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SHAPE ERROR ANALYSIS OF TANGENTIALLY TURNED OUTER CYLINDRICAL SURFACES

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Abstract: The measure of form accuracy is an important task in the development of new and recurrent machining procedures. This requirement leads to studies of the shape error in tangential turning as well. We aimed to carry out an analysis on this property in this initial research work. We carried out cutting experiments on cylindrical workpieces with 60 HRc surface hardness, where we changed the cutting speed, the feed and the depth of cut. The experimental plan was composed according to the Design of Experiments method, where a lower and upper limit are chosen for each parameter. After the experiments we made measurement on a shape accuracy measurement device. During the evaluation, we determined equations which describe the studies parameters in tangential turning. We concluded in the analysis that the cutting speed has the most effect on the shape error values, and its value should be higher. The feed and depth of cut influences the shape error mostly according to the alteration of the chip size and chip shape, which result in different cutting forces.
Keywords: cylindricity, design of experiments, roundness, tangential turning

INTRODUCTION

Among the many requirements for the different machining procedures, form accuracy is one of the more important properties. Deviation from the designed shape can be caused by many factors, and the prediction of such errors can be a difficult task. Since inaccuracy in the shape is caused by the elastic deformation of the machining system, a proper force model can help the prediction of the deflection, thus allowing the estimation of radial, diametric and various geometric errors of the turned surface [1]. When engineers are trying to lower the shape deviation, different requirements should be prescribed during the process planning, e. g. the increased rigidity of the machine tool [2]. However, Kundrák et al. showed in their work that with the proper choice of machining procedure, the accuracy of the machined parts can be significantly increased [3]. Molnár also proved, that among the frequently analysed surface topography parameters, the extent of the shape error are equally significant [4]. However, the analysis of the form accuracy presents a new difficulty: the required time for such measurements are usually high, thus creating the choice between the lower measurement time and higher accuracy [5,6]. Many methods can be applied in the analysis of shape error, the use of the Design of Experiments method is one of these as showed by Ferencsik and Varga in the study of burnished surfaces [7]. Nagy and Varga also used the DoE method and proved after their experiments, that the feed increases the cylindricity errors in most cases [8]. Increasing the cutting speed decreased that in the case of wet machining and increases that on dry turned surfaces in their work.

In this paper, we analyse tangential turning [9] in the point of view of the achievable form accuracy. This machining procedure cam into the front due to its many advantageous properties. It can produce twist-free surfaces [10] which can be an alternative to rotational turning in machining of outer cylindrical surfaces [11]. Leichner et al. proved in their study that oil leakage, wear of the tool and machining costs can be reduced, when tangential turning is applied on sealing surfaces [12]. A good alternative can be the combined procedure, where turning and grinding is done on the same machine [13], however MQL technique can be applied when tangential turning is used as finish machining. The different insert and feed motion results in better tool life than in traditional turning [14].

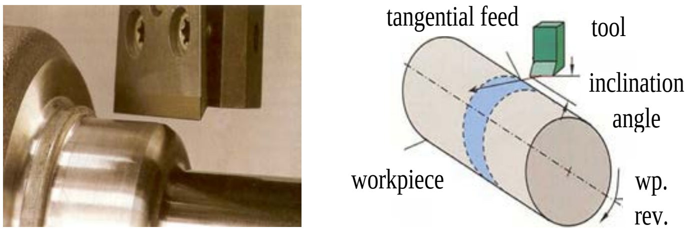

Figure 1. Tangential turning and its kinematic scheme [14]

Machining accuracy depends on many factors in this procedure as well [15], for example the value of the inclination angle, the tangential feed or the depth of cut. The application of tangential turning is widely developed by machine tool manufacturers as well (e. g. EMAG [16]).

In this paper, we study the achievable shape correctness in tangential turning by changing the cutting speed, feed and depth of cut. We analyse certain parameters of cylindricity and roundness with the Design of Experiments method.

EXPERIMENTAL CONDITIONS AND METHODS

The aim of our study was the analysis of the shape error in tangential turning. We carried out cutting experiments and theoretical evaluation using the Design of Experiments method to achieve this goal.

The equipment used during the experiments was the following. A tangential tool with 45° inclination angle was used. The indexable turning tool is made by HORN Cutting Tools Ltd. and consisted of two parts S117.0032.00 insert and H117.2530.4132 holder. The working part of the tool was an uncoated carbide insert (MG12 grade).

In the experiments, a cylindrical workpiece is machined, which outer diameter was 70 mm. The chosen material was 42CrMo4 grade alloyed steel, which processed by hardening heat treatment to 60 HRc hardness before the experiments. The tangentially turned surfaces was prepared before the experiments by turning with a standard CNMG 12 04 12-PM 4314 cutting insert made by SANDVIK Coromant, which was put into a PCLNR 25 25 M12 tool holder. An EMAG VSC 400 DS hard machining centre was applied for the study.

We intended to analyse the alteration effect of the setup parameters of tangential turnig, therefore the cutting speed (v_c), the feed per workpiece revolutions (f) and the depth of cut (a) were changed during the experiments. A lower and an upper limit value were needed to be chosen for each studied parameter according to the Design of Experiments method. We aimed to study first the lower value range of the parameters in our initial research of the topic. Therefore, the cutting speed was chosen to be 100 m/min and 200 m/min, the feed was set to 0.3 mm and 0.6 mm. Two kinds of depth of cut were also chosen: 0.1 mm and 0.2 mm. This 3x2 limit values resulted in 2^3 = 8 different setups, which can be seen in Table 1.

Table 1. Experimental setups

Setup	1	2	3	4	5	6	7	8
v_c [m/min]	100	200	100	200	100	200	100	200
f [mm]	0.3	0.3	0.6	0.6	0.3	0.3	0.6	0.6
a [mm]	0.1	0.1	0.1	0.1	0.2	0.2	0.2	0.2

Shape error measurements were carried out after the cutting experiments on a Talyrond 365 accuracy measuring equipment. The setup parameters in the program were chosen according to the standard and our earlier practical experience. The analysed parameters were the following (ISO 12180-1 and ISO 12181-1) [17]:

- CYLt – the minimum radial separation of two cylinders, coaxial with the fitted reference axis, which totally enclose the measured data [μm]
- CYLv – the valley maximum departure from the reference cylinder into the material of the workpiece [μm]
- COAX – The diameter of a cylinder that is coaxial with the datum axis and will just enclose the axis of the cylinder referred for coaxiality evaluation [μm]
- RONt – the maximum deviation inside and outside the reference circle [μm]
- Conc – the diameter of the circle described by the profile center when rotated about the datum point [μm]
- Slope – average of the absolute values of the gradient dz/dφ (where z represents axial departure from the reference plane and φ represents angle) at each point in the profile [μm/deg]

The cylindricity was measured using 7 different plane with 2,75 mm separation. The roundness values were resulted by evaluating the profile in the first, fourth and seventh plane.

The results were processed according to the Design of Experiments method. In this process, the lower and upper limits were transformed according to Table 2.

Table 2. Transformed values of the studied parameters

Setup	1	2	3	4	5	6	7	8
v_c	-1	1	-1	1	-1	1	-1	1
f	-1	-1	1	1	-1	-1	1	1
a	-1	-1	-1	-1	1	1	1	1

Equations were determined for the calculation and presentation of the analysed parameters, which equations were defined in a polynomial form. This presented in Equation 1, where the analysed factors (v_c, f, a) and their products can be seen and k_i represent the constant of the different factors. The analysed cylindricity and roundness parameters is represented as y(v_c, f, a).

$$y(v_c, f, a) = k_0 + k_1 v_c + k_2 f + k_3 a + k_{12} v_c f + k_{13} v_c a + k_{23} fa + k_{123} v_c fa \quad (1)$$

EXPERIMENTAL RESULTS

The cutting experiments and the form accuracy measurements were carried out according to the description of the former section. The values of cylindricity error parameters – described in the former section – can be seen in Table 3. The valley depth (CYLv) values were also evaluated as a ratio of the cylindricity error (CYLv / CYLt) since this rate describes better the effect of the different parameters on the bearing capability of the profile.

Table 3. Results of the cylindricity measurements

Setup	1	2	3	4	5	6	7	8
CYLv [μm]	5.29	2.61	3.52	3.28	5.37	2.00	9.64	5.42
CYLt [μm]	17.58	23.66	12.80	12.06	10.62	10.58	21.50	21.97
CYLv/CYLt [μm]	0.30	0.11	0.28	0.27	0.51	0.19	0.45	0.25
Coax [μm]	0.30	0.15	0.28	0.02	0.33	0.14	0.43	0.07

Table 4. Results of the roundness measurements

Setup		1	2	3	4	5	6	7	8
RONt [μm]	1	23.24	4.97	11.21	13.37	10.52	7.97	16.04	11.14
	2	12.69	17.11	8.34	3.46	7.69	11.62	17.17	7.01
	3	8.46	1.44	4.55	1.86	11.17	6.70	13.77	15.91
	Avg.	14.80	7.84	8.03	6.23	9.79	8.76	15.66	11.35
Conc. [μm]	1	0.97	2.03	1.31	3.63	2.21	1.28	4.07	1.50
	2	2.14	2.64	0.26	1.88	1.45	1.11	2.98	1.50
	3	0.65	0.29	0.40	1.19	1.63	0.80	0.16	0.36
	Avg.	1.25	1.65	0.66	2.23	1.76	1.06	2.40	1.12
Slope [μm/deg]	1	4.60	1.52	5.03	0.50	3.11	0.96	6.89	1.01
	2	5.47	1.63	3.00	0.44	2.67	1.40	6.04	0.86
	3	3.12	0.45	0.58	0.46	3.13	0.76	4.73	1.30
	Avg.	4.40	1.20	2.87	0.46	2.97	1.04	5.89	1.05

The results of the roundness error measurements are presented in Table 4. A lesser studied parameter is the slope.

This parameter was originally developed for the bearings industry, and it is a measure of how rapidly the measured profile is changing along its periphery. Both the average and maximum value of this parameter is given by the measurement device, however in this paper we analyse its average value, because it tells more about the overall behaviour of the surface.

The measurements and their evaluation were followed by the determination of the calculation methods of the studied parameters in the form of equations described in the previous section. The function of the cylindricity error (CYLt) can be seen in Equation 2. The ratio between the maximum departure from the reference material into the material and the cylindricity error (CYLv/CYLt) is determined as seen in Equation 3. The coaxility (COAX) of the reference cylinder axis and the datum axis can be calculated with Equation 4. Equation 5 shows the determination of total roundness error (RONt). The slope of the periphery is defines as Equation 7.

$$\begin{aligned}\mathrm{CYLt}(v_c, f, a) = {} & 18.63 + 0.2635v_c - 20.97f \\ & - 91.70a - 0.4717v_cf \\ & - 1.345v_ca + 277.7fa \\ & + 2.443v_cfa\end{aligned} \quad (2)$$

$$\begin{aligned}\frac{\mathrm{CYLv}}{\mathrm{CYLt}}(v_c, f, a) = {} & 0.4155 - 0.003248v_c \\ & - 0.8491f + 2.895a \\ & + 0.00867v_cf - 0.005339v_ca \\ & + 1.375fa - 0.02421v_cfa\end{aligned} \quad (3)$$

$$\begin{aligned}\mathrm{COAX}(v_c, f, a) = {} & 0.47 - 0.0006v_c - 0.3f - 1.1a \\ & - 0.001667v_cf + 0.002v_ca \\ & + 6.01fa + 0.02v_cfa\end{aligned} \quad (4)$$

$$\begin{aligned}\mathrm{RONt}(v_c, f, a) = {} & 65.66 - 0.2647v_c - 109.9f \\ & - 319.9a + 0.4528v_cf \\ & + 1.436v_ca + 702.02k_{23}fa \\ & + 2.81v_cfa\end{aligned} \quad (5)$$

$$\begin{aligned}\mathrm{Conc}(v_c, f, a) = {} & 4.013 - 0.01437v_c - 15.9f \\ & - 13.87a + 0.09789v_cf \\ & + 0.0660v_ca + 99.89fa \\ & - 0.5867v_cfa\end{aligned} \quad (6)$$

$$\begin{aligned}\mathrm{Slope}(v_c, f, a) = {} & 20.74 - 0.08951v_c - 34.83f \\ & - 108.3a + 0.1494v_cf \\ & + 0.4966v_ca + 271.2fa \\ & - 1.232v_cfa\end{aligned} \quad (7)$$

DISCUSSION

The results of the measurements and evaluations are presented in surface diagrams, which can be seen in Figure 2-7. We analyse the cylindricity error firstly in our study. Figure 2 shows that the alteration of the cutting speed in the studied range resulted no significant change, however the alteration of the other 2 parameters shows an interesting behaviour.

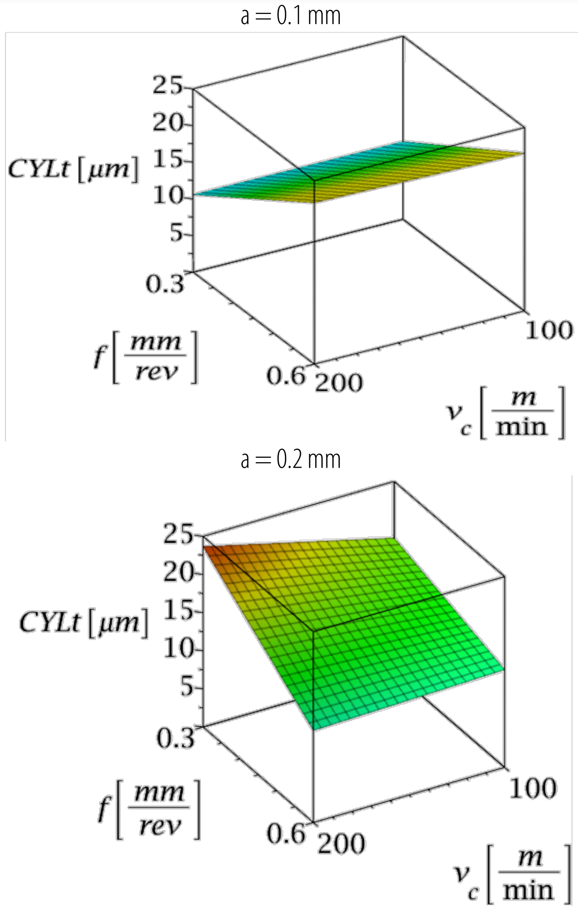

Figure 2. Cylindricity error (CYLt) as a function of the technological parameters

Increasing the feed increases CYLt when 0.1 depth of cut is set; while at 0.2 depth of cut the cylindricity decreases with the increasing feed. This phenomenon should be related to the change in the chip width and height. The former is related to the feed while the latter is calculated from the depth of cut. Low f and a values mean small chip width, height and cross sectional area, which results in a lower deformation in the machining system. If only the feed is increased, the chip width is increased, but its height remains almost the same, which leads to higher vibrations due to the longer contact. If only the depth of cut increased, the height of the chip also increases leading to lower specific cutting force, which unstabilizes the process. If both parameter is increased, the cutting force increases significantly, which stabilizes the process. However this hypothesis needs further investigation in our later works.

The ratio between the valley maximum departure from the reference cylinder into the material of the workpiece and the cylindricity error is shown in Figure 3. Increasing the depth of cut increases the studied ratio in three from the four cases, because the higher the depth of cut is the higher the chip height became. This results in larger parts of the material to break off from the surface, deepening the analysed profile. Increasing the cutting speed lowers this value in overall. The feed has a small impact on this parameter.

The coaxility is analysed in Figure 4. Here the opposite can be seen from the cylindricity error. The alteration of the depth of cut shows low impact on this parameter. The increase of the feed has a small, almost negligible lowering effect. However, increasing the cutting speed has a very good effect on the coaxility. When v_c is increased from 100 m/min to 200 m/min, the analysed parameter is halved in average. This is a result of better chip formation and less chatter.

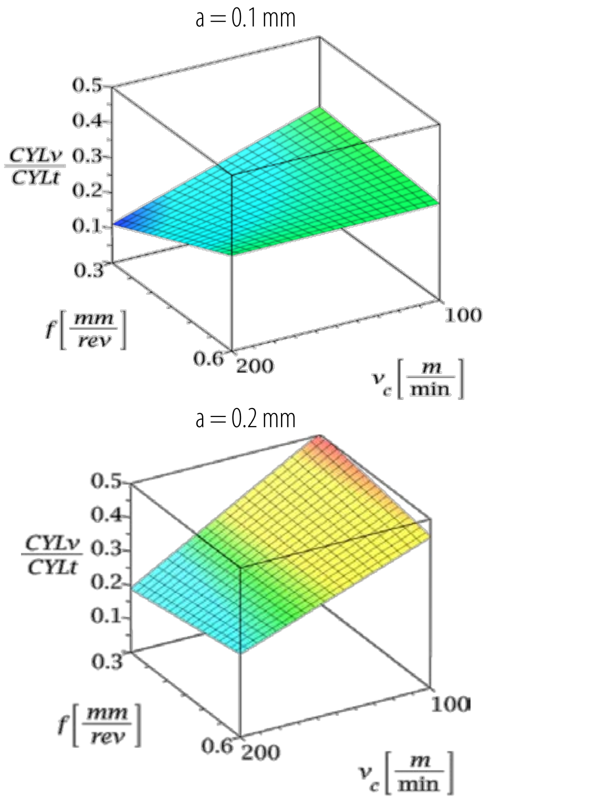

Figure 3. Ratio of the valley depth and cylindricity error (CYLv/CYLt) as a function of the technological parameters

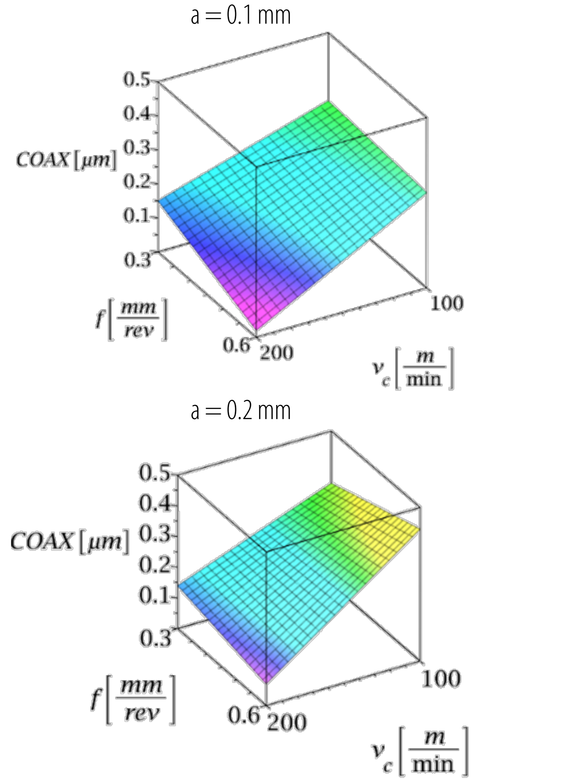

Figure 4. Coaxility (COAX) as a function of the technological parameters

Continuing with the roundness error parameters, we analyse the total roundness error on the basis of Figure 5. A better roundness can be achieved by increasing the cutting speed in overall, lower values are measured at v_c = 200 m/min. The depth of cut has an increasing effect on the analysed parameter: RONt is greater at 0.2 mm depth of cut three out of the four cases. At 0.1 mm depth of cut, increasing the feed decreases RONt, while at 0.2 mm depth of cut the feed increases the roundness error. This caused by the changing chip shape and cross sectional are. The geometry of the chip alters as the cutting tool generates the cylindrical surface (according to the run-in, constant, and run-out phase). RONt is more sensitive to this change than CYLt, which causes a deviation between the two parameters. This phenomenon needs further study, which we will continue in our future work.

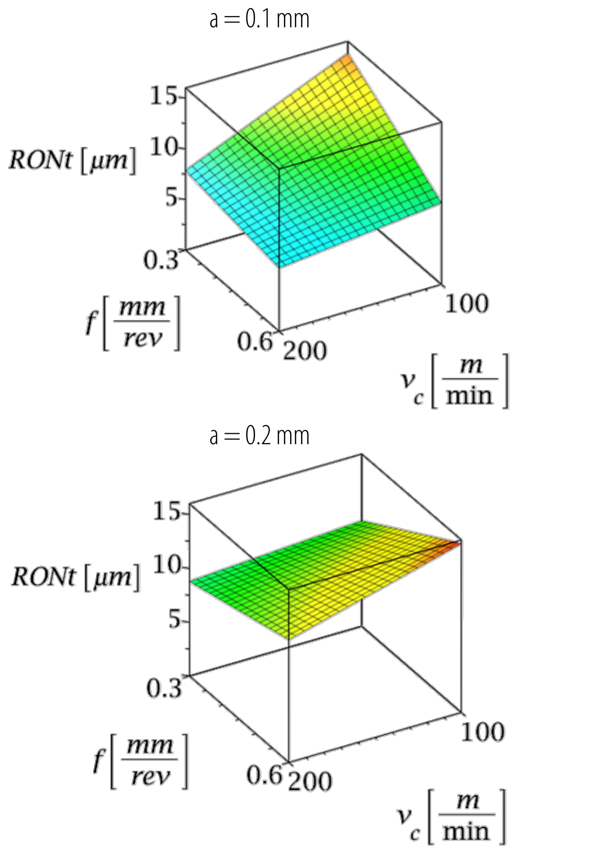

Figure 5. Roundness error (RONt) as a function of the technological parameters

We conclude from the analysing the concentricity in Figure 6, that altering the depth of cut results a different effect of the cutting speed increase. At 0.1 mm depth of cut, a two-fold increase in the cutting speed results higher error, while at 0.2 mm depth of cut this change results in lower error. The feed rate has an almost insignificant effect on this shape error parameter.

Finally, we analyse the slope of the periphery. This parameter describes the functional parameter of surfaces which turns on each other (e. g. bearings.) Figure 7 shows the reducing effect of the cutting speed on the slope: a two-fold increase of v_c results in 3-5-fold lower value, which caused by the better material removal at higher speeds. The depth of cut and feed has a varying effect. At 200 m/min cutting speed, increasing the feed lowers the slope, while at 100 m/min cutting speed its effect is not unidirectional. Increasing the depth of cut shows no clear effect on the slope.

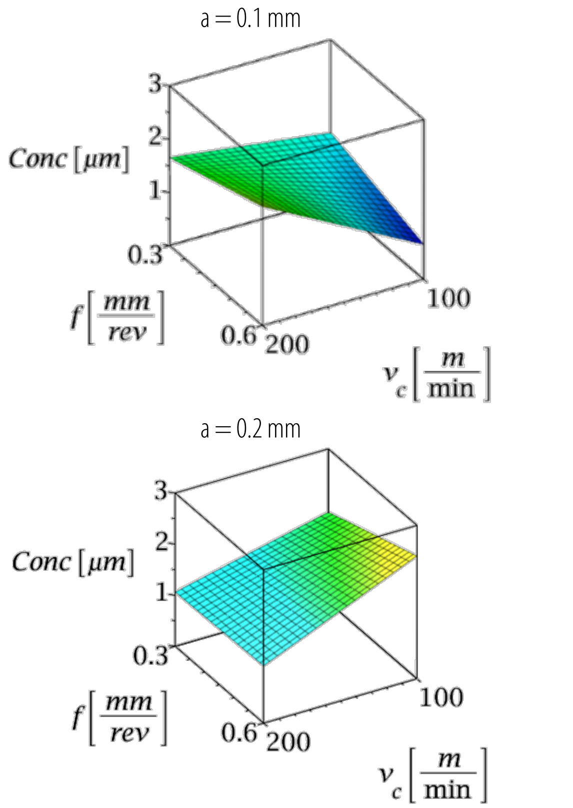

Figure 6. Concentricity (Conc.) as a function of the technological parameters

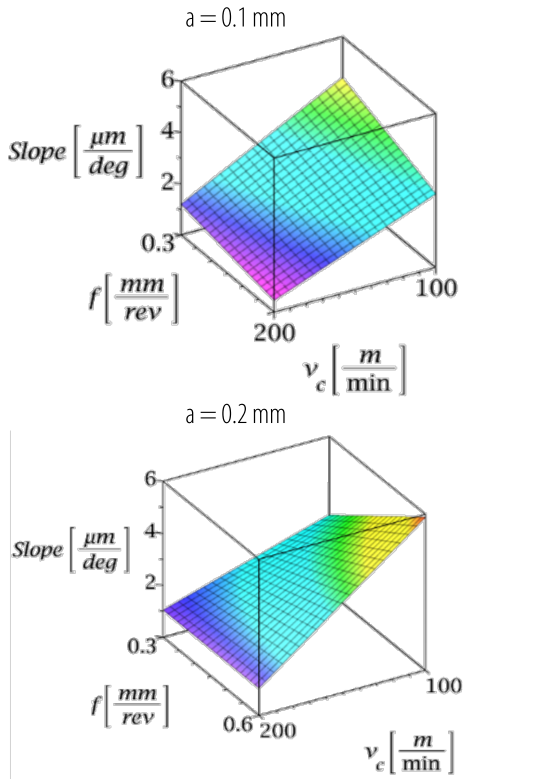

Figure 7. Slope as a function of the technological parameters

At the end of the discussion we would like to point out the following conclusions:

- Among the analysed parameters, the cutting speed has the most effect on the studied shape error values.
- Between 100 m/min and 200 m/min cutting speeds the latter is the favourable.
- The feed and depth of cut influences the shape error mostly according to the alteration of the chip size and chip shape, which result in different cutting forces.
- Functional parameters of the surface topography should be analysed.
- Cutting speed higher than 200 m/min and feed higher than 0.6 mm must be analysed in the next research step.

SUMMARY

The shape correctness of the machined parts is important in finish machining, thus the study of the effect of different technological parameters is need for better production planning. We studied several parameters of the cylindricity error and roundness deviations outer cylindrical surfaces machined by tangential turning in this paper by changing the cutting speed, feed and depth of cut. By the application of the Design of Experiments method, equations were also determined for the calculation and presentation of the analysed shape error parameters. In this study, the following parameters were measured and evaluated: CYLt, CYLv, COAX, RONt, Conc. and Slope. We showed the advantage of increasing the cutting speed, while we also pointed out further goals for our future studies.

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