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ON THE MODERN CNC MILLING WITH A COMPENSATION OF CUTTING TOOLS AND THIN-WALLED WORKPIECE DEFLECTIONS

Accuracy of machined components is one of the most critical considerations for any manufacturer. However, when milling the radial force deflects the cutting tool and workpiece. It affects the precision and quality of machined surfaces. The extent of the deviations can be predicted in various mathematical models. Thus, the errors can be compensated in NC programme effectively. So it is possible to machine with high cutting conditions, and also a high quality of machined surface can be achieved. In this paper are predicted deflection of milling tools and thin-walled workpiece. The experimental results show that the overall error in the flexible milling can be captured and predicted with very high accuracy.

1. INTRODUCTION

Machining of thin walls of components with a shank milling tool is shown schematically in Fig. 1a and is addressed e.g. in [1],[2],[3],[5],[6],[7],[8],[9]. Ideally, the forces acting on the cutting tool or on the workpiece are small enough so that it does not cause their technologically significant deflection during milling. This condition is needed to approach especially during finish machining. Wear development of the milling tool while milling or e.g. a change of the radial depth of cut cause an increase in the force loading of the tool-workpiece system and also leads to technologically significant elastic deformation of individual elements of this system (Fig. 1b). On five-axis milling centres with continuous control, the paths (spline or/and polynomial interpolation) of the cutting tool might already be applied while using milling technology. Into these paths e.g. temporal or positional dependence of the cutter or workpiece deflection is then integrated. Using progressive controlling of the milling tool, the technologically significant effects of elastic deformation of the tool and workpiece might be partially removed.

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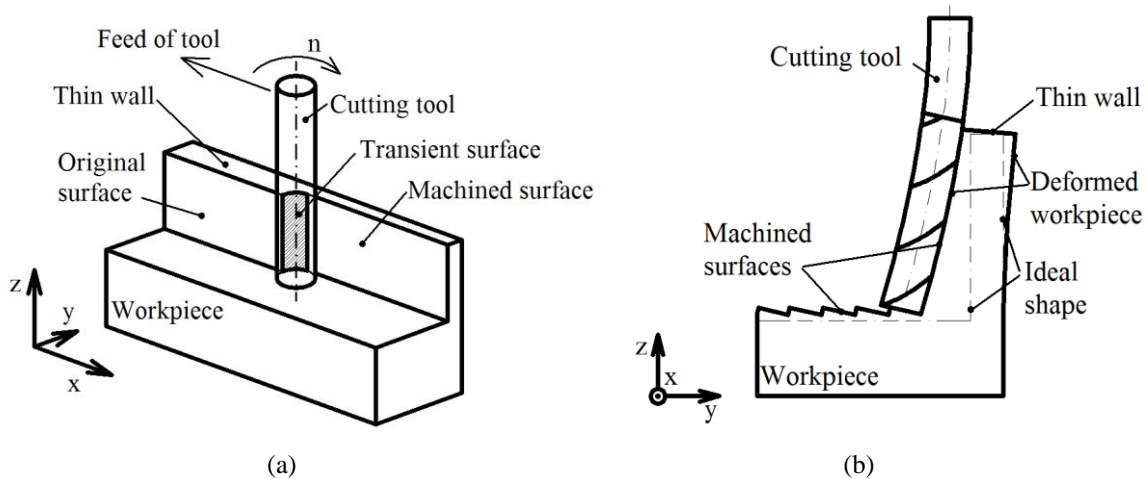(a)   (b)

Fig. 1 Machining of thin walls of components with a shank milling tool: (a) Model of shoulder milling [9],
(b) Deformation of the tool and workpiece deteriorating surface finish

2. PREDICTION OF THE DEFLECTION OF A MILLING TOOL AND THIN WALLED WORKPIECE

In specialized literature, the attention is focused primarily on static prediction of deformation (deflection). Deflection of end mill tool in a holder (Fig. 2) and thin-walled workpiece (Fig. 3) can be simply expressed [4]:

- deflection of cylindrical cantilever beam with two cross-sectional characteristics

$$w_{max} = \frac{F_r \cdot L_1^3}{3 \cdot E \cdot I_1} + \frac{F_r \cdot [(L_1 + L_2)^3 - L_1^3]}{3 \cdot E \cdot I_2} \tag{1}$$

where: F_r- the loading radial force, L_1- the length and d_1- the diameter of the cutting part of milling cutter with flutes (Fig. 2), L_2- the length and d_2- diameter of end mill tool without flutes (without cutting edges), E- Young's modulus of the cutting tool, I_1- moments of inertia of circular cross section L_1 and I_2- moments of inertia of circular cross section L_2- deflection of the workpiece in the shape of rectangular cantilever beam

$$w_L = \frac{12}{E \cdot b \cdot h^3} \left(\frac{F_n \cdot L^3}{3} - 2 \cdot F_n \cdot L^2 \right) \tag{2}$$

where: F_n- the loading normal force, b- the width of the thin wall, h- the thickness of the thin wall and L- the height of the workpiece thin wall (distance between the clamp and loading force), E- Young's modulus of the cutting tool.

To measure the forces loading when machining the workpiece it is possible to use e.g. Piezoelectric dynamometer 9257B, Multi-Chanel Charge Amplifier Type 5070 and DynoWare software from company Kistler. After the necessary filtering of data in ASCII format and statistical processing of the individual force components the input values for the prediction of deformations are available. Loading force F_r = 300 N for theoretical analysis of roughing and F_r = 50 N for analysis of finishing simulate a radial force component acting
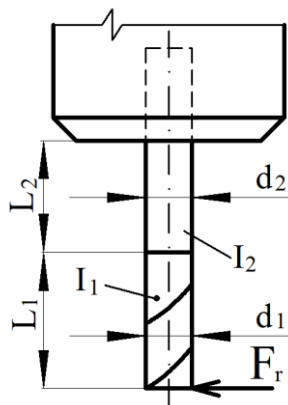
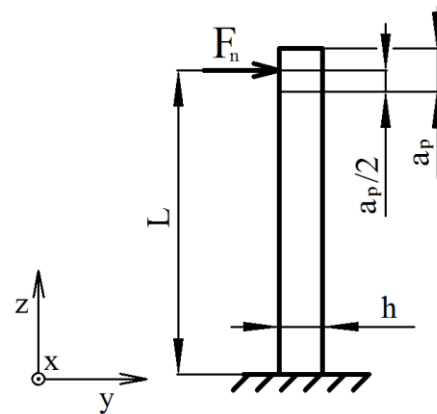Fig. 2. Model of an end-mill cutter with two cross-cutting characteristic

Fig. 3. Model of cantilever rectangular beam (the thin-walled workpiece)

on the cutting tool in the radial direction. Equally large oppositely directed force acts in a direction of a normal to machined surface (F_n or F_y). The values of predicted deflection by using formulas (1) and (2) are summarized in Table 1 and are also shown in the graph, see Fig. 6.

Table 1. The prediction of the deflection of simplified models of the milling tool and the workpiece

	Dimensions of simplified models	Young's modulus of elasticity E [GPa]	Loading force [N]	Predicted deflection w [mm]
End-mill cutter	$d = 20$ mm $d_e = 18$ mm $L_1 = 38$ mm $L_2 = 24$ mm	520	$F_r = 300$	$w_{max.} = 0.007$
			$F_r = 50$	$w_{max.} = 0.001$
Thin-walled workpiece	100x10x75 mm $L = 70$ mm	71	$F_n = 300$	$w_L = 0.053$
			$F_n = 50$	$w_L = 0.009$

For more detailed predictions of thin-walled workpiece deflection when milling might be used Ansys Workbench software. This software enables the FEM to predict e.g. amount of deflection of thin-walled workpiece at the contact point of the tool with the workpiece. It takes into account the linear milling movement and progressive removal of material (axial depth of cut - $a_p = 10$ mm, radial depth of cut for simulation of roughing - $a_{eR} = 0.5$ mm, radial depth of cut for simulation of finishing - $a_{eF} = 0.02$ mm). Simulated progressive change of position of the milling cutter and point of loading force on the machined thin-walled component (Fig. 4 and 5) leads to the prediction of compensation values (Fig. 6) suitable for implementation into the CNC machine programs. In reality and even in the 3D graphical simulation the milled thin-walled workpiece is being curved on the corners more than in the middle (Fig. 4 and 5). That cannot be quantified by formula (2) (see the constant line w_L in Fig. 6).

For a comparison of FEM results (static analysis) with a calculation in accordance with (2), the predicted deflection of the thin-walled workpiece (Fig. 6) is firstly solved by loading only with using the force (component) $F_y = 300$ and 50 N ($F_x = F_z = 0$). Environment temperature used for calculation is 22°C and the material properties are following: Young's modulus 71 GPa, Poisson's Ratio 0.33, Density 2.77E-09 tonne/mm, milling tool diameter is 20 mm and the point of loading force is located in the middle of the transition surface.
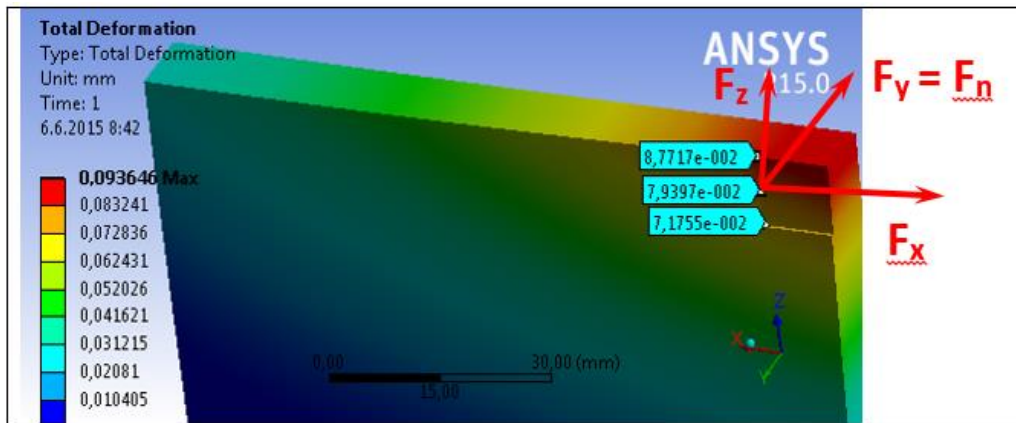

Fig. 4. Prediction of deformation w_R at the begining (X = 90 mm) of roughing cut (down milling)

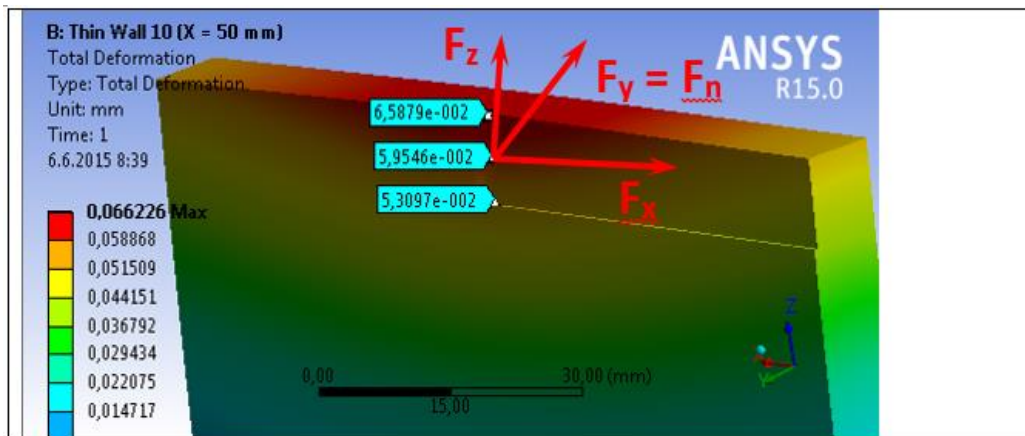

Fig. 5. Prediction of deformation w_R in the middle (X = 90 mm) of roughing cut (down milling)

Fig. 6 presents a constant values of predicted deflection w_L calculated with the equation (2) for roughing and finishing. Position of cutting tool in X axis is not expressed in the equation (2).

Fig. 6 also presents an inconstant maximum and minimum deformation values w_R (roughing when $F_n = 300$ N) and w_F (finishing when $F_n = 50$ N) predicted from FEM software. The coordinate X axis expresses the contact position of the cutting tool with the workpiece during one horizontal milling cut (sidemilling).

The introduced maximum and minimum values of thin-walled workpiece deflection in different points of contact with the tool allows to calculate the predicted the angle of inclination of the machined surface ($a_p = 10$ mm). This inclination is for programming of mill motion also needed to be predicted in detail by FEM because of its inconstancy.

It is preferable that the linear trajectory of a milling tool without compensation or with compensation by one constant deflection value of a thin-walled workpiece is replaced by curvilinear path. That path integrates the values of deformation predicted with respect to the position of the milling tool. After machining the surface, therefore after removal of the cutting forces of the process, the elastic deformation of the thin wall of the component come back to zero and it is possible to measure a improved flatness of the machined surface.
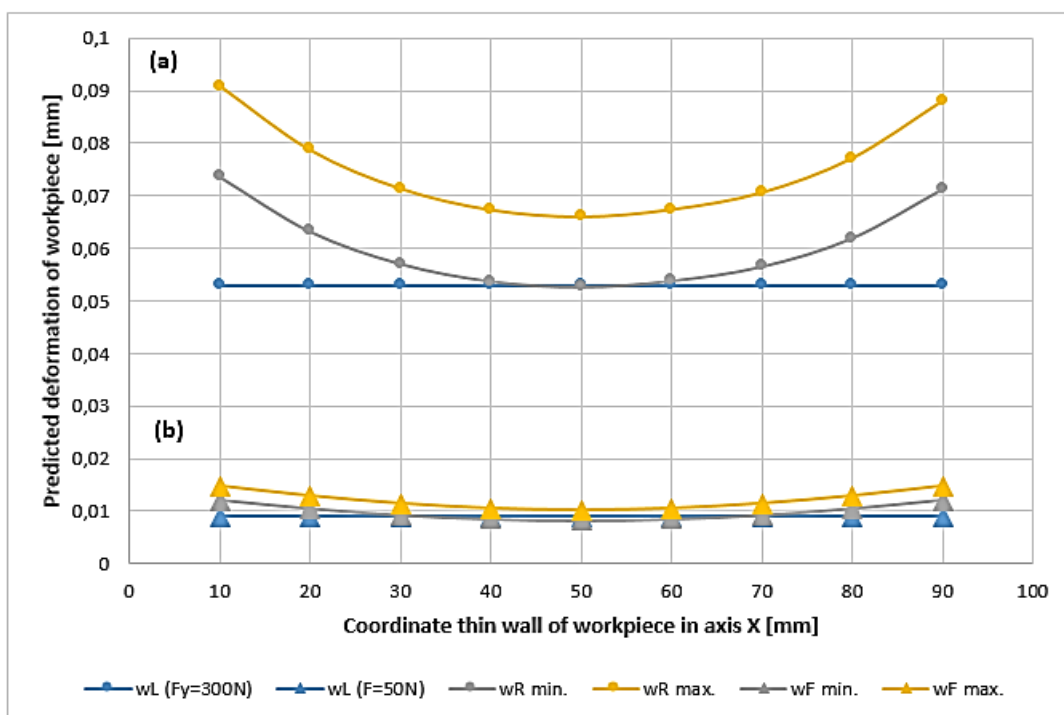

Fig. 6. Values of the predicted deformation of a thin wall, depending on the position

3. PRACTICAL COMPARISON OF THE SURFACE FLATNESS OF THE MACHINED SURFACES

During the experimental rough milling of thin-walled component (Fig. 1a and Fig. 7) there were recorded the individual force components (F_{x1}, F_{y1}, F_{z1}) in the Cartesian coordinate system of a dynamometer (x_1, y_1, z_1). By the subsequent measuring the coordinate of the machined surface positioned in the Y axis of machine tool, the matrix of the deviations from flatness was created (Fig. 8).

Key parameters of the experiment:
- Milling machine: MCV1210/Sinumerik 840D pl. (manufacturer Tajmac-ZPS, Inc.);
- Cutting tool: type 20E3S100-38A20 SUMA (manufacturer Pramet Tools Ltd.);

- Hydraulic tool holder (HSK 63 A);
- Compact high accuracy touch probe OMP 400 (manufacturer Renishaw plc);
- Procedural liquid: Cimstar 597, 12 % concentration;
- Cutting speed and cutting tool revs: $v_c = 1000$ m/min, $n = 15{,}923$ min^{-1};
- Feed per tooth and moving speed: $f_z = 0.1$ mm, $v_f = 4{,}777$ mm/min;
- Axial depth of cut: $a_p = 10$ mm;
- Radial depth of cut: Roughing $a_{eR} = 0.5$ mm;
                        Finishing $a_{eF} = 0.02$ mm;
- Machining direction: consecutive milling;
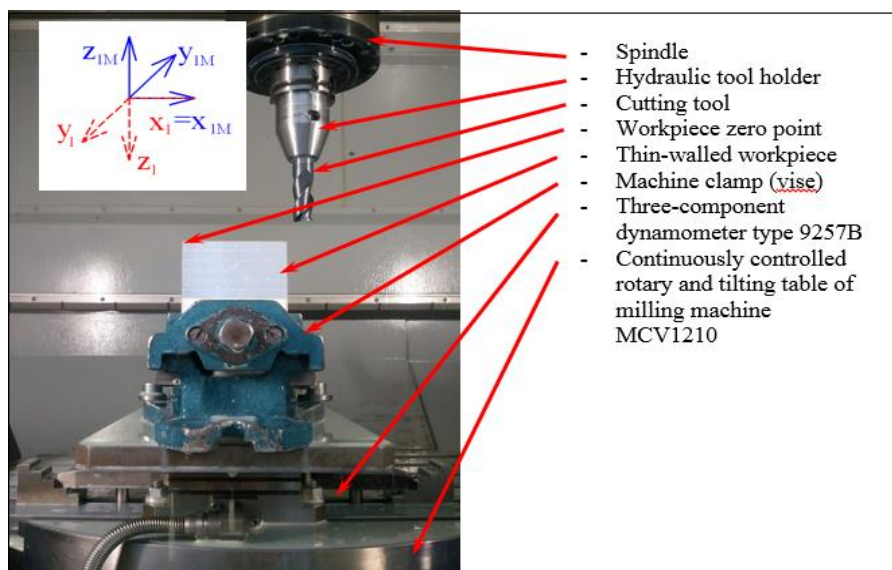- Workpiece material: AlCuMgPb (DIN 3.1645, EN AW-2007).

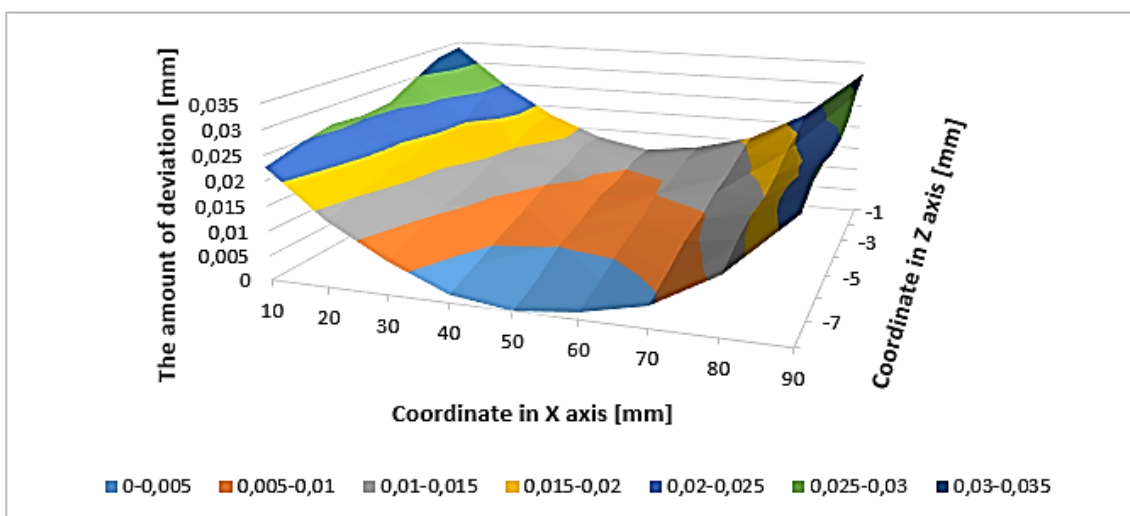Fig. 7. Cartesian coordinate systems for milling machine and 3-axes dynamometer

Fig. 8. Visualization of surface deviations of thin-walled component machined when the force $F_y = 302.66$ N (roughing without compensation)

By filtering and statistical processing of measured values of the force component F_{y1} initially and of the other components F_{x1} and F_{z1} for the following experiments were obtained average input values F_x = 65.66 N (σ = 11.80 N), F_y = 49.57 N (σ = 6.55 N) a F_z = 11.75 N (σ = 1.68 N) for the predictions in the Ansys Workbench R15 software. Values of predicted thin wall deflection when roughing and the subsequent finishing cut were implemented as compensation data in the NC program. Resulting variations in surface roughness after roughing and finishing cut are shown on Fig. 9.
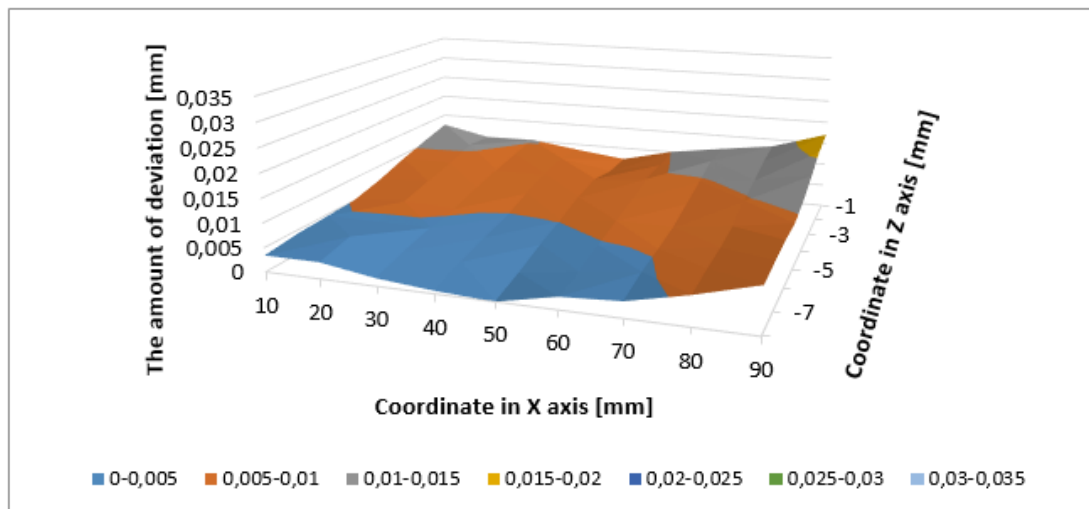

Fig. 9 Visualization of surface deviations when the thin wall has been machined by finishing cut with implemented compensation of predicted deflection caused only by the force component F_y= 49.57 N

Although for compensating of deflection at this phase are used only force components F_y, which corresponded to roughing (F_y = 302.66 N, σ = 10.03 N) and a finishing (F_y = 49.57 N, σ = 6.55 N), the maximum deviation of flatness machined surface is reduced from 0.0337 mm to 0.0187 mm. Considering the force components which are loading during milling process along the other Cartesian coordinate system axes (see Fig. 4 and Fig. 5) is possible to reduce the difference between the deviation on the right side of the machined surface and at in its centre part of about 0.0007 mm according to the FEM prediction.

It is possible to reduce this disparity of the machined surface further of 0.003 mm as predicted by the involvement of rotary axes into the machining milling center with a deflection compensations. However, that method of machining requires a machine with continuous 5-axis control. NC program must contain following:
- the predicted angle of rotary axes considering the differences in:
  - slope of the right edge of the thin wall (0°1'1.36"),
  - slope of the center of the thin wall (0°0'40.73"),
  - slope of the left edge of the thin wall (0°0'56.68"),
- the path of milling cutter in the form of the curve Akima-spline type,
- active so-called adaptive control,

- activated constant acceleration of the machine axes,
- other specialized functions of Sinumerik 840D control system for smooth movement of a milling cutter (for example: FFWON, SOFT, etc.).

4. CONCLUSIONS

In this paper, it is presented how to get the reduction of the flatness deviation of the machined surface. The achieved reduction is of 44.51%. This improvement was achieved by adding a so-called finishing cut compensated by using of the predicted deflection. NC program controlled the movement of the cutting tool along the curved path instead of the original linear path. It is presented that in case of this workpiece it is theoretically possible to get the deviation reduced of about another 11%. For this further refinement it is necessary to use all the loading force components and the changes of the rotation of the machine tool rotary axes must be programmed at the same time.

The maximum flatness deviation of 0.0187 mm, which was measured on the machined surface after finishing cut with compensation only by the force F_n and without the slope of the machine rotational axis can be further reduced by the predicted value of 0.0037 mm. This additional reduction has not been verified in practice. For further practical measurements, the financial resources are obtained by solving the part of the grant project TA CR number TE02000032 (Project title: Advanced Aerostructures Research Centre).

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