STUDY OF THE MILLING FORCES AND DEFORMATIONS IN THE MANUFACTURING OF PARTS WITH THIN WALLS

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ABSTRACT: In the paper are presented some results of experimental and by simulation researches in the CAD-CAM field concerning the processing by milling of plane surfaces using end mill tools and establishing the values of the cutting force components. It is used a modern dynamometer and a data acquisition system for the cutting forces measurement. The elastic deformation and the stress values of the processed part are determined by experimental tests and simulated FEM analysis. Depending on the data that geometrically define the part and the cutting tool, their materials and the cutting parameters are set values of the cutting force and power. There are presented the results of values comparison obtained by measuring during the process with those established by applying FEM. This study results lead to some remarks and useful recommendations for determining the process parameters and the imposed conditions for the technological system in the processing of parts having thin walls with minimum deformations.
KEY WORDS: thin wall milling, cutting conditions, force measuring, stress and deformation analysis.

1 INTRODUCTION

The use of modern CAD-CAM techniques in the parts manufacturing processes has a large application in all the mechanical industry domains. The specialty literature (Constantinescu, 2006) also highlights results of FEM applications in order to determine the elastic deformations values and the stresses leaded in parts by the contact with the tools during the working processes. The influences of the technological system (machine-tool, tools, fixture devices) (Perovic, 2006) determine dimensional variations and irregularities of the processed surfaces, dynamical behaviour of the machine-tool in the cutting process and also the premature wear of the cutting edges (Trent, 2000). The results of the surfaces generation by simulation, with the aid of CAM techniques offer a large number of data: processing times, surface accuracy, behavior of the machine-tool in working conditions (cutting forces and power). Also, by FEM simulations there are determined the stress and deformation values created by the cutting forces in the thin walls of the analyzed parts (Budak & Altintas, 1994), (Rao, 2006). For the optimization of the technological process there are considered and applied various criteria, software environments, tables of data.

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2 THE CAM SIMULATION

Preparing the part for processing on a machine-tool with numerical control involves the generation of command information, all data is then stored in a preset order within a storage device. Programs can be generated directly on the machine, the operator writes the necessary instructions using the interface or by using a CAD-CAM program and a virtual model of the piece (Ghionea & al, 2009). Defining the piece in a CAD environment is used as the entry date to generate the program with one of the complex existing programming languages. Thus, the simulation is justified to optimize the process because CAM programs elaborate the NC machine code. For the study, it is considered a part having its 3D model made in CATIA Part Design module and presented in figure 1. The overall dimensions of the stock part are 80×80×37 mm. This part has a side thin wall and a cavity. The machined surface of this thin wall is marked with S1 and it has a 1 mm thickness. The stock part has two side pockets for direct clamping on the machine-tool table. The CAM simulation involves multiple passes in conditions of roughing and finishing millings with specific technological parameters.

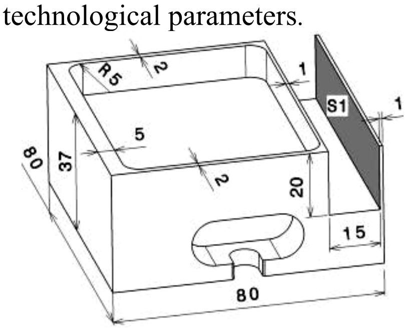

Figure 1. 3D model of the analyzed part

To simulate the manufacture of the part it is used a 3-axis CNC vertical milling machine-tool having the following main characteristics: • spindle speed: 18000 rpm with infinite variable speed range (direct drive spindle), movement on axes X = 550 mm, Y = 450 mm, Z = 500 mm, the power of the main spindle motor: P = 15 kW (continuous rating), machining feedrate max: 8000 mm/min and rapid feedrate: 20000 mm/min, • the machine-tool has a CNC Sinumerik controller.

The tools used in manufacturing simulation are chosen from a company catalogue (CoroGuide, 2008). Also, the toolholders are in correspondence with the spindle nose and the holding system of the machine-tool. Only two steps of the CAM simulation (surface S1) in the case of a steel (OLC45) workpiece, 190 HB are presented below (figure and parameters):

a. *Slot mill*, three passes, D_c = 12 mm - tool diameter, h_m = 0.06 mm – average chip thickness, v_c = 280 m/min - cutting speed, n_c = 7400 rpm - spindle speed, v_f = 2900 mm/min - feed speed, P_c = 13 kW - cutting power for removal of chips, M_c = 17 Nm - cutting torque, Q = 235 cm^3/min - metal removal rate, f_z = 0.1 mm – feed per cutting edge, a_p = 6.6 mm - cutting depth, z_c = 4 – number of teeth, t_m = 6 s – machining time, t_t = 9 s – total time.

b. *Side wall finishing end mill* (Fig. 2), two passes, D_c = 10 mm, h_m = 0.01 mm, v_c = 300 m/min, n_c = 9500 rpm, v_f = 1900 mm/min, P_c = 1.7 kW, M_c = 1.7 Nm, Q = 19 cm^3/min, f_z = 0.05 mm, a_p = 20 mm, a_e = 0.5 mm – working engagement, z_c = 4.

Figure 3 presents a fragment of the NC code obtained after the CAM simulation (Ghionea, 2009) in the case of the finishing milling.

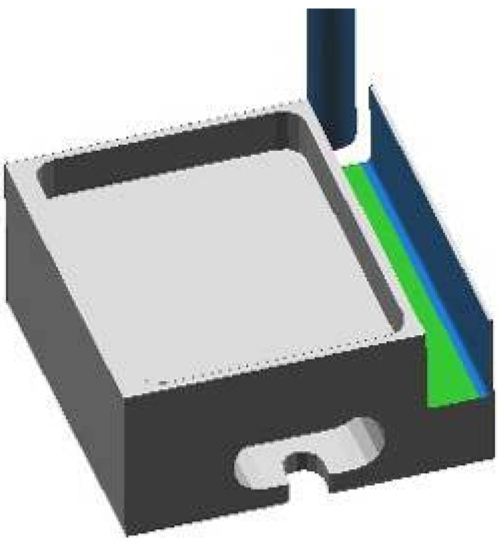

Figure 2. Finish milling of S1 surface

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N260 ;=== TOOL CHANGE ===
N290 T2 M06
N300 D2
N310 G0 G90 G40 G17
N320 G94 F2900 S7400 M3
N330 G64 SOFT
N340 G1 X33.45 Y30 Z-34 S9500 F4000
N350 Z-57
N360 Y40 F1900
N370 Y120
N380 Y130
N390 G0 Z-36
N400 G0 X33.95 Y30
N410 G0 Z-57
N420 G1 Y40 F0.1
N430 Y120
N440 Y130
N450 Z-34 F4000
N460 M5
N470 M5 M9
N480 M30
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Figure 3. Fragment of the NC code

3 THE FEM SIMULATION AND ANALYSIS

In this FEM simulation it is considered a finishing end mill with the diameter D_c = 10 mm, number of cutting edges z_c = 4, pitch of the helical cutting tooth L_{sh} = 28 mm, helix angle $\omega = 50^0$ (Tănase, 2009). On the contact line between the milling edge and the part there are created three cutting spots placed on the height of the helical pitch, shown in figure 4.

In order to establish these spots where the radial medium cutting force is applied it was necessary to determine the contact length of each helical edge with the part. The dimensions and the positions of the spots depend on the contact angle φ between the part and the cutting edge and the helical pitch of the cutting teeth, determined using the equations (1), (2) and (3).

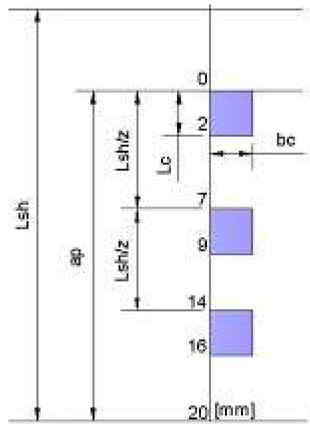

Figure 4. The dimensions and the position of the cutting spots

$$\varphi = 2 \cdot \sqrt{\frac{a_e}{D_c}} = 0.447 \text{ , [rad]} \quad (1)$$

$$L_c = \frac{L_{sh} \cdot \varphi}{2\pi} = \frac{28}{\pi}\sqrt{\frac{0.5}{10}} = 2 \text{, [mm]} \quad (2)$$

$$b_c = \sqrt{0.25 \cdot D_c^2 - (0.5 \cdot D_c - a_e)^2} = 2.18 \text{, [mm]} \quad (3)$$

where: L_c – length of the cutting spot, b_c – width of the cutting spot and L_{sh} - helical pitch of the cutting tooth.

The medium cutting force acting on a contact spot is determined using the values for cutting power P_c depending on the cutting parameters (Metalcutting, 2005):

$$F_{tm} = \frac{60000 \cdot P_c}{v_c} \text{, [N]} \quad (4)$$

and has the values: 287 N (roughing), respectively, 203 N (finishing).

The radial medium cutting force (which is practically applied on the three spots) is $F_{rm} = (0.5 \ldots 1) \cdot F_{tm}$, considered $F_{rm} = 0.9 \cdot F_{tm} = 183$ N.

As follows, there are presented some results of FEM simulations and analysis in the cases of the part being processed of steel OLC45.

Thus, the radial medium cutting force is F_{rm1} = 61 N on each of the three cutting spots. Figure 5 presents the deformations of the thin wall in the case that the cutting force is applied in it's middle area.

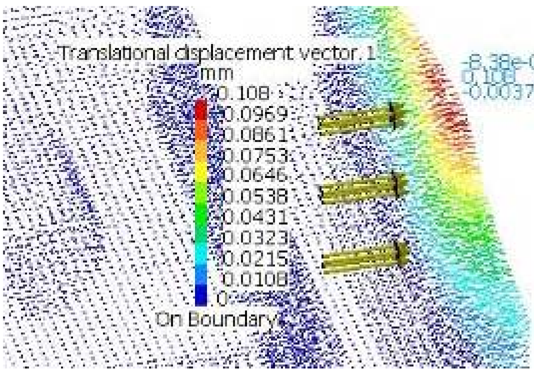

Figure 5. Deformations of the thin wall on the middle area

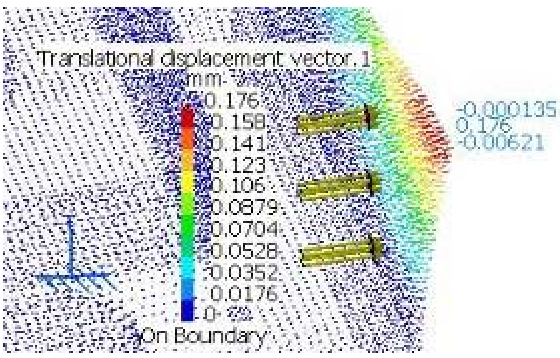

Figure 6. Deformations of the thin wall on one of the ends

Also, figure 6 shows the deformations when the cutting force is applied on one of the thin wall's ends. Using the CATIA software FEM analysis capabilities, there is simulated the distribution of the stresses in both situations.

Figure 7 shows the Von Mises Stresses calculated in the case the force applied in the middle area of the thin wall. For a force of 61 N (on each cutting spot) the results are: max. stress = 1.07×10^8 N/m^2 and max. elastic deformation Δx = 0.108 mm (Fig. 5) with an error of 27.7 %.

Figure 8 shows the Von Mises Stresses calculated in the case the force applied in one of the ends of the thin wall. For a force of 61 N (on each cutting spot) the results are: max. stress = 1.58×10^8 N/m^2 and max. elastic deformation Δx = 0.176 mm (Fig. 7) with an error of 31.2 %.

The considered steel has the yield strength of 2.5×10^8 N/m^2.

In the FEM practice, an error of 20% - 35% is acceptable and it's very close to the real case (Constantinescu, 2006). Anyway, in both situations for the flat surface S1, the max. stresses are lower than the materials' yield strengths, so the thin wall is deformed only in the elastic domain.

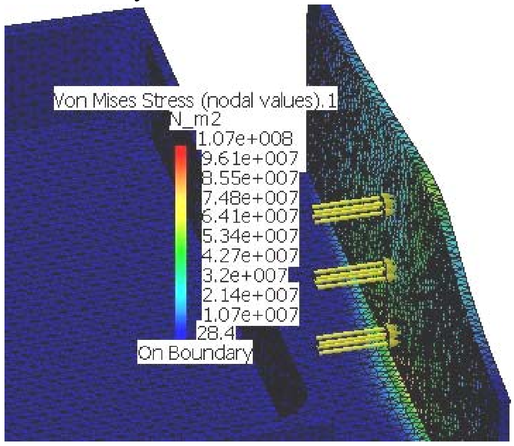

Figure 7. Von Mises stresses of the thin wall on the middle area

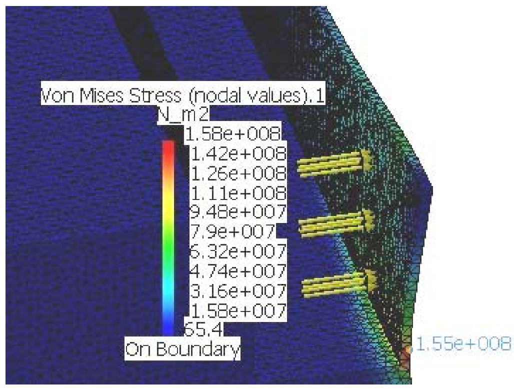

Figure 8. Von Mises stresses of the thin wall on one of the ends

4 EXPERIMENTAL RESEARCHES

4.1 Experimental setup

The purpose of the experimental researches was to determine the elastic deformations of the thin wall for the considered part, in real conditions of milling. In the process it was used an universal milling machine, type FN-32 (TOS). Also, for the cutting tool it was chosen an end mill, single casting type of metal carbide CoroMill Plura (GC 1620), with diameter D_c = 10 mm, tool helix angle = 50^0, helical pitch of the cutting teeth = 28 mm, total length = 100 mm, length of the active part = 26.5 mm. The cutting conditions were: cutting speed v_c = 63 m/min, feed per cutting edge f_z = 0.02…0.04 mm, cutting depth a_p = 20 mm, working engagement a_e = 0.2 …0.5 mm. The milling process was done without cooling, in the sens and in contrary sens of the cutting feed.

The technical installation for the experimental determination of the cutting forces and for the measurements of the elastic deformations it was composed of the next components (Fig. 9): workpiece (1), Quartz 3 component Dynamometer Type 9257 B Kistler (2) fixed on the machine table (5); Multi-Channel Charge Amplifier for Multicomponent - Force Measurement Type 5070 A (6); Data acquisition board Type PCIM-DAS1602/16 (7); DynoWare Type 2825A data acquisitions (Instructions Kistler, 2008) and manipulation software (7) PC with Windows XP. The tool (3) was fixed in the main spindle of the orientable milling head (4), through a toolholder.

The measuring of the elastic deformation of the machined thin wall S1 (fig. 10) was done with a dial gauge *C* with a division of 0.001 mm whose detector was located at the midle of the wall length of the workpiece *W*, at its maximum height. The tool *T* is presented at the end of the finishing milling pass, done by down milling. In the cutting zone there are chips *Ch* resulted from machining process.

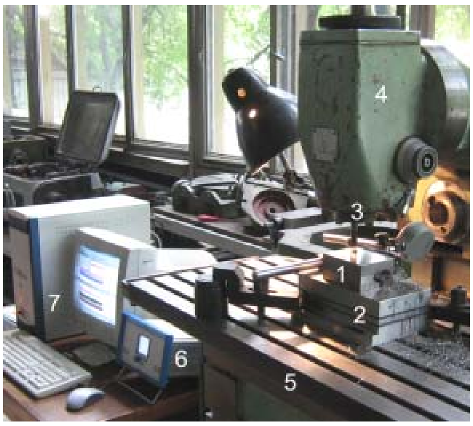

Figure 9. Experimental installation

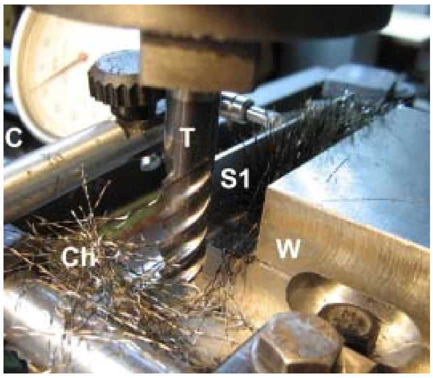

Figure 10. Machining area

The components of the cutting force, F_x, F_y and F_z were measured with the dinamometer on the directions of the considered reference system. The component F_x is normal orientated on the surface of the processed wall and cause its deformation. The component F_y is orientated on the direction of feed movement, and the F_z component is on the direction of tool's axis.

4.2 Results of the experimental determinations

The cutting forces were measured in conditions of roughing and finishing millings, with corresponding cutting speeds. There were done 12 measurements in order to determine the cutting forces and the maximum deformations of the thin wall, machined from the thickness of 3.5 mm to 1 mm. Within each measurement it was realised a file with procesed data and the measurements results of 8 components using the Kistler dinamomenter data. Every data file contains a page with comments (fig. 11) which allows the user to annotate each measurement.

By processing the data with Dyno-Ware type 2825 A there are obtained variations diagrams of the cutting forces' components previously selected by the user, and also the minimum, medium and maximum values of the choosen intervals of time, as needed (for example, for a tool rotation).

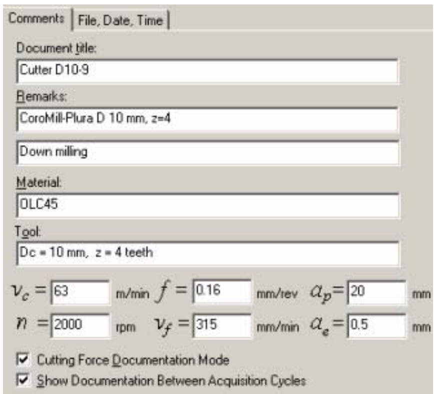

Figure 11. Comments for cutting conditions

Table 1. Experimental measurements

Det. No.	F_x[N]		F_y[N]		F_z[N]		f_z [mm/tooth]	a_e [mm]	Thickness wall [mm]	Deflection Δx[mm]
	med	max	med	max	med	max				
D10-1	- 170	- 216	26	52	- 205	- 263	0.025	0.5	3	0.008
D10-6	- 149	- 184	55	81	- 167	- 215	0.025	0.5	2	0.012
D10-9	- 248	- 325	100	134	- 141	- 187	0.04	0.5	1.5	0.035
D10-12	- 227	- 305	98	122	- 135	- 174	0.04	0.5	1	0.14

The components F_x, F_y and F_z are determined at the first tool's pass, noted with D10-1, on a time interval of 0.5 s and they are presented in the figure 12. The graphics appear overlapped and they could be distinguished by different colours.

The numerical values of each force component may be determined for each moment or interval of the determination using options from the program's toolbar (Edit, View, Cursor, Mean Value, Drift Compensation, Horizontal Grids, Vertical Grids). Some results for a few of the 12 experimental determinations are shown in table 1. The values of the measured forces are determined directly by the cutting depth a_e and by the feed per cutting edge f_z, all the other parameters being mantained constant. In the studied case it presents a great interest the F_x force component (fig. 13) oriented normal to the surface of the machined thin wall.

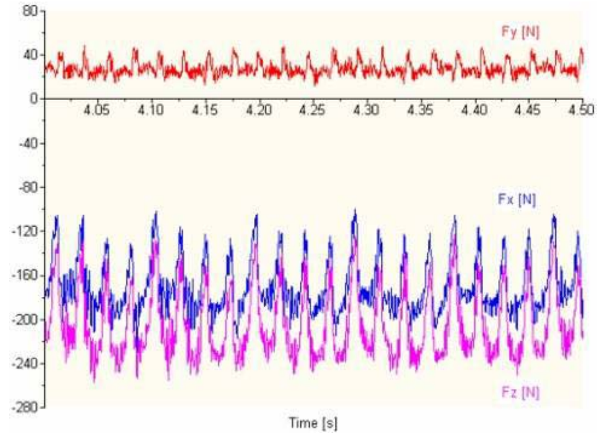

Figure 12. Cutting forces for the determination D10-1

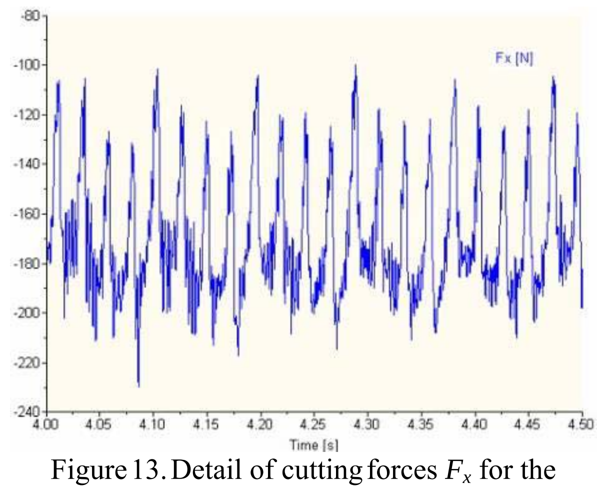

Figure 13. Detail of cutting forces F_x for the determination D10-1

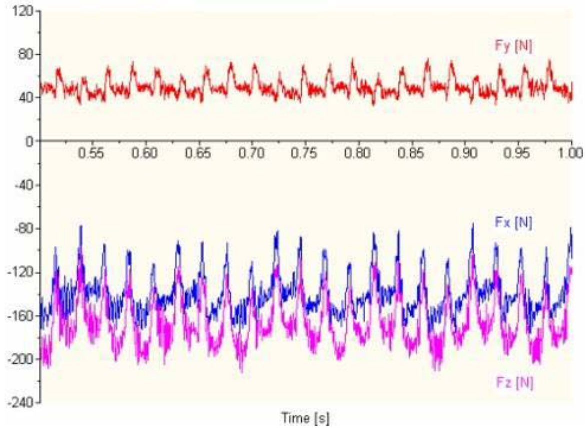

Figure 14. Cutting forces for the determination D10-6

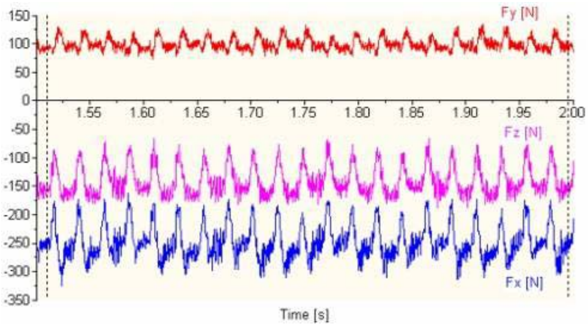

Figure 15. Cutting forces for the determination D10-9

During the milling pass for a wall thickness of 2 mm, test noted with D10-6, there were obtained the components of the cutting force represented in the figure 14. For another test D10-9, the cutting force components had the variation represented in the figure 15, for a wall thickness of 1.5 mm.

Also, for the determination of the cutting force component F_x it was applied a calculus algorithm using some data from the Coromant catalog, or a specialized software CoroGuide for the process parameters. For the rough milling regime, corresponding to the test D10-9, the average tangential force results: $F_{tmed\,9} = 287$ N. The average radial force is: $F_{rmed9} = (0.5\ldots1)\, F_{tmed\,9} = 229$ N. The measured value for F_x component in the D10-9 determination was $F_{xmed} = 248$ N and the corresponding deformation was Δx = 0.035 mm.

For the finish milling regime, corresponding to the test D10-6, the calculated values for these two force components are: $F_{tmed6} = 203$ N and $F_{rmed6} = 162$ N. The measured value for F_x component in the

D10-6 determination was $F_{x\text{med}}$ = 149 N, for the calculated radial force $F_{r\text{med6}}$.

By comparing the results obtained by measurement with a dynamometer of the component F_x, the calculated values of the average radial force is found that the differences are below 10%, thus confirming the validity of measurements and calculations made in the experimental tests. The diagrams of the components F_x, F_y and F_z of the cutting force shows relatively large cyclical variations with the corresponding period of time of a tool rotation. Thus, in the working conditions, when the spindle speed n_c = 2000 rpm, the corresponding time to a tool rotation is 0.03 s. This force variation is due to inherent radial run-out of the edge to the tool's axis of rotation, and also, to a low feed per cutting edge.

5 CONCLUDING REMARKS

The determination of the cutting forces that the cutting edges action on the machined surface was made using an experimental setup based on multicomponent Quartz dynamometer.

The value of the thin wall's maximum elastic deformation, measured during the finish milling is very high compared with the wall thickness.

This shows that the cutting regime (the parameters a_e and f_z) has to be decreased if the permissible deviations (precision required during real machining by milling) are smaller than the resulted maximum elastic deformation.

The elastic deformations Δx are higher at both ends of the wall (0.176 mm) compared to the deformation at the middle of the wall (0.108 mm). The result is an unexpected variation of the wall thickness in both directions, length and height. The measured values of the radial forces and elastic deformation Δx are in a good correspondence with the calculated values.

Also, these deformations corresponding to the considered working regime seem to be unacceptable influencing the accuracy of the machined surfaces. If the aim is a higher precision, the parameters of the machining regime should be decreased and the simulation process resumed.

6 REFERENCES

► Budak, E., Altintas, Y., (1994). *Peripheral milling conditions for improved dimensional accuracy*. International Journal of Machine Tools and Manufacture. 34 (7), ISSN 0890-6955, pp. 907-918.

► Constantinescu, N. I., Sorohan, Şt., Pastramă, Şt., (2006). *The practice of finite element modeling and analysis*. Editura PRINTECH, Bucureşti, ISBN 978-973-718-511-2.

► Ghionea, I., (2009). *CATIA v5. Aplicatii in inginerie mecanica*. Editura BREN, Bucuresti, ISBN 978-973-648-843-6.

► Ghionea, I., Ghionea, A., Tanase, I., (2009). *Application of CAM-FEM techniques in the establishement of milling conditions of the parts with thin walls surfaces*. 4nd International Conference Optimization of the Robots and Manipulators, OPTIROB, 28-31 May 2009, ISSN 2066-3854, Constanta, Romania. Editura BREN Bucharest, ISSN 2066-3854, pp. 27-32.

► Rao, S. V., Rao, M. V. P., (2006). *Tool deflection compensation in peripheral milling of curved geometries*. International Journal of Machine Tools and Manufacture. Design, Research and Application 46 pp. 2036-2043.

► Tanase, I, (2009), *Scule aschietoare*, Editura BREN, ISBN 978-973-648-849-8.

► Trent, E., Wrigt, P., (2000). *Metal cutting*, Butterworth Hinemann, Oxford, Boston.

► ***, (2008). *Operating Instructions KISTLER Instrumente* AG, Switzerland

► ***, (2008). *Metalworking products CoroGuide 08.2*, SANDVIK Coromant.

► ***, (2005). *Metalcutting Technical guide* SANDVIK Coromant, C-2900:3 ENG/01. Printed in Sweden by Elanders.