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ALTERATION OF THE CUTTING FORCE COMPONENTS IN TANGENTIAL TURNING

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Abstract. *In the development of cutting procedure, the study of the cutting force is important to evaluate the possible loads and elastic deformations in the machining system. The unusual relative position of the cutting tool leads to a changing characteristic of the cutting force in tangential turning. Therefore, it is particularly important to study the values and ratios of the cutting force components in different setups in this finishing procedure. In this paper the depth of cut, feed, and cutting speed are changed, and the effect of these parameters are analysed on the major cutting force, feed force and passive force. The full factorial design of experiment method is applied in the selection of setup parameters and the evaluation of the results. The maximal values and the ratio of the force components were analysed by the determination of equations.*

Keywords: *design of experiments; feed force; major cutting force; passive force; tangential turning.*

1. INTRODUCTION

The machining processes are needed to be developed continuously due to meet the prescribed requirements of achievable surface quality, obtainable efficiency, and increasing productivity [1]. The quality management of cutting tools is also an important field [2]. In turning of cylindrical surfaces, one direction of the developments is the correct selection of process parameters. Experimental examination of turning operation, analysis of the most relevant parameter, and optimization strategies is all part of the current research [3]. If material removal rate, surface roughness and tool wear are considered, the usual order of impact of these parameters are the depth of cut, the cutting speed, and the feed [4]. However, cutting speed is more important, if we consider tool life [5], and tool wear is directly related to the machined surface quality of the workpiece [6]. Moreover, the process parameters also affect the shape accuracy [7]. Process conditions should be selected with care to be able to reduce the machining time without increasing cutting forces excessively [8]. Other effects must be taken into consideration, since the depth of cut to feed ratio alters the force components [9], while the shear angle is also an important factor [10].

The application of tangential turning [11] as finish machining is spreading in the industrial application, due to the achievable surface roughness [12] and form accuracy [13], while obtaining low machining times. However, the analysis of cutting forces is needed, to study the possible elastic deformations of the machining system. In this paper, the cutting force components are studied in tangential turning by changing the cutting speed, feed, and depth of cut. The maximal values of Major cutting force, Feed force, and Passive force were measured and analysed. During the measurement, the recommended adjustment values are set.

2. EXPERIMENTAL CONDITIONS AND METHODS

The aim of this research was the evaluation of the cutting forces acting between the workpiece and tool in tangential turning. Therefore, several cutting experiments were carried out to accomplish this task on a EMAG VSC 400 DS hard machining centre. Cylindrical workpieces with 70 mm outer diameter were machined. 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 were pre-machined by a standard turning tool with a SANDVIK Coromant CNMG 12 04 12-PM 4314 cutting insert. An inserted turning tool with 45° inclination angle is applied in the tangential turnings, which made by HORN Cutting Tools Ltd. and consisted of two parts: S117.0032.00 insert and H117.2530.4132 holder. The cutting edge of the tool was an uncoated carbide insert (MG12 grade).

The effect of the cutting speed (v_c), the feed per workpiece revolutions (f) and the depth of cut (a) were analysed in this study. The 2^3 factorial design method was applied in the parameter selection and analysis. A lower and an upper limit value were chosen for each studied parameter. The lower value range of the parameters are aimed in this study in the 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. 8 different setups are resulted, 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

The cutting forces were measured during the experiments with a Kistler 9257A three component dynamometer. The measurement setup also contained three Kistler

5011 charge amplifier, a NI-9215 data acquisition unit with cDAQ-9171 chasing and NI Labview software. The forces measured by the dynamometer are equivalent to the forces to be analysed, therefore no further calculations were needed.

In this paper, the following cutting forces are studied:

- F_c – Major cutting force, acting in the direction of cutting speed [N]
- F_f – Feed force, acting in the direction of feed [N]
- F_p – Passive force, acting perpendicular to F_c and F_f [N]

Equations were worked out for the analysis of the cutting process using the form in Equation 1 according to the 2^3 full factorial experimental design method. The y is the dependent value and k_i are the coefficients describing the effect of the different factors on the dependent value. The independent variables are the cutting speed (v_c), feed (f) and depth of cut (a)

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

3. EXPERIMENTAL RESULTS

The experiments were carried out and the cutting forces are measured for each setup. The resulted force-time curves were evaluated, and the maximum value of the force components were calculated for each studied cutting force component in the constant chip cross-sectional phase. These values are shown in Table 2. Equation 2-4 shows the determined mathematical formulas, which are calculated by the application of the necessary numerical analysis.

Table 2 – Measurement results

Setup	1	2	3	4	5	6	7	8
F_c [N]	188.0	197.9	313.0	283.1	315.3	393.1	597.7	554.2
F_p [N]	137.7	205.9	238.6	298.2	202.2	463.6	369.1	457.7
F_f [N]	61.3	61.1	104.9	108.4	114.0	149.4	242.1	237.8

$$F_c(v_c, f, a) = 192.6 - 0.9953 v_c - 246.5 f - 1793.2 a + 1.387 v_c f + 14.93 v_c a + 7960.3 fa - 27.14 v_c fa \quad (2)$$

$$F_f(v_c, f, a) = 132.7 - 0.8291 v_c - 293.7 f - 1109.6 a + 1.569 v_c f + 7.897 v_c a + 4265.7 fa - 14.45 v_c fa \quad (3)$$

$$F_p(v_c, f, a) = 319.1 - 2.808 v_c - 402.8 f - 3591.1 a + 5.190 v_c f + 35.75 v_c a + 7676.4 fa - 54.76 v_c fa \quad (4)$$

During the study of the cutting forces, it is important to look at the ratio of these forces. It can tell a lot about the chip removal process, if these ratios are changing in different setups. Therefore, using the result presented in Table 2, the F_c /F_p, F_c /F_f and F_p /F_f ratios are also calculated in the 8 experimental setups. These outcomes can be seen in Table 3. Equation 5–7 present the mathematical formulas for these values, which will be used in the deeper discussion of the results.

Table 3 – Calculated ratios of the cutting forces

Setup	1	2	3	4	5	6	7	8
F_c /F_p [-]	1.37	0.96	1.31	0.95	1.56	0.85	1.62	1.21
F_c /F_f [-]	3.07	3.24	2.98	2.61	2.77	2.63	2.47	2.33
F_p /F_f [-]	2.25	3.37	2.28	2.75	1.77	3.10	1.52	1.92

$$F_c / F_f (v_c, f, a) = 1.657 + 0.0157v_c + 4.082f + 7.693a - 0.03626v_cf - 0.085v_ca - 25.31fa + 0.1807v_cfa \quad (5)$$

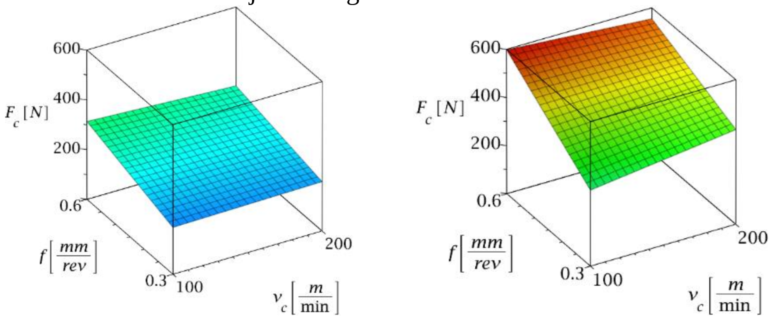
$$F_c / F_p (v_c, f, a) = 1.213 + 0.00124v_c + 0.1803f + 6.507a - 0.00735v_cf - 0.05695v_ca - 4.953fa + 0.08726v_cfa \quad (6)$$

$$F_p / F_f (v_c, f, a) = 1.125 + 0.0128v_c + 2.243f - 6.81a - 0.012146v_cf + 0.04891v_ca + 0.127fa - 0.09437v_cfa \quad (7)$$

4. DISCUSSION

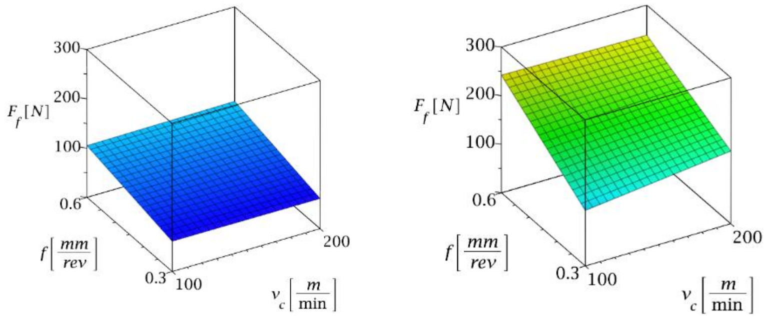
The analysis of the effect of the setup parameters on the cutting forces consists of two sections. First the maximal values of each force components were analysed, which is followed by the evaluation of the ratios between those.

Figure 1 presents the cutting force in function of the feed and cutting speed on two levels of the depth of cut. Firstly, we can see, that both *f* and *a* has an increasing effect on F_c. From the two, the depth of cut has a more significant effect, because the two-fold increase of *a* resulted in nearly two-fold increase of the major cutting force. However, the two-fold increase of the feed has a lower impact resulting with around 1.5-1.8-fold increase. This can be explained by the fact, that the depth of cut affects the chip width, while the feed affects the chip height. Increasing the letter lowers the specific cutting force, which results in a lower increase in the cutting force by the same increase in the chip cross-sectional area. The cutting speed has a neglectable effect on the major cutting force.



a_p = 0.1 mm a_p = 0.2 mm

Figure 1 – Alteration of the F_c in the studied range

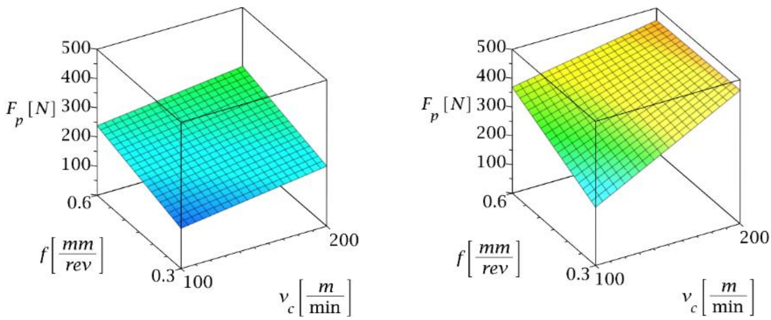


a_p = 0.1 mm a_p = 0.2 mm

Figure 2 – Alteration of the F_f in the studied range

We can see the feed directional force in function of the feed and cutting speed in Figure 2. It can be seen, that in case of 0.1 depth of cut, the alteration of the feed has a lower (increasing) impact than in case of 0.2 depth of cut. However, the two-fold increase of the depth of cut resulted a nearly 2.5-fold increase in F_f in the studied range. This can be explained by the change in the shape of the cross-sectional area of the chip. The projection of the cutting tool in the base plane can be described with a hyperbolic function. If the depth of cut is higher, this results in the change of the direction of the resultant force in the base plane, which shifts from the direction of the tool holder to the direction of the feed. Therefore, the depth of cut has a higher impact in the studied range. The cutting speed has a low effect on this cutting force component.

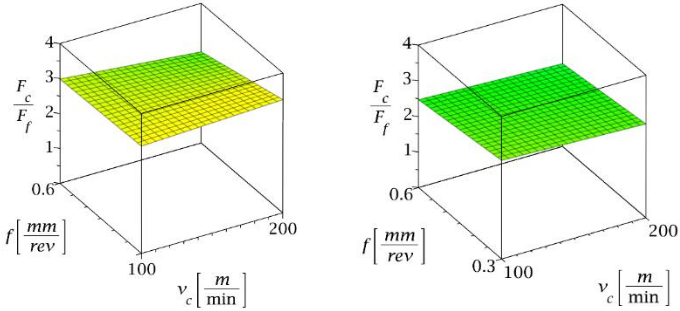
In Figure 3, the alteration of the passive force can be seen. The first, and most interesting conclusion can be drawn by the analysis of the cutting speed change. The two-fold increase of the cutting speed results in a 1.5-2-fold increase in the F_p value. This phenomenon can be explained by two suggestions. First, the increase of the cutting speed results in a different, much higher deformation rate in the workpiece material, which results in a higher plastic deformation as well. This causes a higher radial load on the tool. Secondly, higher v_c results in a greater area of material, which will be in contact with the cutting tool in a given time period. However, this phenomenon should be analysed more thoroughly in a later study. The effect of the feed on F_p is higher than its effect on F_f, while the effect of the depth of cut lowers. this can be explained by the previously mentioned change in the chip shape.



a_p = 0.1 mm a_p = 0.2 mm

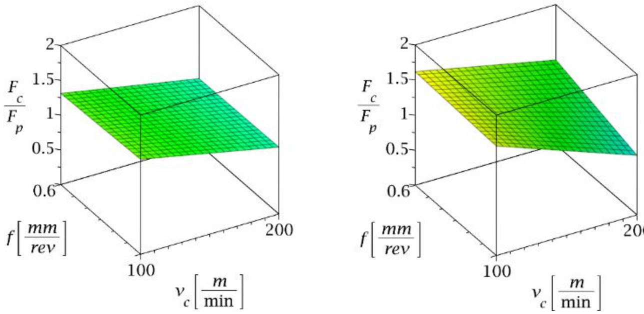
Figure 3 – Alteration of the F_p in the studied range

The study continues with the evaluation of the ratios between the cutting force components. Figure 4 presents ratio between the major cutting force and the feed directional force. In this figure it can be clearly seen that the feed and cutting speed have a small effect on this ratio, however the two-fold increase of the depth of cut results in a nearly 1.3-fold increase in F_c/Ff. This means, that by the variation of the setup parameters in the studied range, the direction of the active force (the resultant from the summation of F_c and F_f) remains nearly the same. Figure 5 presents the alteration of the ratio between the major cutting force and the passive force. The effect of the cutting speed on F_p also affects the alteration of the ratio: increasing the v_c results in a lower ratio. The two-fold increase of the depth of cut increases the studied attribute by 1.2-fold, however the increase of the feed has a neglectable effect. Among the analysed setup parameters, the cutting speed has the highest effect. Finally, the ratio between the passive force and the feed directional force is analysed using Figure 6. Here we can see the increasing effect of the cutting speed on the studied ratio. This is caused by the fact that the passive force is affected by the change in v_c, however the feed directional force is unaffected. The depth of cut has also an increasing effect on this ratio: a two-fold increase in *a* results in a nearly 1.3-fold increase in F_p/F_f. The feed rate has a neglectable effect on the ratio.



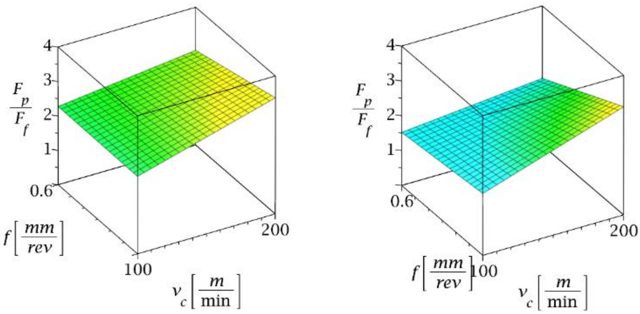
a_p = 0.1 mm a_p = 0.2 mm

Figure 4 – The ratio of F_c and F_f in the studied range



a_p = 0.1 mm a_p = 0.2 mm

Figure 5 – The ratio of F_c and F_p in the studied range



a_p = 0.1 mm a_p = 0.2 mm

Figure 6 – The ratio of F_p and F_f in the studied range

5. CONCLUSIONS

The need to improve of productivity draws the attention of researchers on machining procedures, where high feed rate can be applied, while the surface roughness can be held below the prescribed values. Tangential turning allows the creation of ground-like surfaces, however the feed rate can be set to higher values, than used to in traditional turning. In this paper, cutting experiments were carried out to study the cutting force components in tangential turning, which values play an important role in the shape correctness. In the evaluation of the resulted data the following conclusions were drawn:

- The major cutting force and the feed directional force is unaffected by the alteration of the cutting speed; yet, it has an increasing effect on the passive force.
- The change of the depth of cut changes the shape of the active section of the cutting edge, which changes the direction of the resultant cutting force.
- The ratio between the analysed cutting force components can be manipulated by the adjustment of the setup parameters.

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ЗМІННІСТЬ СКЛАДОВИХ СИЛИ РІЗАННЯ ПРИ ТАНГЕНЦІАЛЬНОМУ ТОЧІННІ

Анотація. *При розробці процедури різання важливе значення має вивчення сили різання для оцінки можливих навантажень і пружних деформацій в системі обробки. Незвичайне взаємне розташування ріжучого інструменту призводить до зміни характеристики сили різання при тангенціальному повороті. Тому особливо важливо вивчити значення та співвідношення компонентів сили різання в різних установках у цій процедурі фінішної обробки. Аналіз впливу параметрів установки на зусилля різання складається з двох розділів. Спочатку були проаналізовані максимальні значення кожної складової сили, після чого проводилась оцінка співвідношень між ними. Видно, що глибина різання має більш значний вплив, оскільки дворазове її збільшення призвело до майже дворазового збільшення основної сили різання. Однак дворазове збільшення подачі має менший вплив, що призводить до збільшення сили приблизно в 1,5-1,8 рази. Це можна пояснити тим, що глибина різання впливає на ширину стружки, в той час як подача впливає на її висоту. Збільшення швидкості знижує питому силу різання, що призводить до меншого збільшення сили різання за рахунок такого ж збільшення площі поперечного перерізу стружки. Швидкість різання незначно впливає на основну силу різання. У даній роботі змінюються глибина різання, подача і швидкість різання, а також аналізується вплив цих параметрів на основну силу різання, силу подачі і пасивну силу. Повний факторний план експерименту застосовується при виборі параметрів установки та оцінці результатів. Максимальні значення і співвідношення силових складових були проаналізовані шляхом рішення рівнянь. При оцінці отриманих даних були зроблені наступні висновки: на основну силу різання та спрямовану силу подачі не впливає зміна швидкості різання; Проте вона все більше впливає на пасивну силу; зміна глибини різання змінює форму активної ділянки ріжучої кромки, що змінює напрямок результуючої сили різання; співвідношенням між аналізованими компонентами сили різання можна маніпулювати, регулюючи параметри установки.*

Ключові слова: *планування експериментів; сила подачі; основна сила різання; пасивна сила; тангенціальний поворот.*