Technologia i Automatyzacja Montażu

Volume 120, Issue 2/2023, Pages 41-49
https://doi.org/10.7862/tiam.2023.2.5

Original Research

SIMULATION OF DISPLACEMENT OF CUTTING TOOL HOLDERS USED FOR TURNING

SYMULACJA ODKSZTAŁCEŃ I ODCHYLEŃ UCHWYTÓW NA NARZĘDZIA SKRAWAJĄCE STOSOWANYCH DO TOCZENIA

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Abstract

This paper gives a comparison of the deformation and deflection of two types of tool holders used in turning processes. Comparison of the deflection and stresses has been performed on the location where the highest value of deflection can be measured i.e. on the tip of the cutting insert. Selected tool holder types (TH1 and TH2) have rectangular and polygonal shank. Tool holders were 3D modelled in SolidWorks and Autodesk Inventor software packages and exposed to the loading with ANSYS structural analysis FEM software. In FEM analysis, two elements size of the network are selected (mesh size 5 and 1 mm). The simulation was carried out for five different loading values acting on the tool holder model. Obtained results confirm lower deflections on CAPTO tool holders.

Keywords: FEM, cutting tool holder, deflection, turning.

Streszczenie

W artykule porównano odkształcenie i ugięcie dwóch typów oprawek narzędziowych stosowanych w procesach toczenia. Porównanie ugięcia i naprężeń wykonano w miejscu, w którym można zmierzyć największą wartość ugięcia, czyli na czubku płytki skrawającej. Wybrane typy oprawek narzędziowych (TH1 i TH2) mają chwyt prostokątny i wielokątny. Uchwyty narzędziowe zostały wymodelowane w 3D w pakietach oprogramowania SolidWorks i Autodesk Inventor i poddane obciążeniu za pomocą oprogramowania do analizy strukturalnej FEM ANSYS. W analizie MES wybierane są dwa rozmiary elementów sieci (rozmiar oczek 5 i 1 mm). Symulację przeprowadzono dla pięciu różnych wartości obciążeń działających na model oprawki. Uzyskane wyniki potwierdzają mniejsze naprężenia i ugięcia oprawek narzędziowych CAPTO.

Słowa kluczowe: MES, oprawka narzędzia skrawającego, ugięcie, toczenie.

1. Introduction

During machining process with clamped tool shank, the most of mechanical energy that is required to remove the chips from the workpiece has been spreaded over the contact surfaces. Cutting edge has been exposed to the workpiece resistant forces that are transmitted on tool holder and as a result appears tool deformation and deflection. Because of force action, extensive contact stresses are present and combined elastic and plastic deformations may appear.

Both of processes (deformation and deflection) achieves maximum values on cutting contact surfaces between cutting tool and finish product. Many researchers explore deflection either tool (tool holder) either workpiece. In inner surface turning process and sculptured surface milling process, more interested is tool deflection. In contrast, deflection of participant with bad ratio of length and cross dimension which appears in thin wall and small diameter workpieces is also interesting.

Furthermore, over the tool holder clamping contact surfaces displacements and deformations has been transferred on the third participant of the machining process, machine tool individually. Deformations and deflections also occur on each certain sequentially connected parts of the machine tool, making tool and workpiece clamped together. Therefore, determining the effect of total deformation and deflection during machining on machining accuracy is very complex.

The cutting force generated with regime of turning process in regards with slenderness causes certain values of deflection. Consequently deflections, the true depth of cut differs from the planned value, manifesting as surface or dimensional errors on the workpiece or increased tool wear.

Deflections can influence many other unfavorable effects like loss of tolerances on workpiece, change of shearing angle and difficulties in chip formation, friction and tool wear condition.

As a mainly adverse effect of deflection, dimensional errors in turning, chatter appearance etc. have been recently analyzed by many researcher [1],[2],[3]. Duan et al. [1] estimates tool deflection variation as a result of inclination of tool edge and workpiece. Their tool deflection model gives more precise results when higher deflections appear if comparing model results with real experiment measurement. Gasagara et al. [2] determine that dynamic behavior of tool deflections induces chatter vibrations. Furthermore, conclusion was that deflections varies throughout the tool. It has maximum at tool tip and minimum at the position of clamping. In his work Kalasua et al. [3] determine the cutting tool deflection as a result of acting cutting forces which were influenced by cutting regime and tool geometry. Kops et al. [4], [5] perform deflection analysis by using an analytical formulation and obtaining an interrelationship between the workpiece deflection and depth of cut. Yang et al. [6] perform FEM analysis on model developing a real-time workpiece deflection error compensation system facing also with different deflection values along the workpiece. In both work, only the radial component of the cutting force is considered.

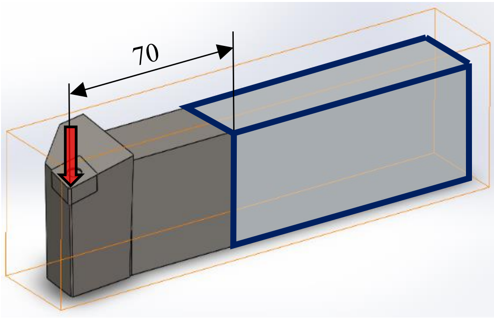
Some other researcher expand the analysis on multi-diameter workpiece bars [7] and tapered workpieces [8] including all cutting force components and FEM.

Too much deflection can lead to catastrophic failure on the tool if chatter appears and lead to workpiece surface roughness increase [9]. Kiyak et al. [9] explore in their work the influence of functional tool length (tool overhang) on tool deflection, surface roughness and flank tool wear. Cross section of tool holder was 25x25 mm and functional tool length varies from 50 to 90 mm. With increasing of the tool length, deflection and roughness increases also, but flank wear decreases.

Analysis performed in this paper is oriented towards deformations and deflections that appear on the cutting tool holder. Selection of tool holder is very important role in planning of cutting process. Tests were made on selected tool holders with rectangle and polygonal clamping surfaces commonly used in turning process. Analysis has been performed assuming that all parts of the machine tool and contact surfaces during the loading condition affected by cutting process are considered rigid.

Depending on value of the force and its orientation during cutting process, as well as orientation and size of clamping shank surface, various deflection on the edge tip can appear. Shank surfaces in rectangular holder are parallel (angle between contact surfaces are 0^{o}) and in CAPTO polygonal clamping system contact surfaces are under the angle $2{,}88^{o}$. The higher the angle of contact surfaces the higher deflection can be expected. Main difference between CAPTO and rectangular shank is that CAPTO allows additional flange contact (see Fig. 1). To be comparable, selected tools has different functional length of cutting edge on holder 1 (TH1) and holder 2 (TH2) with values 70 and 50 mm respectively (see Fig. 1).

Cross-section area of rectangular tool holder shank was 32x25 mm and fixation length was 100 mm, while polygonal shank holder was C4 (ISO 26623-2:2014 specifies dimensions for polygonal taper interfaces with flange contact surface). Some dimensions and data of CAPTO holders are given in Table 1. Cross section dimension of tool holder influence deflection values with power of 4 and functional length with power of 3.



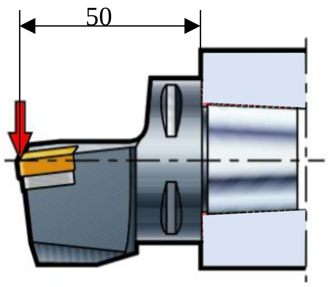


Fig. 1. Functional length of tool holders

Table 1. Some data of CAPTO holders

Holder type	**Functional length, mm**	**Flange diameter, mm**	**Clamping force, kN**
C3	40	32	13
C4	50	40	22
C5	60	50	30,5
C6	65	63	39
C8	80	80	48

Deflections can be given in absolute values (values in mm) or relatively (values in mm/m – Figs. 2 and 3) values. Relative values of deflection shown in Figs. 2 and 3 are approximative values used just to select comparable size of holder for this experiment (in our tests similar approximative deflections have C4 and PCLN3225 holders). For selected tool holders (marked with red color in Figs. 2 and 3), we expect similar and comparable deflection values of tool tip. This relative deflection parameter is obtained by dividing absolute deflection value with functional length of cutting tool. Results should enable better tool holder selection in planning process.

The high compressive and frictional contact stresses on the tool/workpiece interface can be simplified and replaced with a total cutting force F as shown in Fig. 4. Dependence of forces and its influence on deflection has been analyzed by Kowalik et al. [10]. The cutting force vector is defined in terms of orthogonal cutting with force components F_c, F_f, F_p .These components are most often shown in the literature, and their vectors are oriented in the direction of cutting speed, feed and cutting depth (v_c, f, a_p) Fig. 4.

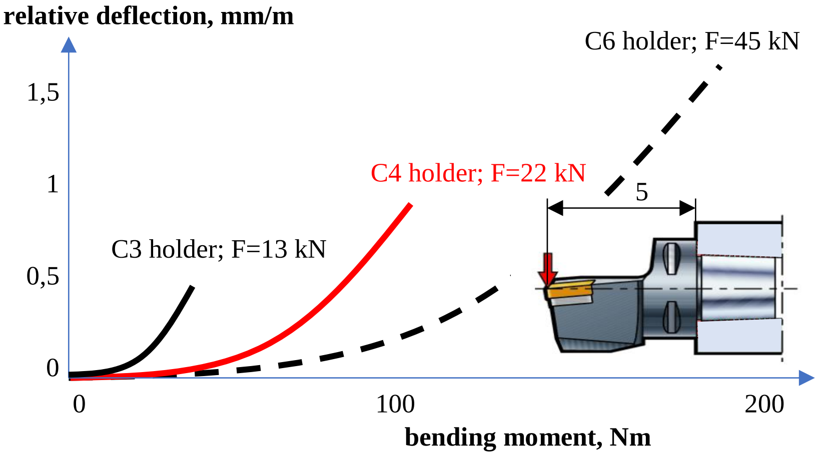


Fig. 2. Influence of selected polygonal shank tool holder on relative deflection of tool tip

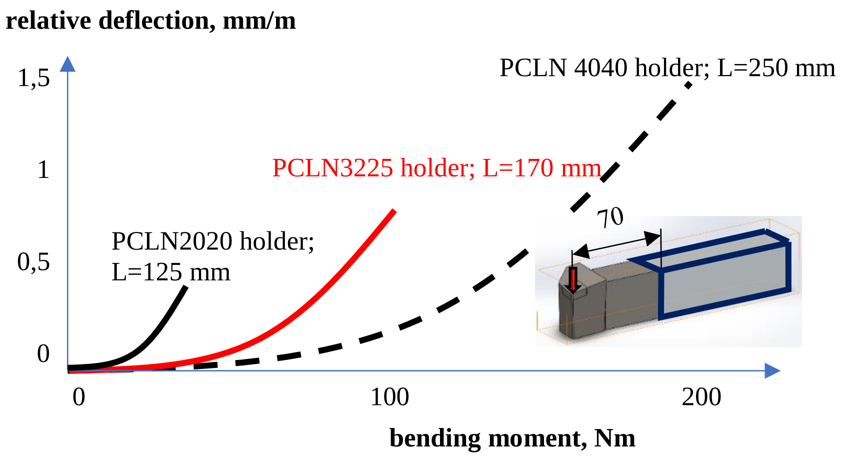


Fig. 3. Influence of selected rectangular shank tool holder on relative deflection of tool tip

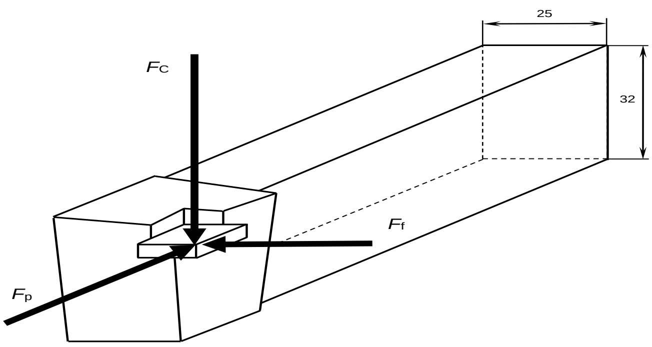


Fig. 4. Force components acting on rectangular shank turning tool

2. Tool holders modeling

The 3D models of two holders consists of several merged bodies: an external turning tool holder and a cutting insert with fixation devices for its fixation on the holder. The dimensions of the model are defined by the dimensions declared by producer of real holder and the insert.

For rectangular (TH1) shank model, it was used the Corloy CNMG 120408HA (NC 3220) insert. The dimensions of the insert are: l = 12.0 mm, t = 4.76 mm, r = 0.80 mm, d = 12.70 mm, d1 = 5.16 mm. The insert was inserted and fixed into the PCLNL 3225M12 tool holder. The holder and the insert are molded in the package SolidWorks (Fig. 5). For polygonal (TH2) shank holder, it was used Sandvik Coromant model C4DCKNR-27050-12 (Fig. 6).

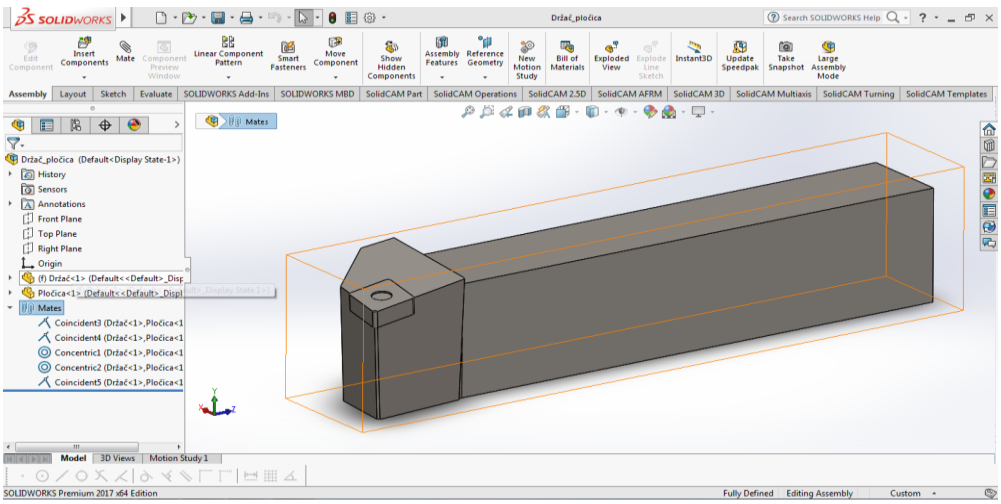


Fig. 5. Model of cutting tool holder with insert

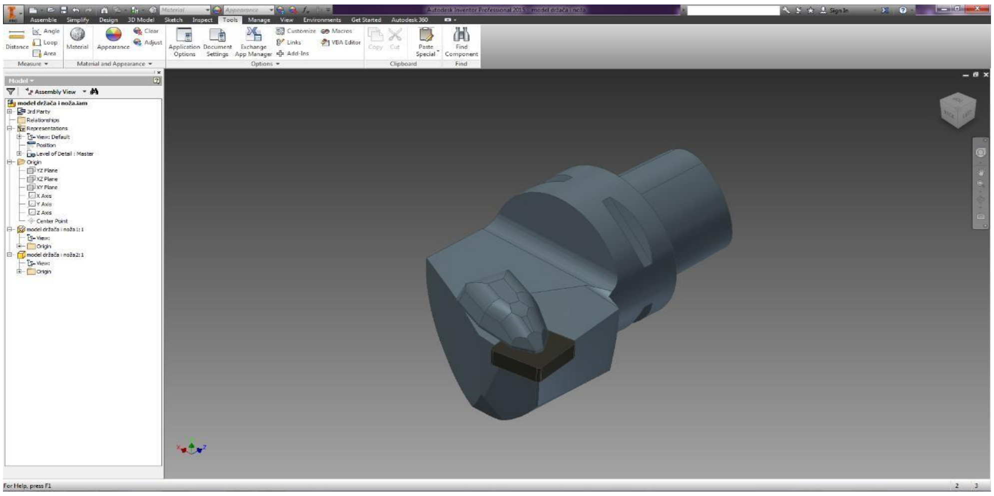


Fig. 6. 3D model of CAPTO tool holder prepared in Autodesk Inventor

The contact surfaces between the model parts (tool holder and insert) have been merged and thus the model position within the space has been defined. To obtain accuracy of modelled stresses and deformation during simulation, it is necessary to merge all the contact surfaces to each other because the forces in reality are transmitted over all of these surfaces.

3. Mesh size selection

The developed finite element models of considered tool holders were analyzed using static structural approach within the ANSYS software. Using of this software needs short time training and is not complicated in use [11].

Results obtained by this software can be used for better tool holder selection. The software enables simulation of problems in multiple scenarios and with different parameters. This is the reason why this software can be used in almost all industries and enables product optimization and cost savings comparing with physical tests. [12]

Two network mesh of finite elements is defined for selected tool holders. By choosing a smaller size of elements, a model with a flawed grid is obtained, i.e. the model has multiple elements. Also, by choosing smaller mesh elements the results obtained by simulation are more accurate but FEM calculation process last longer. For comparison purposes, two dimensions of the elements were selected for this work. One net is less common (popular) with the size of the 5 mm elements, the Fig. 7 - left and the other the mesh is louder with the size of the 1 mm elements, Fig. 7 - right.

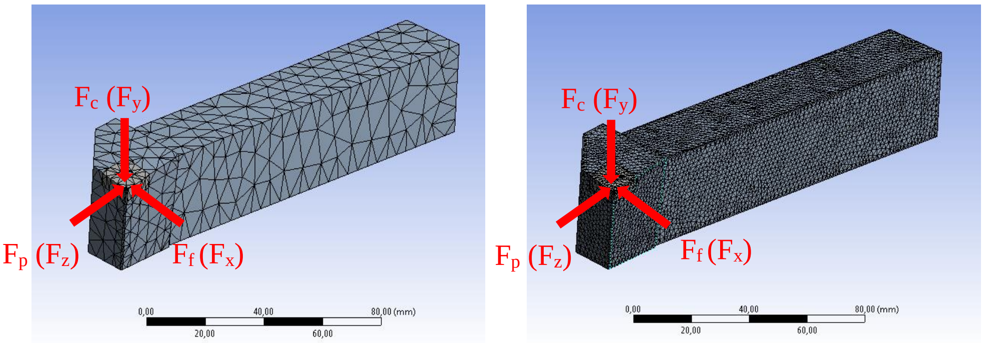


Fig. 7. Spreading of FEM mesh over the rectangular cutting tool (5mm-left, 1mm-right)

The force action location is nested on one single point on edge tip. This location represents the contact surface between the insert and workpiece during turning process. The force components (F_x, F_y, F_z) are set in the direction of all three axes substituting appropriate (F_c, F_f, F_p) components.

Before the simulation starts, it is necessary to select the desired mesh size elements. Of course, as many elements are selected, longer simulations will last because of the greater number of equations that needs to be solved. For this analysis two parameters have been observed. These are data on overall (total) deformation and stress.

For simplification of force components value selection, the equal values of the cutting force components in the direction of the x and z axis were selected (in reality, the passive and shear components of the cutting force). The highest value of the force is in the direction of the axis y, which is also in real load conditions.

4. Results

The simulation was carried out for five different values of force acting on the model. Each of these 5 force values were used through simulation of the above-mentioned two variants of the finite element mesh node numbers.

The cutting deflection (δ) of the cutting edge is particularly important as the size of the deformation affects the machining accuracy, as well as on other geometrical size tribology processes on the cutting tools contact surfaces. For this reason, only the size of the deformation will be presented in simulation results. Deformation values $\delta 5$ and $\delta 1$ are obtained for different FEM mesh size 5 and 1 millimeters respectively.

Table 2 shows the results for five different load combinations (five values of loading) and for different FEM mesh size (two mesh size). Displacement values given in table 2 are total values of displacements.

The picture of deformations shown in table 3 shows that the greatest deformations (deflections) appear at the very top of the inserts, exactly on location where the force acts. In the area of cutting tool support, they do not even appear because they are assumed as a rigidly fixed contact. Highest value of deformations (deflections) and the largest stress concentration is created also at the location of force action.

Table 2. Results of displacements

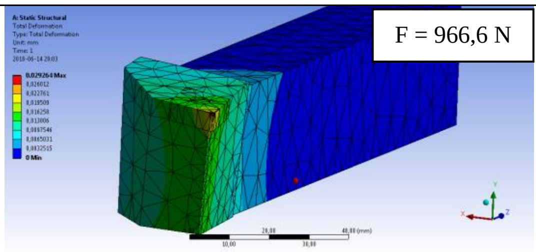
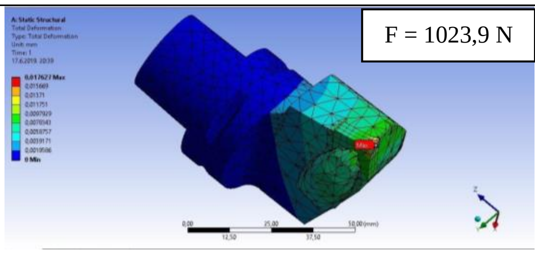
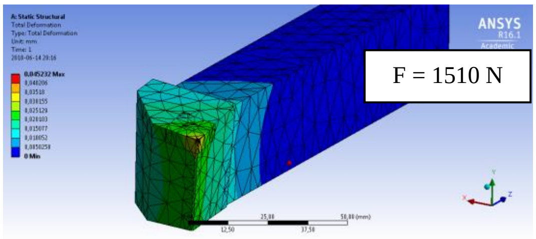
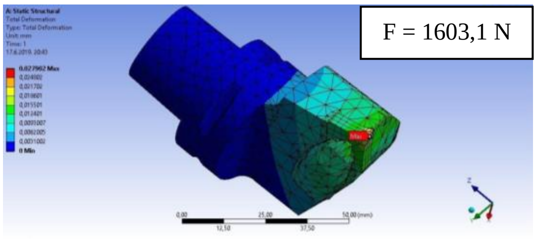
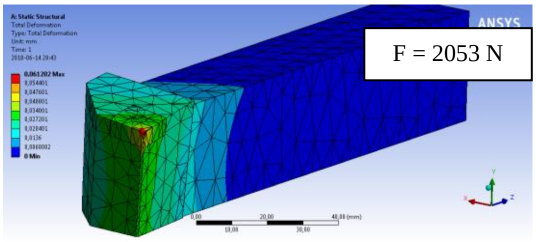
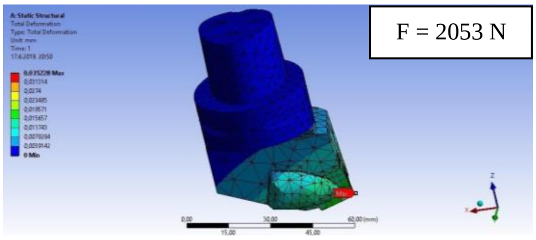
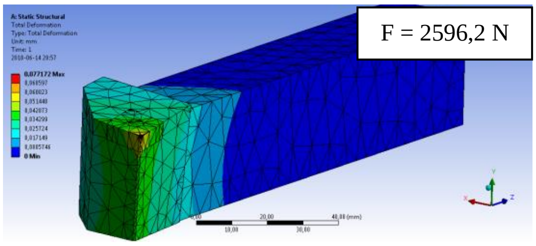
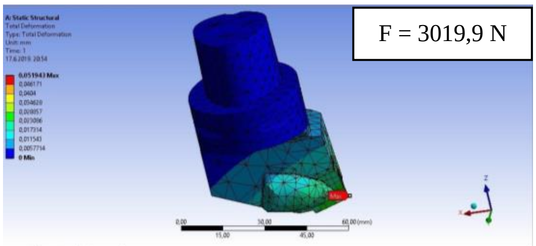
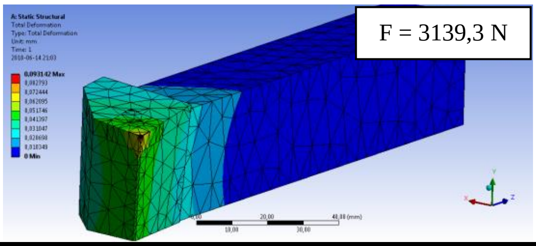
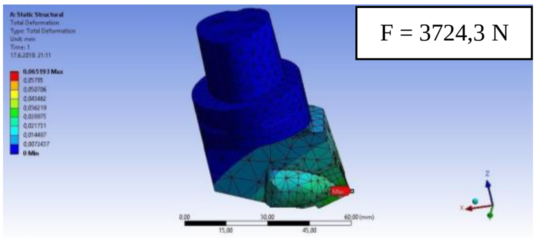
Meas. nr	**Tool holder type**	**Total force F, N**	**F_c, N (F_y)**	**F_p,N (F_z)**	**F_f, N (F_x)**	**FEM - mesh size 5 mm**	**FEM - mesh size 1 mm**	**Δ (δ_5- δ_1), %**
						Deform. δ_5, µm	Deform. δ_1, µm	
1	Rectagular shank, TH1	966,6	900	250	250	29,264	30,605	4,38
2		1510	1400	400	400	45,232	47,321	4,41
3		2053	1900	550	550	61,202	64,039	4,43
4		2596,2	2400	700	700	77,172	80,758	4,44
5		3139,3	2900	850	850	93,142	97,477	4,45
1	Polygonal shank, TH2	1023,9	950	270	270	17,627	18,572	5,09
2		1603,1	1500	400	400	27,902	29,392	5,07
3		2053,0	1900	550	550	35,228	37,119	5,09
4		3019,9	2800	800	800	51,943	54,729	5,09
5		3724,3	3500	900	900	65,193	68,667	5,06
6		4242,6	4000	1000	1000	74,583	78,55	5,05

Table 2 shows that the results with the smaller mesh size are slightly different, or higher than those of the previous ones. The reason for this is just the number of elements that are smaller on the model and the results are more precise.

But, it is also apparent that the differences in the model obtained deformations are less than 5% (Table 2) which can be considered as sufficiently accurate if a mesh with larger elements is applied.

Comparison of deflection results obtained for two holder are given in absolute values (Fig.8). Better deflection results have been obtained for polygonal shank holder (TH2). Reason for such results some can explain with better slenderness of this holder. There is also visible slightly higher distancing of lines for higher loading. The reason for this fact lies in different cross section dimension and functional length of tool holders (deflection increase with these parameters with power of 4 and power of 3 respectively). If deflection results are compared in relative values, difference between these two holder becomes lower (Fig. 9). Deflection data are given for the model with mesh size 5 mm. Some author show the deflection results as a function of bending moment. If the comparison of deflection has been made in this frame, better results are obtained for rectangular tool holder TH1 (Fig. 10).

Table 3. Deformation (δ5) distribution over the cutting tool holder model

nr	Rectangular tool holder deflection values δ_5, mm	Polygonal tool holder deflection values δ_5, mm
1		
2		
3		
4		
5		

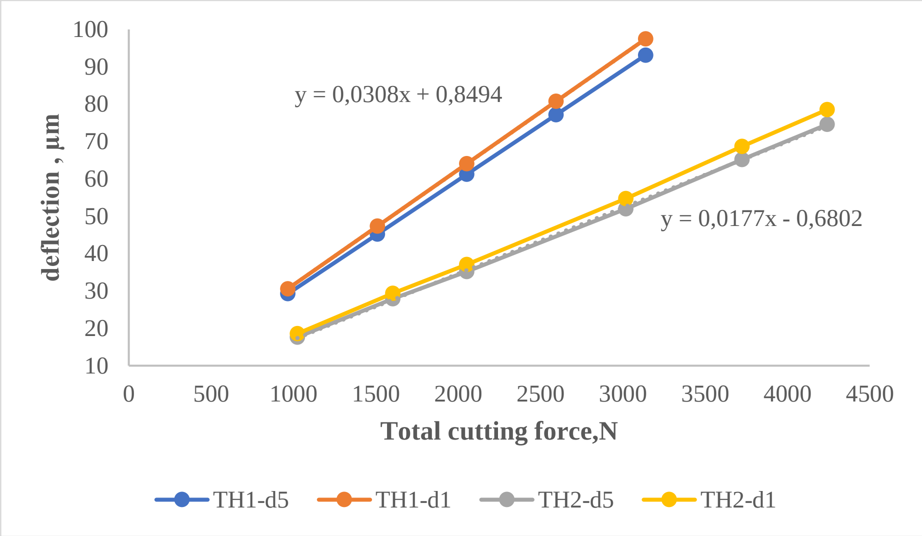


Fig. 8. FEM results of absolute deflection data

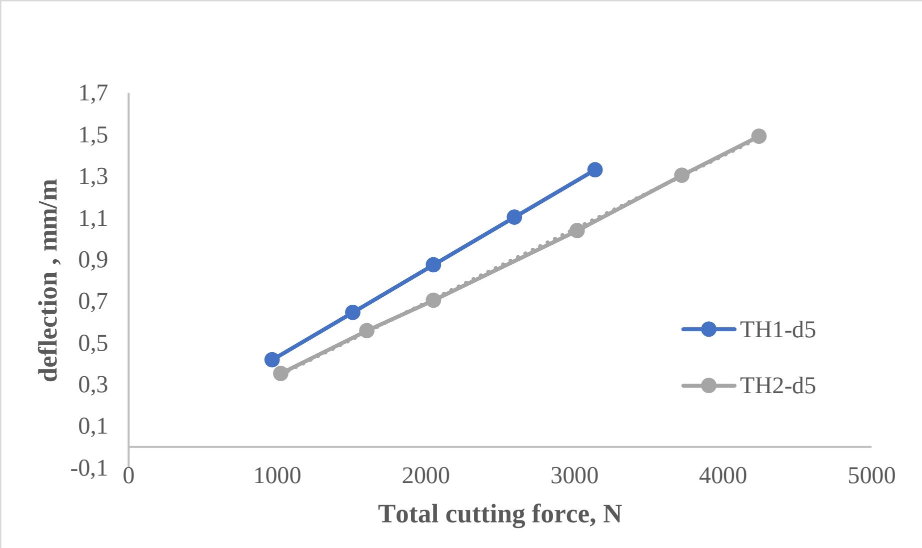


Fig. 9. FEM results of relative deflection data

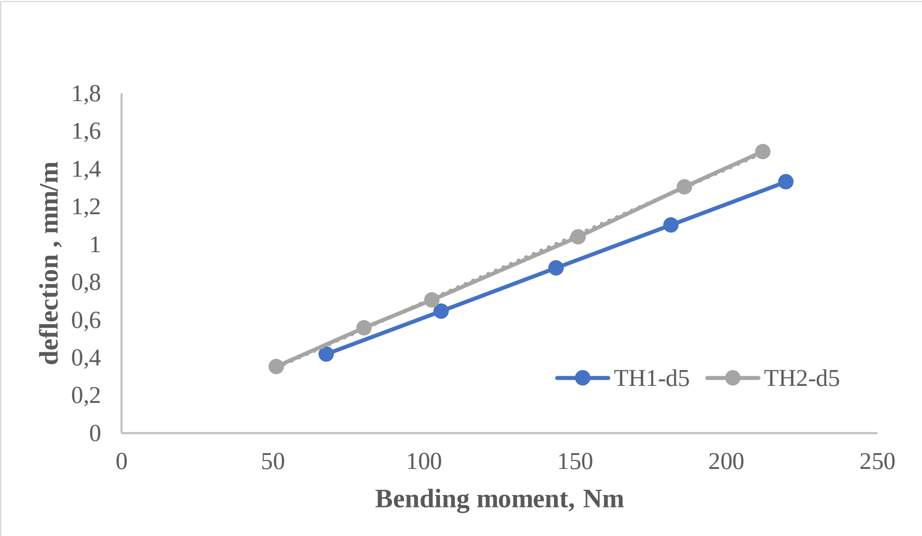


Fig. 10. FEM results of relative deflection data vs bending moment

5. Analysis of results and conclusions

The results of tool holder deflection shown in this paper, and obtained by FEM simulation of loading of two types of cutting tool holders, can be expected during real turning process. The results obtained by the simulation even without the use of the machine tool offers useful information for process optimization. Comparison of calculated tool deflection values for selected tool holders offers the answer which tool holder has bigger impact on dimensional accuracy of workpiece resulting from tool holder deflection. Tool deflection values for both tool holders are relatively small and for OD turning process these deflections have no the most significant influence on dimensional accuracy. More important influence on machining accuracy could have deflection of workpiece.

The differences in the model obtained deflections for different FEM mesh element size are less than 5% and mesh element size of 5mm is capable to offer acceptable results. FEM calculation with larger mesh size allows also very fast obtaining of results.

The increase of the force acting on the model increase deformations and stresses of tool holder.

Beneficiary, FEM deflection analysis offers possibility of exposing the tool holder model to various forces and processing modes without the risk of damage and material destroying. By optimizing the turning process parameters experimentally instead of on a computer, some will spend a lot of time, generate greater material consumption and, most importantly, there is a risk of fractures and failures due to wrongly selected regime parameters.

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