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ANALYSIS OF THE EFFECT OF VARYING THE CUTTING RATIO ON FORCE COMPONENTS AND SURFACE ROUGHNESS IN FACE MILLING

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Abstract. *Traditional machining processes, such as face milling, still play a very important role in the production of machine parts and are the subject of ongoing research. One important area of research is the investigation of high-feed milling processes. However, due to the increased feed per tooth value f_z, it is advisable to reduce the depth of cut (a_p) in order to maintain the cutting forces at an appropriate level. In this way, the ratio of these two technological parameters, the so-called cutting ratio, changes and we can move into the range of inverse machining, where $a_p / f_z < 1$. In this paper, the consequences of this change is investigated on the surface roughness and the components of the cutting force, and it is discussed how the optimal cutting ratio can be found.*

Keywords: *high feed milling; cutting force components, surface roughness.*

1. INTRODUCTION

Face milling is a very frequently used process in the production of various machine parts. It is an unavoidable procedure during the production of practically all larger flat surfaces. As a consequence of this, researchers have long been interested in examining, perfecting, and pushing the limits of the process [1]. Nevertheless, it still has areas that are unexploited and still need to be investigated [2].

The topic of the paper is the experimental investigation of the effect of changing the so-called cutting ratio (which is the ratio of the depth of cut to the feed, a_p / f_z) on the components of the cutting force and the roughness of the machined surface during face milling. Traditionally, this cutting ratio is usually a value greater than one ($a_p / f_z > 1$), which means that the allowance is removed with a large layer thickness, but at a low speed. At the same time, nowadays, high-speed milling is becoming more and more a trend, where the feed is drastically increased, and a given layer is removed in much less time [2]. At the same time, due to the increase in feed, it is necessary to reduce the depth of cut, because otherwise the cutting forces may be unmanageably high due to the increase in the chip cross-section [3], [4]. Since the blank products are also manufactured according to increasingly strict tolerances, there is often no need to use more than one cuts, so the entire processing is faster and more economical [5]. Nowadays, machining processes are designed to use the maximum possible machine power and simultaneously ensure the required surface roughness, because there is simply no time to perform roughing and smoothing operations sequentially [6], [7]. So, in fact, the problem to be solved is to remove the same chip cross-section with as much feed as possible and, correspondingly, with as little depth of cut as possible, while ensuring the appropriate performance and roughness data [8]–[10]. That is why the researchers worked on the integration of several different shaped milling inserts into one milling head [11]. At the same time, the use of so-called wiper inserts to smooth-out the milled surface can be considered a common practice [12]. However, the use of a wiper insert sometimes can have negative impact on the stability of the process, so in some cases it is more practical to use a curved invert to avoid unwanted vibrations [9]. The design of the cutting edge is also of great importance when cutting with defined edge geometry [13].

In the present paper, it was investigated what effect the removal of a constant chip cross-section with a changed cutting ratio has on the components of the cutting force, as well as on the surface roughness In particular, we have experimentally investigated the combined effect of the changed technological data on force and roughness, and we were looking for the optimum point up to which it makes sense to increase the feed rate with decreasing depth of cut.

2. MATERIALS AND METHODS

This section describes the machines and tools used, the characteristics of the specimens, and the measuring and other instruments. The setup used in the cutting experiments is shown in Figure 1. A Perfect Jet MCV-M8 type vertical three-dimensional CNC milling machine, a product of the Taiwan-based Ping Jeng Machinery company, was used for the tests. This equipment is specifically designed for high precision, high rigidity and high-speed machining.

Figure 1. The experimental setup used for the cutting tests

During the experiments, a CoroMill 200 R200-068Q27-12L face milling head was used. A CoroMill RCKT 1204M0-PM S40T grade coated carbide round insert was clamped into the milling head, but only one insert was cutting in the milling head at a time (this process variant is also known as fly-cutting, and it is often used for experimental investigations).

The careful selection of the feed and depth of cut values used during the tests was ensured that both traditional and inverse milling ratio values were included. Based on the above, it is considered conventional cutting if the cutting ratio $a_p/f_z > 1$ and inverse if $a_p / f_z < 1$. When choosing the feed values, the tool manufacturer's recommendations were first taken into account, which for this insert is between 0.1 – 0.3 mm for the used C45 steel material. However, in order to ensure the inverse chip ratio, it was also necessary to test feed values much higher than this, so the feed range used in practice was between 0.1 – 1 mm. Since, at the same time, by changing the depth of cut, the theoretical chip cross-section was kept at a constant value (A_c = 0.1 mm^2), so the larger feed could be safely used. The feed and depth of cut values selected according to the above principles are contained in Table 1.

Table 1. Feed rate and depth of cut values used during the tests

Sample No.	1.	2.	3.	4.	5.
Feed per tooth f_t [mm/tooth]	0.1	0.2	0.316	0.5	1
Depth of cut a_p [mm]	1	0.5	0.316	0.2	0.1
Cutting ratio a_p/f_z	10	2.5	1	0.4	0.1

As can be seen in the table, in addition to the two conventional and two inverse cutting ratios, in one case the depth of cut and the feed rate were the same (0.316 mm), here the cutting ratio is $a_p / f_z = 1$. This can be considered a special borderline case. Additional technological data were as follows: spindle speed n = 986 RPM, cutting speed v_c = 270 m/min, which were chosen according to the parameters of the milling machine and the recommendations of the tool manufacturer.

The dimensions of the used test specimen can be seen in Fig. 2, its material is the previously mentioned C45 material quality, the main characteristics of which are shown in Table 2. The center line of the milling head was set to the center of the workpiece.

Table 2: Chemical composition and mechanical properties of C45 steel [14]

Chemical Composition (average), [%]								
C	**Mn**	**Si**	**P**	**S**	**Cr**	**Ni**	**Mo**	**Fe**
0.48	0.74	0.36	0.011	0.01	0.09	0.02	0.002	rest
Yield Strength (min.)						Re=430MPa		
Tensile strength(min.)						Rm=740MPa		

Hardness(min.)	250HB

During milling, the components of the cutting force were measured and recorded using the force measuring instrument inserted in the machining system. The force was measured by detecting the force components in the x, y and z directions acting on the workpiece attached to the Kistler 9257A type dynamometer which was clamped to the machine table.

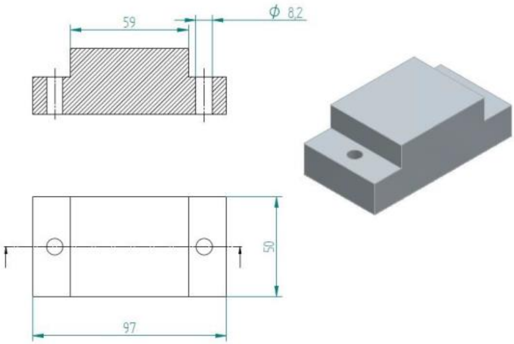

Figure 2. Main geometric characteristics of the used specimen

The dynamometer signals were transmitted by 3 Kistler 5011A charge amplifiers to the National Instruments CompactDAQ-9171 type four-channel data acquisition unit, which communicated with the connected computer via a USB port. The data obtained in this way were processed, displayed and recorded by a measuring program created in the LabView system. The milling configuration used, the main process parameters and the directions of the cutting force components acting on the workpiece are shown in Fig. 3.

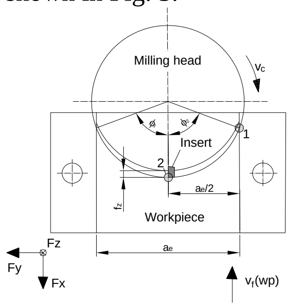

Figure 3. The milling setup and axis directions for force measurements

Two notable points are marked on Fig. 3: Point 1 is the entry point of the insert, and Point 2 is the intersection of the centre line of the tool with the tip of the insert. This is a point of interest because it is at this point that the force data were evaluated and the comparisons were made. It is well known that the surface roughness value is always highest when measured at the centre line, so the 2*D* roughness data reported in the results were also measured here, and it is useful to compare them with the corresponding force data.

The surface roughness was measured using an AltiSurf 520 three-dimensional surface roughness measuring device with a CL2 type confocal chromatic distance measuring sensor. The measuring head was also equipped with an MG140 magnifier, giving a measuring range of 300 µm and an axial resolution of 0.012 µm. The measured roughness data were evaluated using AltiMap Premium software. With respect to the roughness parameters, the parameters R_a and R_z, commonly used in industrial practice, and their three-dimensional equivalents S_a and S_z were investigated. Two-dimensional profiles were measured and evaluated according to EN ISO 4287 and 4288, three-dimensional surfaces according to EN ISO 25178-2:2012. These are not the latest versions of the relevant standards, but the version of the evaluation software used can calculate the values of these parameters, and the newer standards do not carry significant differences in interpretation.

3. RESULTS AND DISCUSSION

The results of the experiments and measurements carried out are reported below. First, the data of the roughness measurements are given in Table 3. The numbers show that the roughness values increase monotonically with increasing feed rate, which primarily affects the surface roughness. The really big jump occurs at $f_z = 0.5$ mm, where there are already 4.5 times higher values of R_a and 3.3 times higher values of R_z. And at 1 mm feed there is already an increase of about 18 times in R_a and nearly 12 times in R_z. For the three-dimensional roughness parameters, these values are very similar (the indicated numbers are the f_z values in mm): $Sa_{0.1\rightarrow0.5}$: 4.6; $Sa_{0.1\rightarrow1}$: 16; $Sz_{0.1\rightarrow0.5}$: 2.6; $Sz_{0.1\rightarrow1}$: 8.9.

Table 3. 2*D* and 3*D* roughness results

a_p/f_z	f_z [mm]	a_p [mm]	*Ra* [µm]	*Rz* [µm]	*Sa* [µm]	*Sz* [µm]
10	0.1	1	0.29	1.92	0.34	2.97
2.5	0.2	0.5	0.42	2.44	0.46	2.99
1	0.316	0.316	0.64	3.43	0.64	4.27
0.4	0.5	0.2	1.31	6.40	1.59	7.87
0.1	1	0.1	5.29	22.81	5.44	26.4

The measured 2*D* roughness profiles and the 3*D* surfaces are shown in Figure 4, where the significant roughness degradation starting from f_z = 0.5 mm is visually well noticeable. In the following, the force measurement data are presented, starting with the values of the force components measured at the centre line of the milling head in Table 4.

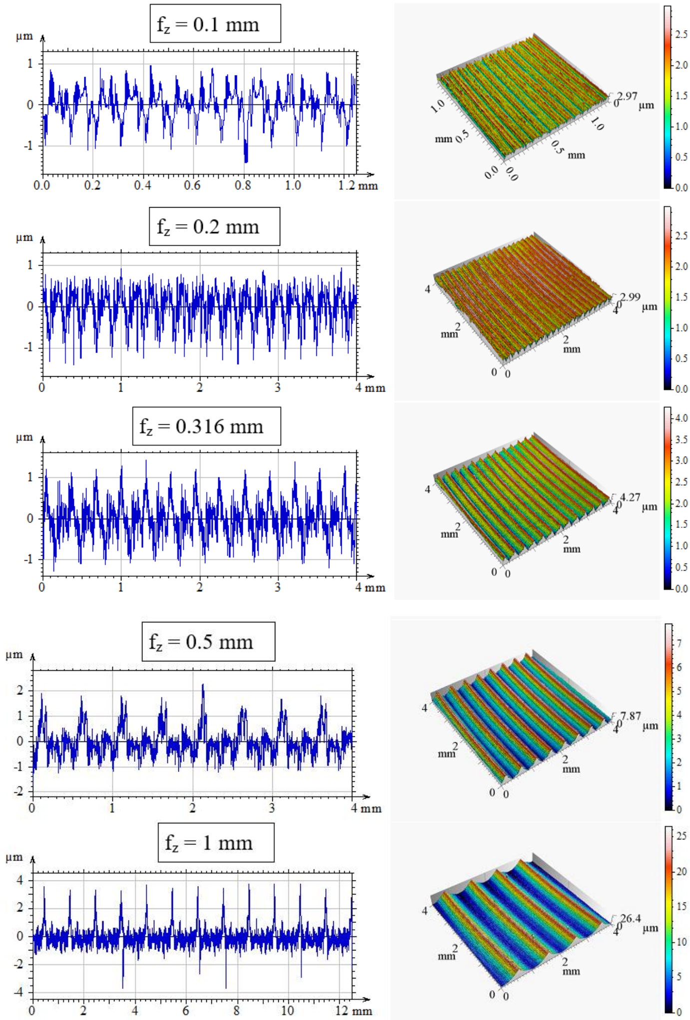

Figure 4. Measured roughness profiles and 3*D* surfaces

When interpreting the force data, it is worth noting once again that the undeformed (theoretical) chip cross section was the same in all cases while the cutting ratio was varied, so, in theory, the same amount of material should be removed in each case. It can be seen from the data that the change in all force components shows a downward trend.

Table 4. The measured force components

a_p/f_z	f_z [mm]	a_p [mm]	Fx [N]	Fy [N]	Fz [N]
10	0.1	1	289	389	812
2.5	0.2	0.5	231	335	659
1	0.316	0.316	201	308	587
0.4	0.5	0.2	180	287	543
0.1	1	0.1	155	264	473

Since the main aim of the investigations was to find some kind of optimum cutting ratio, it is useful to plot the roughness data and the cutting forces in one diagram, a practical implementation of which is illustrated in Figure 5.

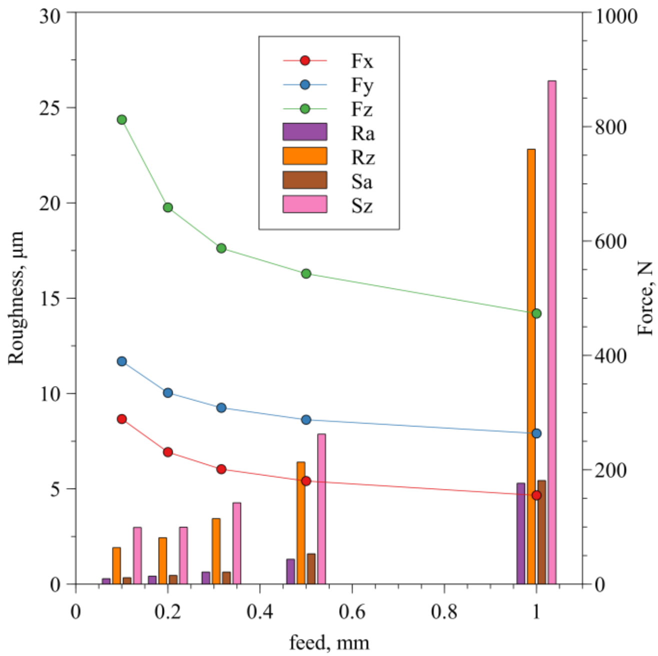

Figure 5. Variation of cutting force and surface roughness per feed change

With the help of this visual representation, the trends of the changes of the two output parameters under study and their relative positions to each other can be seen much more clearly. The values of the force components decrease significantly at low feed rates (up to f_z = 0.316 mm). At the same time, between f_z = 0.5 and 1 mm, there is only a slight decrease, and the curves of the force components Fx and Fy are almost horizontal. This means that a large increase in the feed rate no longer has a significant effect on the force components, provided that the theoretical chip cross-section is kept constant. However, the value of the applicable feed is basically limited by the value of the roughness parameters prescribed for the machined surface: above a certain feed, the roughness deteriorates to a great extent. In the present experiments, this occurs approximately after f_z = 0.316 mm. However, we must also note that the cutting of metals is a very complex process, during which an extremely large number of factors must be taken into account in order to find the optimal technological parameters, which requires great expertise and a thorough examination of the given cutting conditions.

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АНАЛІЗ ВПЛИВУ ЗМІНИ КОЕФІЦІЄНТА РІЗАННЯ НА СИЛОВІ СКЛАДОВІ ТА ШОРСТКІСТЬ ПОВЕРХНІ ПРИ ТОРЦЕВОМУ ФРЕЗЕРУВАННІ

Анотація. *Традиційні процеси механічної обробки, такі як торцеве фрезерування, як і раніше, відіграють дуже важливу роль у виробництві деталей машин і є предметом постійних досліджень. Одним з важливих напрямків досліджень є вивчення процесів різання з високою подачею. Однак у зв'язку зі збільшеним значенням подачі на один зуб f_z доцільно зменшити глибину різання (a_p), щоб підтримувати зусилля різання на належному рівні. Таким чином, змінюється співвідношення цих двох технологічних параметрів, так званий коефіцієнт різання, і ми можемо перейти в діапазон зворотної обробки, де $a_p / f_z < 1$. У даній роботі досліджуються наслідки дії цієї зміни на шорсткість поверхні і складових сили різання, а також обговорюється, як можна знайти оптимальне співвідношення умов різання. Результати проведених експериментів і вимірювань показують, що значення шорсткості монотонно збільшуються зі збільшенням швидкості подачі, що в першу чергу впливає на шорсткість поверхні. По-справжньому великий стрибок відбувається при $f_z = 0.5$ мм, де вже в 4,5 рази вищі значення R_a і в 3,3 рази вищі значення R_z. А на 1 мм подачі вже спостерігається приріст приблизно в 18 разів у R_a і майже в 12 разів у R_z. Для параметрів тривимірної шорсткості ці значення дуже схожі (зазначені числа є значеннями f_z в мм): S_a 0,1→0,5: 4,6; S_a 0.1→1: 16; S_z 0,1→0,5: 2,6; S_z 0.1→1: 8.9. Значення силових складових значно зменшуються при малих швидкостях подачі (до $f_z = 0,316$ мм). При цьому між $f_z = 0,5$ і 1 мм спостерігається лише незначне зменшення, а криві силових складових F_x і F_y майже горизонтальні. Це означає, що значне збільшення швидкості подачі вже не робить істотного впливу на силові складові за умови, що теоретичний поперечний переріз стружки залишається постійним. Однак величина застосовуваної швидкості в основному обмежена величиною параметрів шорсткості, прописаних для оброблюваної поверхні: з перевищенням подачі, шорсткість в значній мірі погіршується. У цих дослідах це відбувається приблизно після $f_z = 0,316$ мм. Однак потрібно також зазначити, що різання металів є дуже складним процесом, в ході якого необхідно враховувати надзвичайно велику кількість факторів з метою пошуку оптимальних технологічних параметрів, що вимагає великих знань і ретельного вивчення заданих умов різання.*

Ключові слова: *високошвидкісне фрезерування; складові сили різання; шорсткість поверхні.*

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