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MEASUREMENT AND ANALYSIS OF CUTTING FORCES AND DEFORMATION AT MILLING THIN PARTS

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Abstract: *The main results of experimental researches and CAD-CAM simulations at milling plane surfaces of thin walls parts are presented in the paper. The cutting force measurement was done using a multi-component quartz dynamometer with a special data acquisition system for the cutting forces. The elastic deformation and the stress values in the machined part were determined by experimental tests and simulated using the FEM analysis. There is presented a comparison of values 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 requirements for the technological system in the machining of parts having thin walls, with allowable deformations.*

Key words: *cutting conditions, thin wall milling, force measurement, deformation, stress analysis.*

1. INTRODUCTION

The cutting process performances are related to main features and performances of all elements in the system. The performances required at machining of parts with thin walls are: dimensional accuracy, surface quality and productivity. These machining cases require to minimize the workpiece deformation under cutting forces. Many results of FEM applications are presented in the literature [1] in order to determine the elastic deformations values and the stresses induced in parts at the contact with the tools during the machining processes. The influences of the technological system (machine-tool, cutting tools, fixture devices) determine dimensional variations and irregularities of the machined surfaces, dynamic behavior of the machine-tool in the cutting process and also the premature wear of the cutting edges [4].

The results of the surfaces generation by simulation, with the aid of CAM techniques offer a large number of data: machining times, surface accuracy, behavior of the machine-tool in working conditions (cutting forces and power consumption).

By FEM simulations there are determined the stress and deformation values created by the cutting forces in the thin walls of the analyzed parts [1 and 5]. For the optimization of the technological process there are considered and applied various criteria, software environments, tables of data.

2. WORKING CONDITIONS

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.

Defining the piece in a CAD environment is used as the entry data 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 Fig. 1.

The overall dimensions of the stock part are 70×70×36 mm. This part has a an upper thin wall and a cavity under it. The machined surface of this thin wall is marked with *S*1 and the wall has 1.45 mm thickness. The stock part presents two side pockets for direct clamping on the machine-tool table.

The workpiece was machined using a 3-axis CNC vertical milling center MCV 300, located in the Machine-Tools' laboratory, with the following characteristics: • main spindle speed: 120 – 8000 rpm with infinite variable speed range, • the power of the main spindle motor: *P* = 7.5 kW (continuous rating), • working strokes on axes *X* = 610 mm, *Y* = 305 mm, *Z* = 460 mm, • machining feed rate max: 1 – 10000 mm/min and rapid traverse: 20000 mm/min, • AC motors for feed drives with 3...2000 rpm, *M* = 3/6 Nm, for *X* / *Y* axes, *M* = 12 Nm for *Z* axis; • the milling center has a CNC Fanuc controller.

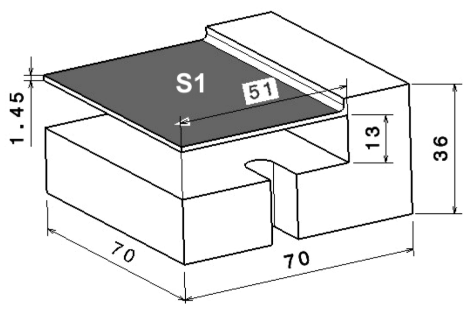

Fig. 1. 3D model of the analyzed part.

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The tools used in the manufacturing process were chosen from a company catalogue [5]. Also, the tool holders are in correspondence with the spindle nose and with the holding system of the machine-tool.

Below three steps of the machining process of the surface $S1$ in the case of a steel XC45 workpiece, 190 HB, are presented:

a. Roughing end milling of the upper surface of the workpiece. Tool: end mill with 6 teeth, D_c = 80 mm diameter (milling tool type CoroMill R365-Q27-S15M 080, square inserts PM).

Working conditions for roughing milling: a_p = 0.5 mm, a_e = 50 mm, f_z = 0.15 mm, v_c = 185 m/min, n_c = 850 rpm, v_f = 765 mm/min, k_r = 65 degrees.

b. Semifinishing milling with two teeth end mill, D_c = 25 mm milling diameter, k_r = 90 degrees (tool type R390 025A25-11L). Working conditions: a_p = 0.2 mm, a_e = 25 mm, f_z = 0.08 mm, v_c = 200m/min, n_c = 2550 rpm.

c. Finishing milling with carbide solid end mill, D_c = 8 mm milling diameter, z = 4 teeth, k_r = 90 degrees. Working conditions a_p = 0.15 mm, a_e = 8 mm, f_z = 0.02 mm/tooth, v_c = 150 m/min, n_c = 5970 rpm, v_f = 478 m/min.

The roughing milling with the specific tool generates the largest cutting forces, of which was taken in the consideration the component Fz in the normal direction to the machined surface.

This component is divided into two spots S_1 and S_2 (Fig. 2) located on the machined surface corresponding two-edged cutting simultaneously.

The position of these spots is determined on the basis of the geometric features of part and tools. The spot sizes are determined taking into account the geometry of the active part of the mill (Fig. 3).

The inserts used in the end milling process are equipped with wiper edges of b_n length and with chamfer edge of b_t length and k_t approach angle.

Corresponding to depth of cut results a_p in contact zone between cutting edge and workpiece, which projected onto the machined surface has the l_c length:

$$l_c = b_t \cdot \cos k_t + b_n \cdot \cos k_{nt} + \left(a_p - b_t \cdot \sin k_t - b_n \cdot \sin k_n\right) / \tan k_r . \qquad (1)$$

The inserts used R365-1505 ZNE-PM have the following dimensions: k_r = 65°; k_n = 60°; k_t = 30°; b_n=1.5 mm; b_t = 0.8 mm.

For the cutting depth a_p = 0.5 mm, results the contact zone length projected onto the machined surface with value l_c = 0.75 mm.

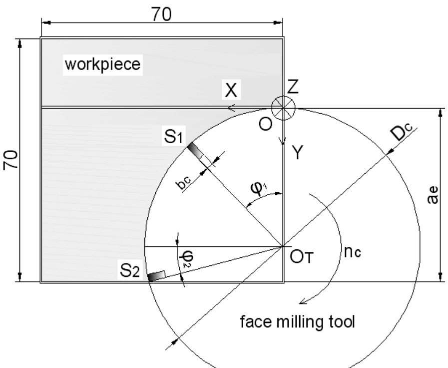

Fig. 2. Positions of the cutting spots.

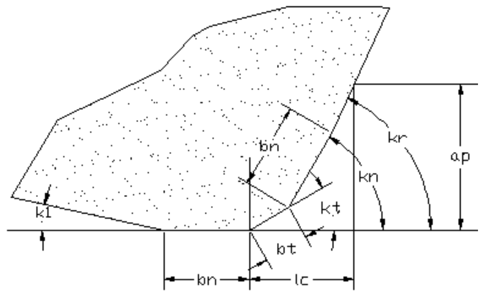

Fig. 3. Contact length between cutting edge and workpiece.

Maximum width of the contact area b_c is determined by taking into account the chip formation mode, based on h_{ex} chip thickness, f_z feed per tooth, k_r contact angle and β_s shear angle [5]. It can be considered a maximum width of the contact area b_c determined by the relationship:

$$b_c = f_z \cdot \sin k_r / \sin \beta_s . \qquad (2)$$

For the feed per tooth f_z = 0.15 mm and β_s = 30° the value b_c = 0.27 mm results.

The medium cutting force acting on the contact spots is determined using the values for cutting power P_c depending on the cutting parameters [4]:

$$F_{tm} = \frac{60000 \cdot P_c}{v_c} \text{ [N]}. \qquad (3)$$

The cutting power P_c for the roughing end milling is determined based on simulation results or on cutting regime experienced data [5]. Corresponding to the workpiece material, with the cutting parameters indicated in the table 1, there is obtained the value of the necessary cutting power P_c = 1.4 kW. The cutting force F_{tm} and consequently the estimated force in axial direction [1] is F_z = 290 N. This force is divided on the spots $S1$ and $S2$.

3. STRESS AND DEFORMATION ANALYSIS BY FEM SIMULATION

As follows, there are presented some results of FEM simulations and analysis in the cases of the part being machined of steel XC45. Thus, the axial medium cutting force is F_{z1} = 145 N on each cutting spot.

Figure 4 presents the *Von Mises* stresses of the thin wall in the case that the cutting forces are applied in the middle area. The simulation results show that the maximum stress of the machined wall in the middle area is 7.52×10^7 N/m^2, an acceptable and safe value, smaller than the steel's yield strength of 2.5×10^8 N/m^2.

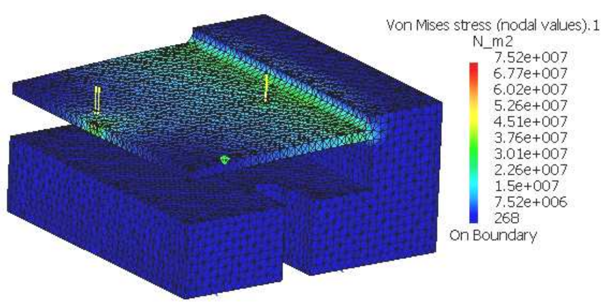

Fig. 4. Von Mises stresses of the thin wall () in the middle area, two forces of 145 N each, wall thin of 2.5 mm.

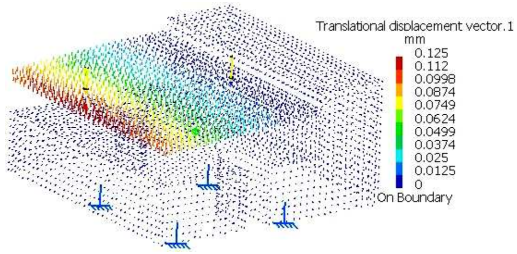

Fig. 5. Deformations of the thin wall in the middle area, two forces of 145 N each, wall thin of 2.5 mm.

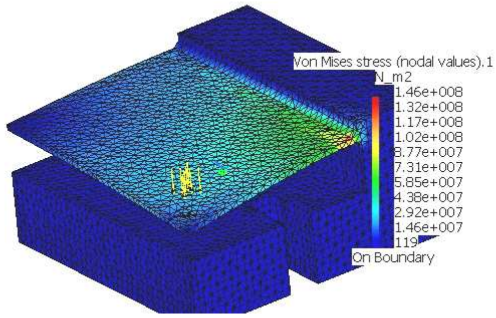

Fig. 6. Von Mises stresses of the thin wall at one of the ends, four forces of 25 N each, wall thin of 1.45 mm.

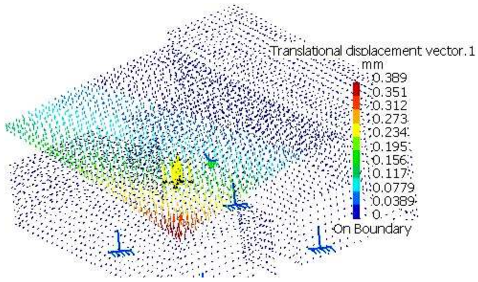

Fig. 7. Deformations of the thin wall at one of the ends, four forces of 25 N each, wall thin of 1.45 mm.

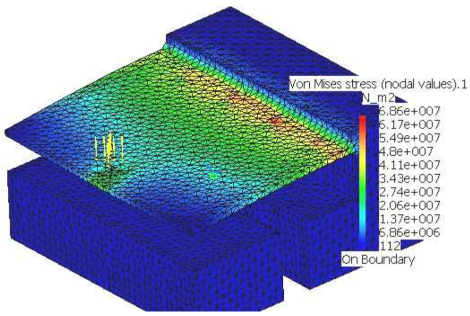

Fig. 8. Von Mises stresses of the thin wall in the middle area, four forces of 25 N each, wall thin of 1.45 mm.

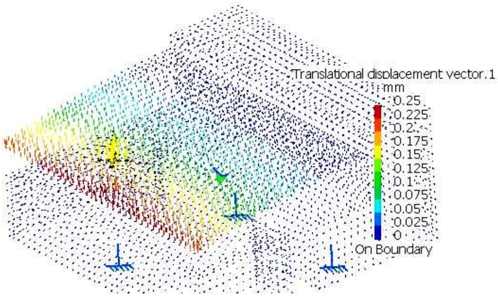

Fig. 9. Deformations of the thin wall in the middle area, four forces of 25 N each, wall thin of 1.45 mm.

Figure 5 shows the corresponding deformations, the maximum value is 0.125 mm, also acceptable for the thin wall milling. The tool used is the end mill with 6 teeth, having D_c = 80 mm diameter. The wall thin is 2.5 mm.

Figures 6 and 7 present the stresses and deformations for a new tool, an end mill having D_c = 8 mm, 4 teeth, when the four cutting forces (25 N each) are applied at one of the thin wall's ends.

The maximum deformation is 0.389 mm, an inadmissible value (compared to the wall thin of 1.45 mm), due to a significant variation of the wall thickness that may results if the surface is machined in these conditions. The maximum occurred stress value (of 1.46×10^8 N/m^2) is also under the steel's yield strength.

As a solution to reduce the deformations values, in this case, the authors propose a decreasing of the milling parameters or/and a reduction of the tool diameter (6 mm).

Figures 8 and 9 show the *Von Mises* Stresses and deformations calculated by simulation in the case of the four forces applied in the middle area of the thin wall. For a force of 25 N (on each cutting spot) the results are: maximum stress = 6.86×10^7 N/m^2 and maximum elastic deformation = 0.25 mm (an acceptable value, but close to the limit). The wall thin is also of 1.45 mm.

During the simulation processes, all the resulted errors are under 20 %. In the FEM practice, an error of 20 %…35 % is acceptable and it is considered close to the real case [2].

Anyway, in all situations for the flat surface *S*1, the maximum stresses are lower than the yield strength of steel, so the thin wall is deformed only in the elastic domain.

4. EXPERIMENTAL RESEARCHES AND RESULTS

4.1. Experimental setup

The experimental researches had the scope to determine the elastic deformations of the thin wall during the machining processes and also to determine the milling cutting forces.

The milling process was performed without cooling by down-milling method. The up-milling procedure has to be avoided because of strong chatter occurring related to flexibility of machined part walls.

The measurement of machined wall deformation was accomplished using an inductive differential transducer together with a carrier frequency amplifier having an adequate calibration.

The experimental stand arranged for the determination of cutting forces and for the measurements of the elastic deformations was composed of the next principal components (Fig. 10): workpiece (1), Quartz 3 Component Dynamometer Type 9257 B Kistler (2) fixed on the machine table (5); inductive differential transducer (4); carrier frequency amplifier (9); Amplifier for Multicomponent − Force measurement Multi-Channel Charge Type 5070 A (6); data acquisition board Type PCIM-DAS1602/16 (7); DynoWare Type 2825A data acquisitions and manipulation software [6]; PC with Windows XP.

The milling cutters (3) were fixed in the main spindle of the vertical milling head (8), through specific holders.

Table 1

Significant results from the experimental determinations

Det. No.	Cutting conditions						F_x [N]		F_y [N]		F_z [N]		Deformation Δz [mm]
	D_c [mm]	a_e [mm]	a_p [mm]	f_z [mm]	v_c [m/min]	w_t [mm]	med	max	med	max	med	max	
1	80	50	0,5	0,15	185	6	- 86	- 248	42	122	202	2×300	0.066
2	80	50	0,2	0,1	238	2,5	- 13	- 184	9	72	29	145	0.132
3	25	25	0,2	0,08	200	2,0	- 8,0	- 278	4,8	157	28	247	0.287
4	8	8	0,1	0,02	150	1,45	- 9,0	- 49	1.0	24	40	92	0.252

Fig. 10. Experimental stand arrangement.

Fig. 11. Machining area.

The components of the cutting force, F_x, F_y and F_z were measured with the dynamometer on the directions of the dynamometer reference system (Fig. 11).

The component F_z is normal oriented on the surface of the machined wall and cause its deformation.

The component F_y is oriented on the direction of feed movement, and the F_x component is normal on tool's axis. Vertical component of the cutting force, F_z, oriented normal to the thin wall surface, is that which determines the main deformation.

The horizontal components F_x and F_y are oriented parallel to the machined surface in order not to produce significant deformation of the wall.

The cutting force components were measured in conditions of roughing and finishing milling, with corresponding feed per tooth and cutting speeds.

Multiple measurements were performed in order to determine the cutting forces and the maximum deformation of the thin wall, machined from a thickness of 6 mm to 1.45 mm.

Within each measurement it was acquired a file with machining data and results of the force components using the dynamometer signals.

By processing the acquired data files with DynoWare 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 on the chosen intervals of time, as needed (e.g. for a tool rotation).

The numerical values of each force component may be determined for each moment or interval of the determination using options from the program toolbar. Significant results selected from the experimental determinations are shown in Table 1. The values of the measured forces are determined directly by the cutting depth a_e and a_p by the feed per tooth f_z and the cutting speed v_c.

The thin wall millings were done in several passes, with three mills having diameters D_c and different numbers of teeth z_c. The wall thickness w_t was decreased with each pass, the part stiffness was reduced consequently, this change imposing effects on cutting forces and vibrations.

All components of the cutting force present similar variation to determination D80-1 (Fig. 12). The average value remains constant during the pass. There are three areas with different amplitudes of force.

At the beginning of each machining pass, large amplitude of normal force F_z area indicates the occurrence of vibration and large deformations in this direction.

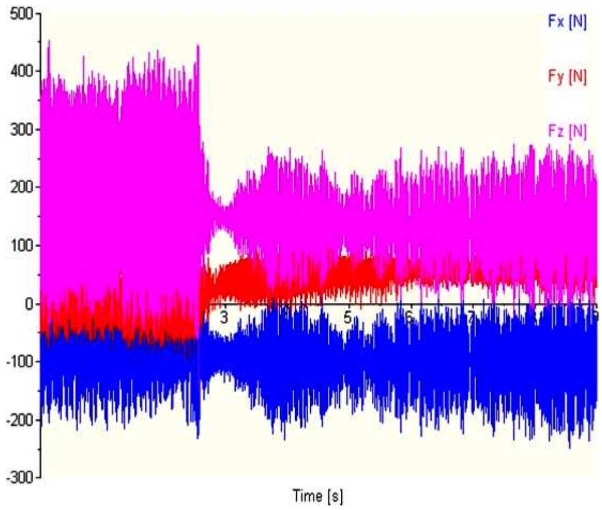

Fig. 12. Cutting forces at end milling, roughing pass.

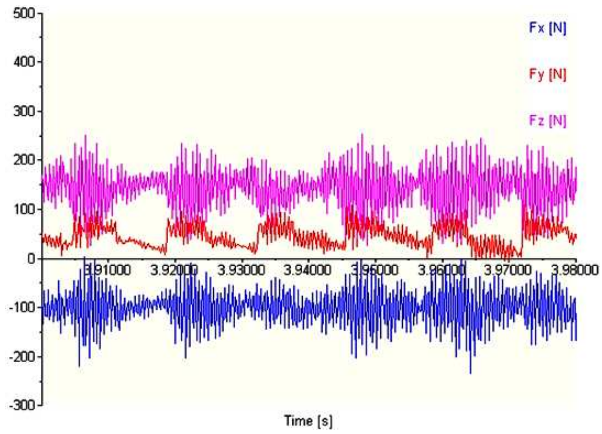

Fig. 13. Cutting force components on tool revolution (0.08 s).

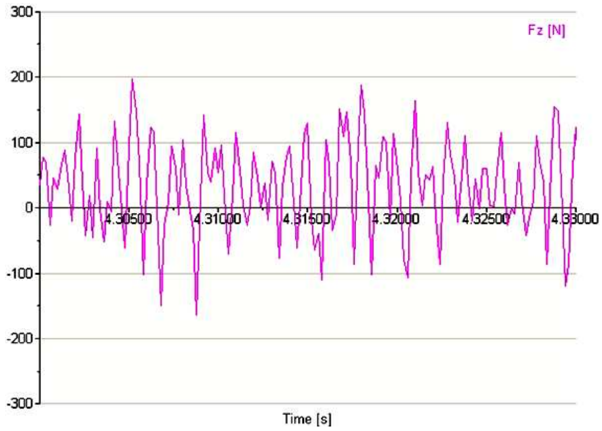

Fig. 14. Cutting force F_z on tool revolution, for the end mill with diameter D_c = 25 mm.

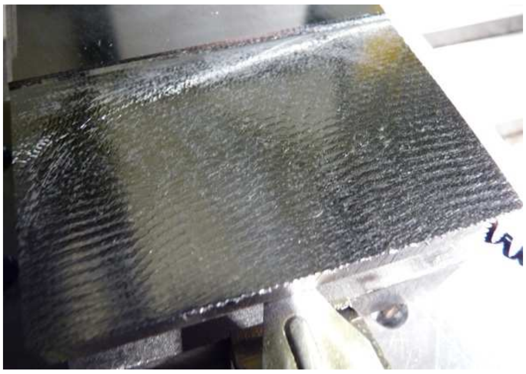

Fig. 15. Machined surface aspect after roughing end milling.

Fig. 16. Machined surface aspect after finishing milling.

When the contact between the cutting edges and the workpiece came around the middle of the machined area, the amplitude variation of the cutting forces decreased more, then had a slight increase towards the end of the pass.

Irregularity of forces on *Z* and *X* directions has generated corrugations and uneven surfaces.

A detail of the cutting forces for a period of 0.08 s (Fig. 13) shows periodic amplitude variation of cutting forces. This variation reveals the instability of cutting process for the six teeth of the cutter in particular *X* and *Z* directions of the dynamometer measurement.

For the end mill having D_c = 25 mm diameter and z_c = 2 teeth, cutting force variation in the direction normal to the machined surface F_z (Fig. 14), a period of 0.024 s corresponding to a rotation of the tool shows a similar instability of cutting process.

The average value of cutting force is low, but the force variation is pregnant, almost 10 times higher than the average force.

The end mills with diameters of 80 mm and 25 mm with indexable inserts used in roughing machining of the thin wall worked in weak stiffness conditions, resulting large roughness marks (Fig. 15).

Finishing machining was done with a solid carbide mill with four teeth, D_c = 8 mm diameter and r_e = 0.5 mm in several passes.

Although the wall thickness in this case was the thinner, stable cutting process was performed, because of that tool having very sharp edges and of the feed per tooth with appropriately chosen value (Table 1).

The diagram of the cutting forces in the finishing milling with an end mill having D_c = 8 mm (Fig. 17) reveals a stable cutting process with low forces.

The largest force variation is revealed by the F_z component, due to the lower rigidity of the wall in *Z* direction and due to an existing undulation on the workpiece surface, generated in earlier machining pass.

Figure 18 presents a detail of the force diagram for a short period of 0.02 s. The feed force F_y has a very small variation around the average value close to zero. The caption of this image was possible due to the smoothness of the used instruments.

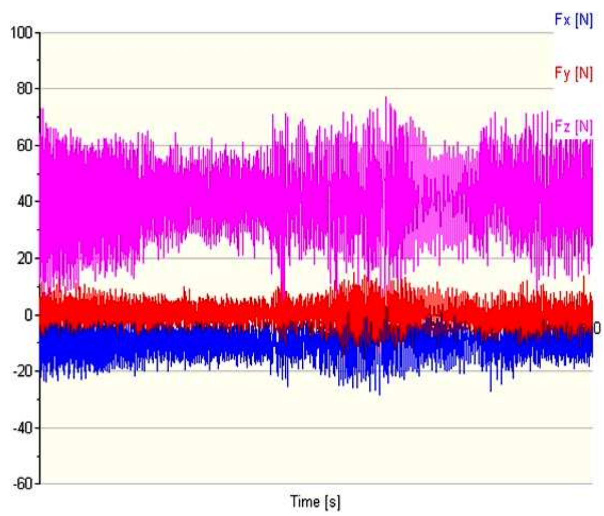

Fig. 17. Cutting forces at milling with an end mill of D_c=8 mm diameter.

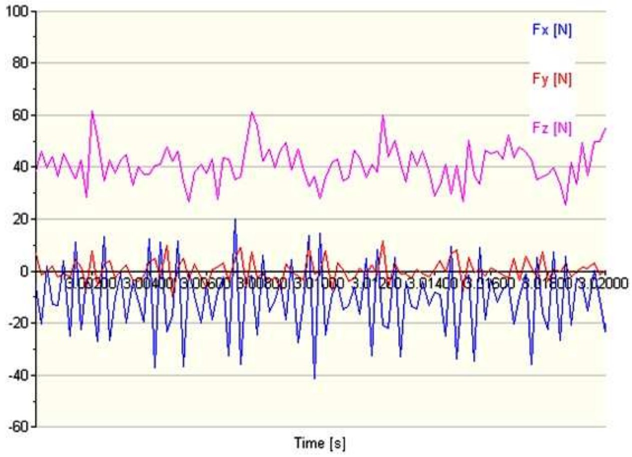

Fig. 18. Cutting forces for 0.02 s at milling with an end mill of D_c=8 mm diameter.

5. CONCLUSIONS

The determination of the cutting forces that cutting edges react on the machined surface was made using an experimental stand based on multi-component Quartz dynamometer.

The value of the thin wall maximum elastic deformation measured during the finish milling is high compared with the wall thickness. Thus, the machined wall thickness results uneven (Fig. 16).

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

The elastic deformations Δz are higher at both ends of the wall (0.389 mm) compared to the deformation at the middle of the wall (0.25 mm).

The result is an unexpected great variation of the wall thickness in both directions, length and width. The measured values of the axial forces and elastic deformations are in a good correspondence with the calculated values by FEM simulation.

Also, these deformations according 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.

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