine tool is used in workshop manufacturing precision tools for making: blanking tools, press tools, dies, forming inserts, injection molds, and other equipment for tools mentioned above. Run time of technological programs on factory components during sample manufacturing was 9000 hrs, and the cumulative operating time of the machining was 17200 hrs.

The last element of the test stand was coordinate measuring machine (CMM). It is combined with PC computer (Fig. 5), with PC-DIMS software installed in MS Windows XP PRO x84 controls the CMM's work.

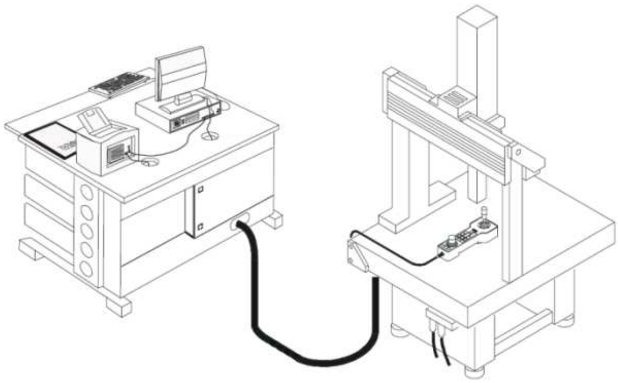

Fig. 5. Equipment used for measuring the element made on CNC machine tool (Lim and Menq, 1997)

Global Performance made by Hexagon Metrology with the producer's declaration of preciousness MPEE = 1.5 + L/333 [µm] is the measuring machine used for coordinate position measurement.

2.2. Experimental studies

Realization of the methodology of compensation machining deviations was mainly based on minimizing differences between the nominal curvilinear NURBS outline modeled in CAD environment and the element manufactured by CNC machine tool.

Firstly, the model consisting NUBRS geometrics was made. Modeling the element was about creating two NURBS curves and drawing them for distance of 10mm with straight drawn surfaces. Extending the surface between curves and the rectangular part that makes the settlement of element easier on coordinate position measuring machine was the next process. The last process was to modeling the base. Geometric model made this way is shown in Fig. 3. This model was used for tool paths programming. The next step was selection of material type, stock size, machining tools and work environment.

Finishing machining of all surfaces taking part in measuring and alignment was done with three flute toroidal end mill with the ø8mm diameter and the 0,5mm fillet radius (picture 6). The tolerance of programmed machining path was 0,015mm. For achieving better quality of surface geometric layer, filtering the arches was used. During machining, besides filtering the arches in MasterCAM environment, filtering in the machining was used, which is done in iTNC530 controller using 'Tolerance' 32 cycle. More fluent tool movement towards machining outline was obtained.

Fig. 6. Analyzed object made on machining centre

The next step after CNC machining was to measure the manufactured element on coordinate measuring machine. After calibration of the measuring head with reference sphere the element was fixed to measuring table. When all the preparative activities were completed, coordinate system orientation of the manufactured object was done. Assignment of the element on the coordinate measuring machine can be divided into following processes:

1. Define the angle between XY plane of the wrought element and the XY plane of the machine.
2. Establishing the coordinate system of fixed element.
3. Define the angle between X axis of the machine and X axis of the element.
4. Establishing the top boundary element's surface.
5. Fit of the coordinate system in automatic mode (*best fit*).

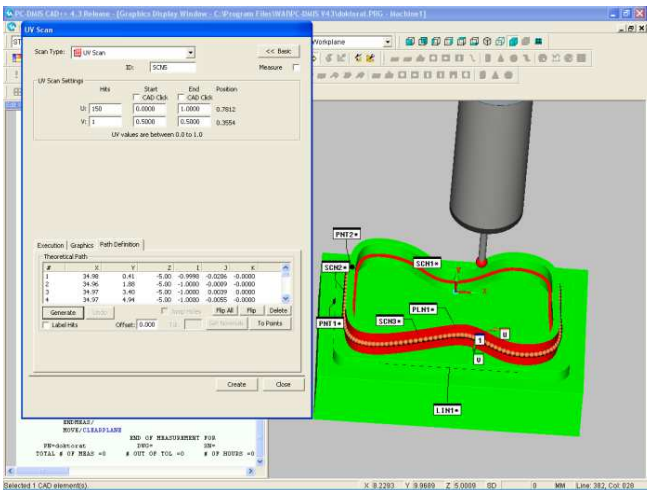

Fig. 7. Parameters of the measuring program

After analyzing the size and shape of examined profiles, it is accepted that the sampling step during coordinate position measurement will be 2mm. Two profiles of the wrought object were measured. As the result of the measurement, for external profile 113 and for internal profile 106 measuring points were obtained.

As the result of the preliminary elements measurement, the digital equivalent of the geometric model with manufactured deviations was obtained. The given data were imported to the Excel sheet, where manufacturing deviations were separated from nominal values of the object. When the values and distribution of the manufacturing deviations were known, the nominal geometric model was modified and machining program was generated again.

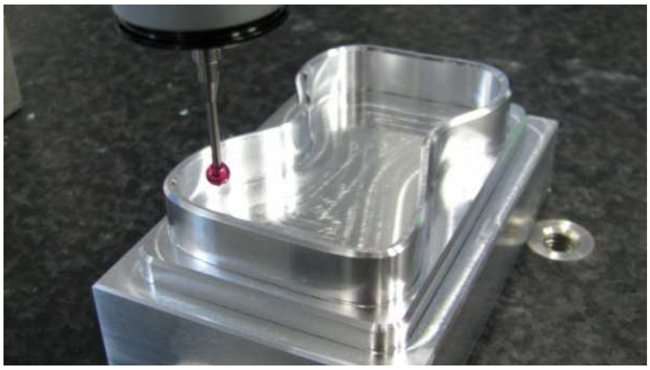

Fig. 8. Measurement of the element with the coordinate position measuring machine

The next process was to manufacture the element using the corrected machining program. The machining process on machining centre numerically controlled was done using the same machining and technical parameters and in the same work environment. After machining again the measurement was done by coordinate machine (Fig. 8) with the same parameters and according to the same assumptions which were in preliminary controlling measurements.

3. TEST RESULT ANALYSIS

Diagrams in Fig. 9 shows machining deviations values of the external and internal outline. Diagrams show deviations before and after machining errors correction. Significant decrease of deviations maximal values after correction can be seen.

Tab. 1 shows numerical values of appointed machining deviations. 0.025mm is the biggest deviation value for external outline before correction and 0.042mm is the biggest for internal outline. Average deviation value before correction for both external and internal outline was 0.008mm. Note, that after correction of geometric model the maximal deviation values decreased (more accurate projection of the manufactured object was obtained) and were: 0.017mm is the biggest deviation value for external outline and for internal outline the biggest is 0.019mm. Average deviation values after correction were about 0.005mm for external outline and 0.006mm for internal. Reduction of the maximal machining deviations of the external and internal outline was the effect of the correction and was appropriately of 7.4μm and 23.6μm. Reduction of the average deviation values was also obtained and was appropriately of 2.2 and 2.0μm.

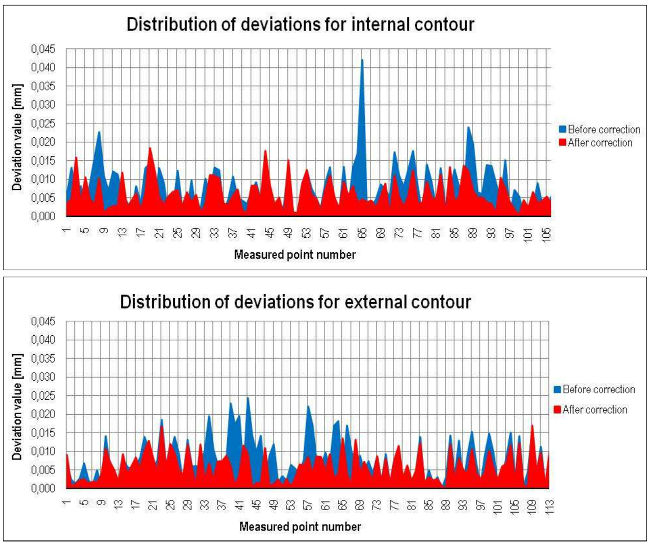

Fig. 9. Magnitudes of the deviation values before and after geometric model correction

Tab. 1. Summary of results [μm]

	Before correction		After correction		Correction result	
	out	in	out	in	out	in
Max	24.5	42.1	17.1	18.5	7.4	23.6
Average	7.8	7.9	5.6	5.9	2.2	2.0

4. SUMMARY

The method of deviation compensation is an effective tool, which enables manufacturing elements with high precision. It also enables to minimize deviations for internal outlines (dies) where the wrapping angle is far more bigger than in external outlines (punches). In producing the blanking dies of high precision this method enables obtaining equal clearance on whole length of the cutting contour. It is crucial for aesthetic and dimensional reasons. In the case of molds for plastic it will enable precious fit of the profile forming insets in sockets, where they will be placed, and they will allow for leek proof sealing of the space filled with superficial plastic.

Significant mitigating (for 0.024mm) of the maximal deviation of internal outline is essential and beneficial effect of the correction. Inaccuracy of that size in manufacturing before correction could cause local seizing on cooperating surfaces or could prevent adjustment of two cooperating elements.

Method of the machining deviations' compensation allowed the fast and effective correction of differences between nominal element and the one manufactured by CNC machining.

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