DEFORMATIONS OF SELECTED MILLING CUTTERS WHILE MILLING Ti6Al4V ALLOY ON A CNC MACHINE TOOL, EXPERIMENTAL TESTS AND FEM MODELING

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S u m m a r y

This paper presents results of investigations focused on the determination of deformations of selected types of milling cutters fixed in the toolholder and spindle of a CNC machine tool used for finishing processes. The experimental investigations were performed on the DMU 80P duoBLOCK machine tool. The components F_x, F_y and F_z of cutting forces were measured during the milling of workpieces made of the hard to machine Ti6Al4V alloy. The experimental studies were also done for computing the static stiffness of applied milling cutters used for finishing processes. The experimental data was used for the subsequent finite element modeling of those cutters. Finally, there were developed the regression models allowing to calculate the average total displacement of the loaded cutting edge. They can be subsequently used for the prediction of machining errors in finishing processes, especially in the case of machining products made of Ti6Al4V alloy.

Keywords: CNC machine tool, milling cutter, stiffness, finite element analysis, machining errors

Odkształcenia wybranych typów frezów podczas frezowania stopu Ti6Al4V na obrabiarce sterowanej numerycznie, badania eksperymentalne i modelowanie MES

S t r e s z c z e n i e

W artykule przedstawiono wyniki badań skupionych na wyznaczeniu odkształceń wybranych typów frezów zamocowanych w uchwycie wrzeciona obrabiarki CNC, stosowanych w procesach obróbki wykończeniowej. Badania eksperymentalne wykonano na obrabiarce DMU 80P duoBLOCK. Prowadzono pomiary składowych siły skrawania F_x, F_y i F_z podczas frezowania przedmiotów wykonanych z trudno obrabialnego stopu Ti6Al4V. Wykonano pomiary umożliwiające wyznaczenie sztywności statycznej frezów do obróbki wykończeniowej. Wyniki badań eksperymentalnych zastosowano w modelowaniu frezów metodą elementów skończonych. Określono modele regresyjne, pozwalające obliczyć średnie wypadkowe przemieszczenie obciążonej krawędzi skrawającej narzędzia. Mogą one być stosowane do prognozowania błędów wykonania w procesach kształtowania wykończeniowego, zwłaszcza w przypadku kształtowania wyrobów ze stopu Ti6Al4V.

Słowa kluczowe: obrabiarka CNC, frez, sztywność, analiza metodą elementów skończonych, błędy obróbki

1. Introduction

Constantly growing competition between all manufacturers on the global market leads, among the others, to important requirements concerning improving

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both machining accuracy and economic efficiency of manufacturing. This competition is very intense in the case of various products in aviation industry. Several factors influence the accuracy of machining products on a CNC machine tool [1−4]. Some of the most important are:

- Kinematics, dynamics and accuracy of particular machine tool;
- Control system and control program of particular CNC machine tool;
- Distribution of temperature in space occupied by a machine tool;
- Loads generated during machining;
- Stiffness of a tool, machine tool and the fixture of a workpiece;
- Mechanical properties of machined material;
- Tool wear and its varying real working length and real working radius.

The variation of overhang length and real working radius can be caused by:

- Multiple fixing of applied tool with toolholder in machine tool spindle, which usually takes place while machining products with complex shapes;
- Misalignments, which can occur in fixing of tool inserts to tool arbor;
- Various levels of repeatability of measurement system used for inspection of tools;
- Rotational speed of applied CNC machine tool spindle, etc.

Many researchers have made a great effort in developing models which relate tool machine setup, applied tool, parameters of a workpiece, material properties and the accuracy of manufacturing [2, 3]. Monitoring of tool wear and prediction of thermal expansion in a precision hard turning is discussed in [2]. An investigation into evaluation of the stiffness chain consisting of the machine tool, the clamping of the shank and the clamping of the tool in the toolholder, is described in [3]. Performances of HSK tool interfaces under high rotational speeds is analyzed in [4]. The factors concerning the variation of overhang length and real working radius are investigated in more details in paper [5].

In this paper attention is mainly paid to the influence of cutting loads and tool stiffness on displacements of cutting edges of applied milling cutters. Information about the magnitudes and distributions of those displacements allows to predict some approximation of the distribution of machining errors. This helps with introducing suitable corrections into the control program of applied CNC machine tool, which might improve the accuracy of machining operations on it. For this purpose it is required to have a reliable and accurate mathematical model for the prediction of possible machining errors.

2. Parametric models of applied milling cutters

Numerical investigations concerning the stiffness of tools were performed using data representing selected types of milling cutters, made by Sandvik Coromant [6] and Kennametal [7], used for finishing operations. The shapes of milling cutters were adequately parametrized (Fig. 1). Such approach allowed for considering in subsequent computations a wide range of milling cutters.

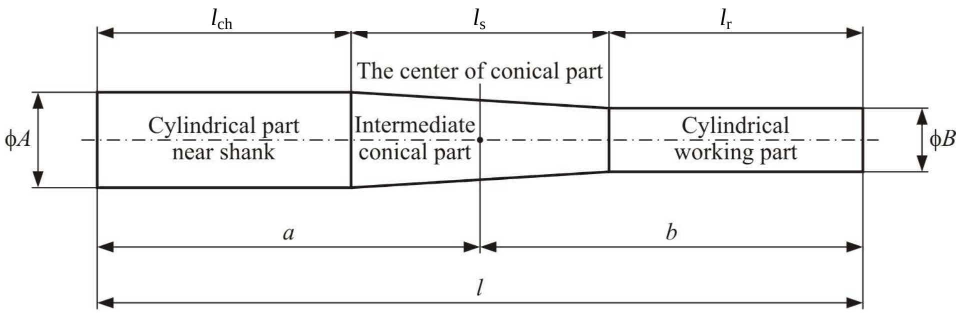

Fig. 1. The main geometric parameters describing the axisymmetric shape of the body of profiling mill cutter

Parametrized numerical models of milling cutters were prepared using the finite element method (FEM), Python programming environment [8] and the software for finite element computations ADINA [9]. For comparison reasons also approximated analytical models of considered milling cutters were defined. They reflected the case of cantilever beam loaded at the free end (cutting edge). In order to take into account in the analytical model of tool various diameters of the body of milling cutter (Fig. 1), which influence its slenderness and stiffness, an equivalent diameter C of approximating cylindrical mill cutter is computed:

$$C = \xi A + (1-\xi)B \quad \wedge \quad \xi = a/(a+b) \tag{1}$$

The parameter ξ in eq. (1) represents the location of geometric center of the conical part of cutter's body. The symbols A and B are diameters and symbols a and b denote the lengths of the parts of tool shown in Fig. 1.

Assuming the axisymmetric shape of considered tool and suitable boundary conditions at its end with diameter A (Fig. 1), reflecting clamping of the mill cutter in tool holder where the deflection $y(x)$ fulfils the requirements $y(0) = 0$ and $y'(0) = 0$, the following equation describing the maximum deflection of cutter's axis at the other end of cutter, i.e. $y_{max} = y(l)$ can be obtained:

$$y_{max} = \frac{64Fl^3}{3\pi E\left[\xi A + (1-\xi)B\right]^4} \tag{2}$$

In eq. (2) F and E denote applied load and equivalent Young's modulus, respectively. In order to consider in numerical modeling the stiffness of the machine tool and toolholder system, the equivalent Young's modulus was determined from the experimental investigations concerning a mill cutter fixed in a toolholder and a spindle of applied CNC machine tool, which is described in the following.

3. Mill cutters used in investigations and experimental settings

Two types of milling cutters were considered. One of them – the profiling mill cutter with round inserts CoroMill 300 made by Sandvik Coromant [6], consisting of the body of cutter and two round inserts (Fig. 2). The second tool was the monolithic ball nose mill cutter made by Kennametal [7] – a monolithic milling cutter (Fig. 3).

Fig. 2. The profiling mill cutter with round inserts CoroMill 300 made by Sandvik Coromant [6]: a) enlarged view of the working part of tool, b) the whole mill cutter with a toolholder

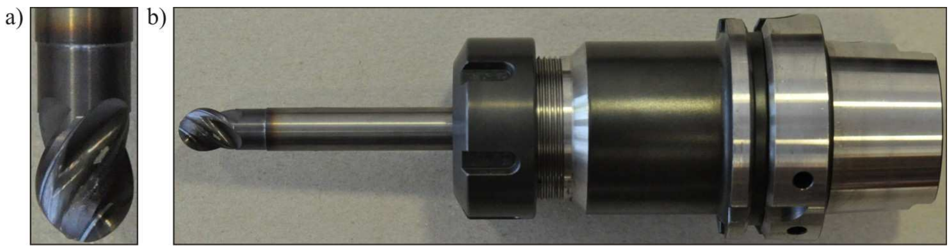

Fig. 3. The monolithic ball nose mill cutter made by Kennametal [7]: a) enlarged view of the working part of tool, b) the whole mill cutter with a toolholder

For each type of the above named milling cutters 9 subtypes were considered. The dimensions were taken from respective classified catalogues by Sandvik Coromant [6] and Kennametal [7]. The cases of subtypes not directly listed in the catalogues were computed by interpolation of known dimensions. The dimensions of profiling mill cutters with round inserts used for FE analysis are given in Table 1. The diameters of monolithic ball nose mill cutters were chosen from the set {6.0, 8.0, 12.0, 16.0, 7.0, 9.0, 11.0, 14.0} where the data is given in mm. The overhang length *l* of each ball nose mill cutter was assumed 76 mm. The diameters *A*, *B* and *C* of all subtypes of those ball nose mill cutters fulfilled the requirement $A = B = C$. The shapes of models of tools were numbered 1−9, respectively. The geometric models of tools were used for subsequent FE modeling. The loads used in computations were determined from experimental measurements. The objective of experimental investigation was measurement of the components of cutting forces F_x, F_y and F_z generated during milling of a hard to machine material – the alloy Ti6Al4V.

Table 1. Geometric dimensions of applied models of profiling mill cutters with round inserts CoroMill 300 made by Sandvik Coromant [6], according to Fig. 1

Model No.	**Geometric dimensions of applied models of profiling mill cutter with round inserts**				
	l_{ch}**, mm**	l_s**, mm**	l_r**, mm**	***A*, mm**	***B*, mm**
1	13.00	49.00	23.00	18.00	14.00
2	11.00	34.00	18.00	15.00	11.00
3	19.00	44.00	28.00	23.00	18.00
4	11.00	37.75	19.25	15.75	11.75
5	12.00	41.50	20.50	16.50	12.50
6	12.50	45.25	21.75	17.25	13.25
7	13.00	36.50	20.50	17.00	12.75
8	15.00	39.00	23.00	19.00	14.50
9	17.00	41.50	25.50	21.00	16.25

Another purpose of investigation was the determination of static stiffness of both applied types of mill cutters. Experiments were done in the Research and Development Laboratory for Advanced Materials at the Rzeszów University of Technology using the CNC DMU 80P duoBLOCK machine tool (DMG), shown in Fig. 4, equipped with the SINUMERIK 840D control system (Siemens).

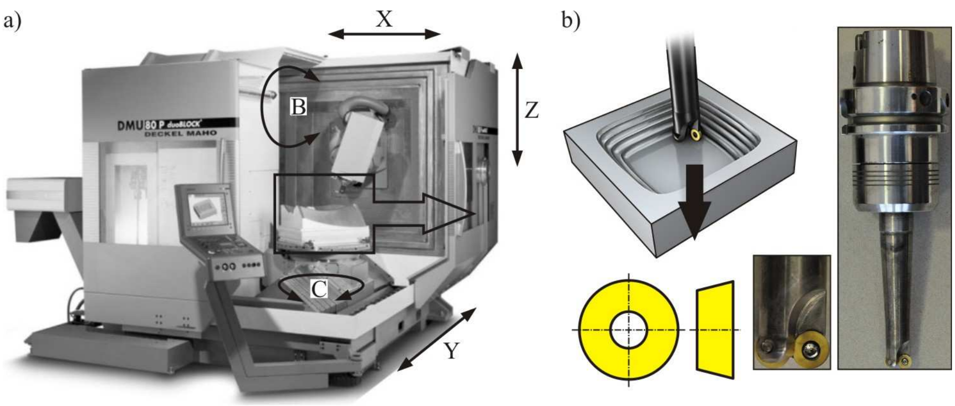

Fig. 4. The DMU 80P duoBLOCK machine tool operating in the Research and Development Laboratory for Aerospace Materials at the Rzeszów University of Technology: a) controlled axes, b) enlarged view of the profiling mill cutter with round inserts CoroMill 300 and workpiece

The components of cutting forces were measured using the Kistler rotational dynamometer 9123CQ05. It enables measurements with the maximum rotational speed of the spindle of a machine tool equal 10 000 rpm. The elements of measurement system were: dynamometer, amplifier, electronic card DAQ and a PC with the software CutPro for the acquisition and analysis of collected signals (Fig. 5). The measurement system used for modal analysis of considered mill cutters consisted of percussive hammer, accelerometer, conditioner, an electronic card DAQ and a PC with the software CutPro for the acquisition and analysis of collected signals (Fig. 6).

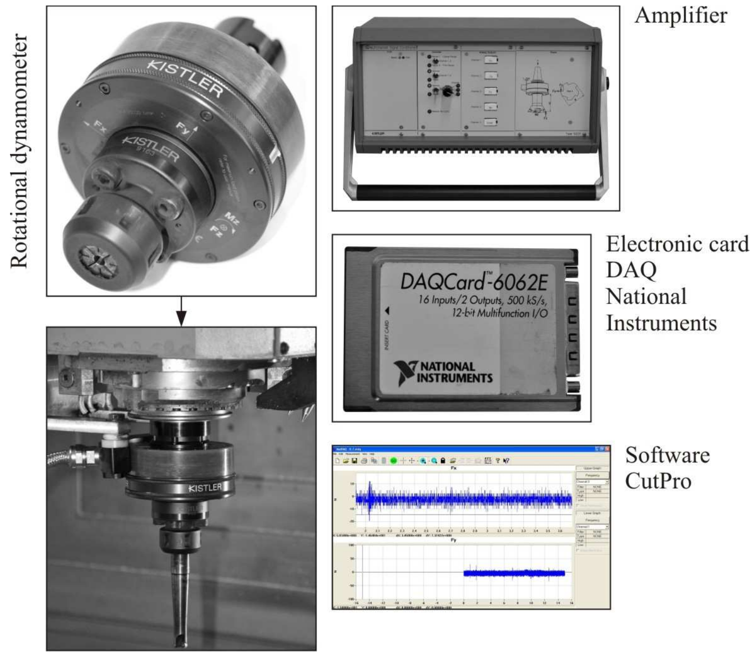

Fig. 5. The elements of measurement system used for the determination of the components of cutting forces: dynamometer, amplifier, electronic card DAQ and PC with the software CutPro for the acquisition and subsequent analysis of collected signals

The tool applied for machining was the profiling mill cutter with round inserts CoroMill 300 consisting of the body of cutter denoted R300-012B16L-07L and two round inserts R300-0720E-PM 1025, made by Sandvik Coromant [6]. Experiments were performed for 27 combinations of the main parameters of machining, created from the following variations of magnitudes of the parameters a_p, f, v_c, i.e.:

- Depth of cutting a_p = 0.1, 0.2, 0.3 mm;
- Feed f = 0.08, 0.1, 0.12 mm per cutting edge;
- Cutting speed v_c = 80.0, 100.0, 120.0 m/min.

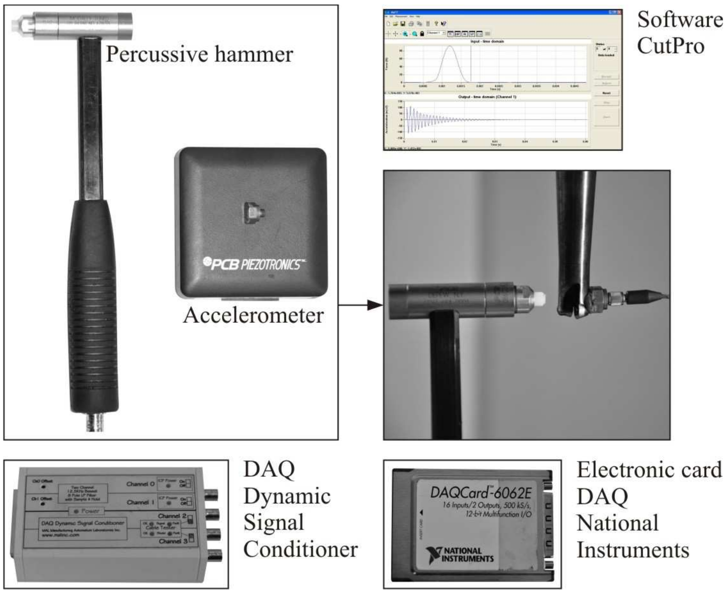

Fig. 6. The elements of measurement system used for the modal analysis of considered mill cutters: percussive hammer, accelerometer, conditioner, an electronic card DAQ and a PC with the software CutPro for the acquisition and subsequent analysis of collected signals

The analysis of the magnitudes and variations of measured components of cutting force F_x, F_y and F_z (according to the axes of the applied machine tool shown in Fig. 4a) generated during the process of finishing milling a workpiece made of alloy Ti6Al4V leads to the following conclusions:

- The magnitude of F_y component of cutting force was slightly increasing with the growing depth of machining a_p.
- The magnitudes of F_x and F_y components of cutting force were increasing with growing feed per cutting edge *f*. There was, however, some exclusion – the decreasing F_x component while increasing cutting speed v_c with the depth of cutting a_p = 0.2 mm.
- The maximum magnitude of F_z component of cutting force took place for the depth of cutting a_p = 0.2 mm and the intermediate magnitude of cutting speed v_c = 100 m/min. The change of the cutting speed to other magnitudes caused decreasing of the F_z component of cutting force.
- The maximum magnitude of F_x component of cutting force occurred for the maximum applied depth of cutting a_p = 0.3 mm. The magnitude of F_x component which was measured for the depth of cutting a_p = 0.1 mm was comparable with the measured magnitude of F_x generated for the depth of cutting a_p = 0.2 mm.

Measurements of static stiffness were performed in two directions parallel to the axes *X* and *Y* of the CNC machine tool (Fig. 4a). The tools applied for machining were:

- The profiling mill cutter with round inserts CoroMill 300 made by Sandvik Coromant [6], consisting of the body of cutter denoted R300-016B20L-08L and two round inserts R300-0828E-PM 1025, made by Sandvik Coromant [6];
- The monolithic ball nose mill cutter denoted F4AW1200AWX38E240 made by Kennametal [7].

The average magnitudes of measured static stiffness k of applied tools are:

- k = 14.17 N/μm, in the case of the profiling mill cutter with round inserts CoroMill 300;
- k = 11.91 N/μm, in the case of the monolithic ball nose mill cutter.

The above listed average magnitudes of k are used for FE analysis of tools.

4. Finite element models of considered milling cutters

The FE models of mill cutters which adequately and precisely represented the shapes of analyzed tools were build of 20-nodes brick finite elements. The isoparametric FEs were chosen due to their reliability, curvilinear shapes of milling cutters and the requirement concerning the continuity of fields of strains and stresses within the whole volume of each modelled cutter. Such elements have nonlinear shape functions – usually polynomials of the second degree [10−12]. For comparison reasons also axisymmetric FE models of tools were made. They were more simple models compared with the ones build of 20-nodes brick finite elements, because they required mainly the description of external profiles of tools and modeling of only the half of section of tool along the tool axis. For this modeling a special type of FEs – the axisymmetric FEs were used. On the other hand, in each case of the 3D solid FE model of tool built of 20-nodes brick FEs there was possible to take into account that certain volumes of material is removed from the body of particular mill cutter. Modeling those volumes of material removed from the body of mill cutter allowed for:

- Proper modeling of cutting edges;
- Taking into account the rounded inserts, in the case of the mill cutter with round inserts CoroMill 300;
- Modeling flutes in the case of the monolithic ball nose mill cutter.

The nodes located at one terminal cross section of tool had all degrees of freedom fixed. The loads were applied at the other end of tool. In particular, the loads were distributed along the active cutting edge of tool. The definition of the model of loaded tool was made by using ADINA commands, which were generated in automatic way by a numerical program prepared in the Python programming environment. The total displacements at the working end of the profiling mill cutters computed using either the 3D solid brick isoparametric or the axisymmetric isoparametric FEs are shown in Figs. 7 and 8, respectively.

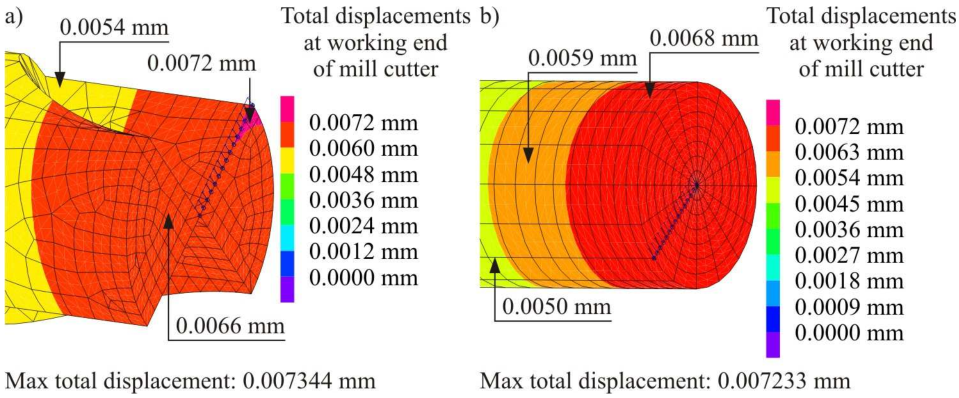

Fig. 7. Total displacements at the working end of the profiling mill cutter: a) computed using 3D solid brick isoparametric FEs, b) computed using axisymmetric isoparametric FEs

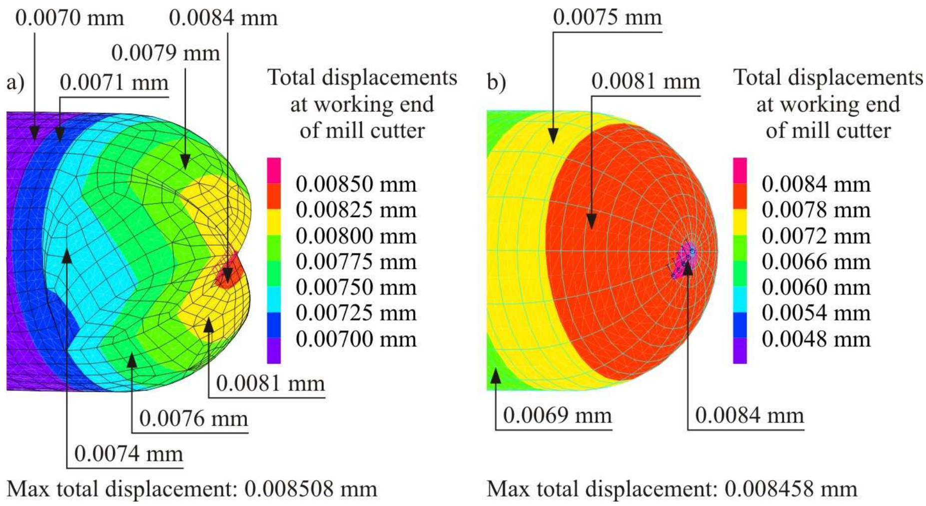

Fig. 8. Total displacements at working end of the monolithic ball nose mill cutter: a) computed using 3D solid brick isoparametric FEs, b) computed using axisymmetric isoparametric FEs

The equivalent Young's modulus for each type of model of mill cutter was updated in a way which allowed obtaining the same average total deflections of points located on cutting edge computed in result of FE analysis and computed from the measurements concerning cutting forces as well as stiffness of tool fixed in the toolholder of applied CNC machine tool δ_{exp}:

$$\delta_{\exp} = F / k \tag{3}$$

where F denotes the resultant load generated during milling and k denotes the average static stiffness of mill cutter determined from experiments. The updated magnitudes of equivalent Young's modulus considered not only the stiffness of mill cutter itself but also the stiffness of the applied CNC machine tool, the clamping of the shank and the clamping of the tool in the toolholder. The measurements also took into account possible clearances both in the tool holder and the spindle.

The FE computations were performed for 27 various combinations of the magnitudes of considered parameters of cutting, i.e.: a_p, f, v_c. Selected results of FE analysis of considered mill cutters are presented in Fig. 9. The graphs given in Fig. 9 show the variation of the average total displacement of cutting edge, the standard deviation of total displacements, the working diameter of tool and the overhang length of tool in function of varying slenderness l^3/C^4. The slenderness was assumed a characteristic parameter reflecting the stiffness of applied tool. The results shown in Fig. 9 were obtained using the FE models of profiling mill cutters built of 3D solid brick 20-nodes isoparametric FEs (Fig. 7a) and the 13. combination of parameters of the magnitudes of parameters of cutting a_p, f, v_c.

The results shown in Fig. 9 consider an average magnitudes of total displacements, not the maximum ones, due to the following reasons:

• Rounded inserts are mounted approximately in the middle part of the edge generated by removing two selected volumes of material from the axisymmetric body of mill cutter (Figs. 7a and 8a);

• Only that part of rounded insert, which is in contact with the body of tool is transmitting loads, generated during milling, to the body of tool;

• The FE model of mill cutter is a discrete one, which leads to discrete distribution of loads applied to a set of nodes.

Results shown in Fig. 9 are representative for all considered variations of geometric parameters of applied profilling mill cutters for the assumed parameters of cutting. In all cases the average total displacements almost linearly depend on the slenderness of tool l^3/C^4. Therefore, in order to obtain more simple models of average deflections of cutting edge than FE models, the linear regression models [13] of deflections were developed for each considered subtype of mill cutter and each combination of the magnitudes of parameters of cutting a_p, f, v_c. Numerical computations showed that in all cases of 3D solid FE models made of 20-nodes brick isoparametric FEs the coefficient of correlation R^2 of the regression models was not less than 0.9993. In the case of axisymmetric models the lowest coefficient of correlation R^2 was 0.9140.

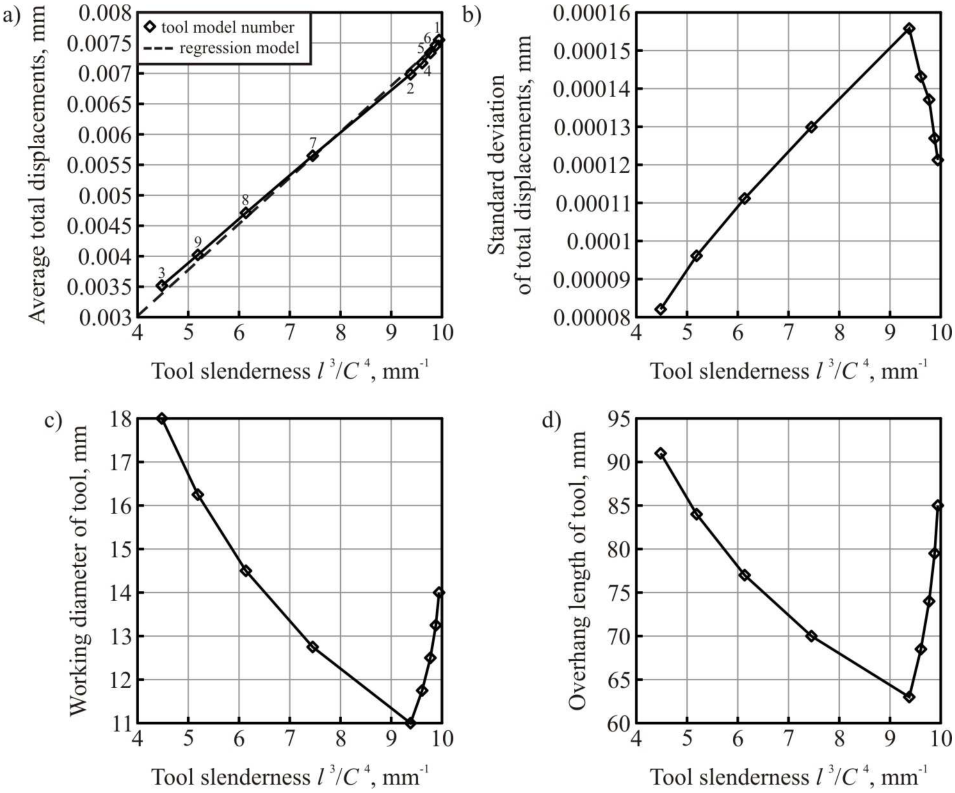

Fig. 9. Selected results obtained for the FE models of the profiling mill cutter computed using 3D solid brick isoparametric FEs and the 13. combination of cutting parameters: a) the variation of the average total displacement of cutting edge, b) the standard deviation of total displacements, c) the working diameter of tool, d) the overhang length of tool in function of varying slenderness l^3/C^4

The developed regression models are more suitable than the FE models for the prediction of possible errors of machining caused by the limited stiffness of the whole stiffness chain tool and clearances in applied machine tool spindle and tool holder. That prediction can be useful for proper distribution of measurement points for coordinate measurements of machined surfaces directly on the CNC machine tool. Usually the strategy of on-machine measurements is based mainly on purely geometric basis [1, 14−17]. Such on-machine measurements should, however, consider also some other factors, like e.g. limited stiffness of applied tool and CNC machine tool.

5. Conclusions

On the grounds of performed experimental and numerical investigations it can be concluded, that in order to obtain a model of deflections of tool caused by the cutting forces generated during the process of machining, both experimental and numerical investigations should be made. Experimental investigation described in this paper concerned the determination of the components of cutting forces and the stiffness of the tool fixed in a toolholder system and applied CNC machine tool. Numerical investigation was focused on developing and testing analytic and FE models of tools, which can be used for computing deformations. In the next step, based on results of preceding computations, simplified regression models of deformations can be obtained. Results are useful for the prediction of the error of machining caused by the limited stiffness of tool and machine tool and possible clearances in machine tool and toolholder system.

The tool slenderness l^3/C^4, associated with the stiffness of applied tool, total effective cutting force F, equivalent Young's modulus E and Poisson's ratio v determine the average total displacement of nodes at the cutting edge of each model of cutting tool considered in this paper. The averaged total deformation of cutting edge is proportional to the magnitude of the tool slenderness l^3/C^4. From the results of FE computations using 20-nodes brick isoparametric FEs it also follows, that with increasing diameter of mill cutter the standard deviation of calculated deformations of cutting edge decreases. One of the main reasons is more uniform distribution of load along the cutting edge for growing working diameters. This diminishes the variations of magnitudes of local deformations of the body of cutter due to the smaller magnitudes of loads generated during milling and applied at nodes located on cutting edge.

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