UDC 621.914.1 **doi: 10.20998/2078-7405.2022.97.13**

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FACE MILLING OF STEEL WITH OCTAGONAL INSERT

Abstract. *Face milling is often used to create flat surfaces, since when used as finishing, a suitable surface roughness can be achieved by fulfilling the specified dimension and tolerance requirements. In addition, high productivity can be reached by choosing the appropriate parameters of the cutting process. The cutting data also affect the cutting force and the wear of the tool, and another consideration is that the resulting vibrations can deteriorate the microgeometry of the surface. Several insert shapes are available for face milling. Experiments were carried out with a milling head equipped with a single octagonal insert. The effect of increasing the feed per tooth was examined through the cutting force components, while keeping the cutting speed and depth of cut fixed. The changes in the specific cutting force components were also analysed.*

Keywords: *face milling; octagonal insert; feed per tooth; cutting forces; specific cutting forces.*

1. INTRODUCTION

Workpiece surfaces machined with face milling are characterized by a high degree of precision and good surface quality, that is why face milling is well liked as a machining process. The productivity of face milling can be increased by increasing the feed rate [1,2]. This can be achieved by increasing two technological parameters, the spindle speed and the feed per tooth [3]. The effect of the forces arising during cutting not only appears on the workpiece (when the chip is being formed); the cutting force also loads the tool, the clamping devices and the machine. The magnitude of the cutting force and its prediction are important from the point of view of the entire machining system.

A novel approach to the theoretical modelling of cutting forces was presented by Zheng et al. in face milling [4]. The operation of the cutter was modelled as the simultaneous operation of several single-edged cutting tools. Subramanian et al. developed a statistical model that predicts cutting force based on cutting speed, feed, and axial depth of cut [5]. They found that cutting speed was the dominant factor in the second-order models, followed by feed and axial depth of cut. Higher cutting speed, lower feed and smaller axial depth of cut resulted in lower cutting force. Čekić et al. investigated the effect of cutting parameters [6]. They found that increasing the cutting speed causes a decrease in the cutting forces, and the feed per tooth has a significant effect on the value of the cutting forces. Chuangwen et al. performed milling experiments under different process conditions with a coated carbide end mill insert on stainless steel [7]. It was found that among the process factors, tool wear and depth of cut significantly affect the cutting force and vibration. Ghorbani and Moetakef-Imani presented a new method for determining specific cutting force coefficients for face milling with circular inserts [8].

An inverse method was proposed to solve the equations of the mechanical force model using a genetic algorithm. The interaction of the cutting speed, the feed per tooth and the depth of cut with the changes in the tangential and radial coefficients of the specific cutting force were examined. They found that, under given cutting conditions, the edge geometry of the circular insert significantly affects the value of the coefficients. Nguyen presents a cutting force modelling method and a combined approach of theoretical and experimental methods in the face milling process with a parallelogram insert [9]. Kundrák et al. examined the effect of different insert geometry characteristics on the cutting force and the values of the specific cutting force components in the case of face milling [10]. The aim was to determine the insert with the appropriate cutting edge geometry that results in the lowest energy consumption for the same material volume removed. Kundrák et al. studied the energetic characteristics of milling with special attention to the shape of the cross-section removed by the tool [11]. It was found that it is advantageous from an energetic point of view if the applied chip ratio is as small as possible. Felhő presented a study about the finite element modelling of cutting force components acting on the workpiece in face milling [12], introducing a method for measuring the cutting edge radius of an insert using an optical method. The simulated cutting force values and real measurement data were compared and good correlation was found.

In this paper, the effect of feed per tooth on the cutting force components was investigated during face milling with an octagonal milling insert. The change in the specific cutting force components which characterizes the specific energy consumption, was also examined.

2. METHODOLOGY

In the cutting experiment presented in this paper, the change in the cutting force during face milling of C45 carbon steel was examined. A single octagonal coated carbide milling insert was clamped in the milling head. The reason for this was that the cutting force could be measured without the interaction of the other inserts, because only one insert was working at a time. The devices used in the experiment are summarized in Figure 1.

The face milling experiments were performed by setting a constant cutting speed and a constant depth of cut. The variable parameter was the feed per tooth, which was set to six values between 0.1 and 1.6 mm/tooth. The workpiece was fixed to the dynamometer on the table of the milling machine with screws. According to the spatial Cartesian coordinate system, the dynamometer generated the cutting force signals in three directions (x – the same direction as the feed direction, y – the direction perpendicular to the feed direction, z – the direction perpendicular to the x and y directions), which were amplified by the three charge amplifiers and then transmitted by the data collection unit to the computer. The special measuring software running on the computer was written in the LabVIEW system-design platform, which was used to obtain the measurement data for evaluation.

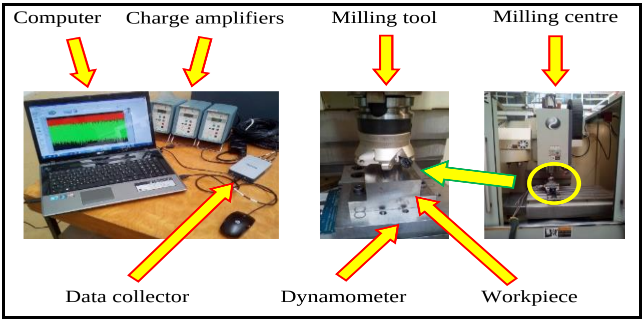

Figure 1 – Experimental equipment [13]

Table 1 – Types and characteristic parameters of experimental devices

Machine tool	
Vertical machining centre	Perfect Jet MCV-M8
Tool	
Milling head	ATORN 10612120 (D=80 mm, κ_r=43°)
Insert	ATORN OCKX 0606-AD-TR HC4640 (γ_o=25°; α_o=7°; r_ε=0.5 mm)
Workpiece	
Material	C45 (1.0503) carbon steel, normalized, hardness HB180
Dimension	cutting width 58 mm, cutting length 50 mm
Cutting force measuring equipment	
Dynamometer	Kistler 9257A
Charge amplifiers	Kistler 5011A (3 pcs)
Data collector	CompactDAQ-9171 (National Instruments)

The specifications of the milling machine, milling tool, workpiece and the elements of the force measuring system used in the experiment can be seen in Table 1. The path of the tool was programmed in relation to the workpiece in such a way as to realize symmetrical milling.

The cutting data of the face milling experiments were chosen in such a way that the effect of the feed change on the cutting force could be examined and analysed. Additional setting parameters affecting the cutting force (cutting speed and depth of cut) were set at a constant value in the range of parameters recommended by the manufacturer of the milling insert. Table 2 summarizes the cutting data set on the milling machine during the experiments.

Table 2 – Summarized cutting data

Cutting data		
Cutting speed	v_c	200 m/min
Spindle speed	n	901.4 rev/min
Feed per tooth	f_z	0.1, 0.2, 0.4, 0.8, 1.2, 1.6 mm/tooth
Depth of cut	a_p	0.4 mm

3. RESULTS AND DISCUSSION

The experimental data were processed. From the measured forces F_x, F_y, F_z (acting on the workpiece) the load on the tool was calculated with the values of F_c (tangential), F_f (radial) and F_p (perpendicular to F_c and F_f, also known as passive) force components operating in the coordinate system rotating with the tool. The values of the measured and calculated force components are illustrated in Table 3.

By showing the values in Table 3 in a diagram, the change in the components of the cutting force becomes clearer. The change in the cutting force components acting on the workpiece (measured values) is shown in Figure 2, and the change in the cutting force components acting on the tool (calculated values) is shown in Figure 3. In both figures, it can be observed that the value of each force component increases with increasing feed per tooth, but it is also clear that the growth is not directly proportional: doubling the feed per tooth shows a smaller increase in each force component, and the force components also change differently compared to each other.

This finding is even more illustrative if the minimum and maximum values of the test range are highlighted. A 16-fold increase in the feed per tooth (from f_z=0.1 to 1.6 mm/tooth) causes a 5.6-fold increase in the force component F_x (from 117 *N* to 657 *N*), a 7.7-fold increase in the force component F_y (from 147 *N* to 1138 *N*), a

4.4-fold increase in the force component F_z (from 119 *N* to 522 *N*), a 8.6-fold increase in the force component F_c (from 128 *N* to 1091 *N*), a 4.2-fold increase in the force component F_f (from 86 *N* to 356 to *N*) and a 4.4-fold increase in the force component F_p (from 119 *N* to 522 *N*).

Table 3 – Values of measured and calculated force components

Feed per tooth	Force components					
	Measured			Calculated		
f_z	F_x	F_y	F_z	F_c	F_f	F_p
mm/tooth	*N*	*N*	*N*	*N*	*N*	*N*
0.1	117	147	119	128	86	119
0.2	166	221	152	201	108	152
0.4	247	361	207	337	148	207
0.8	385	616	300	589	209	300
1.2	512	874	398	838	269	398
1.6	657	1138	522	1091	356	522

In the following, the effect of increasing feed per tooth on the change in the components of the specific cutting force also was examined. The specific cutting force gives the energy required to remove a unit volume of chips, so the relationship between the feed per tooth and the energy requirement of face milling can also be explored. The specific cutting force can be calculated as the ratio of the cutting force and the cross section of the chip. The results of the calculations are shown in Figures 4 and 5.

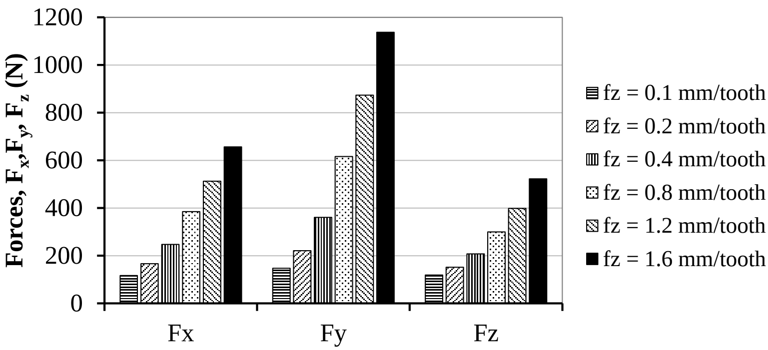

Figure 2 – Measured cutting force components at different feed rates

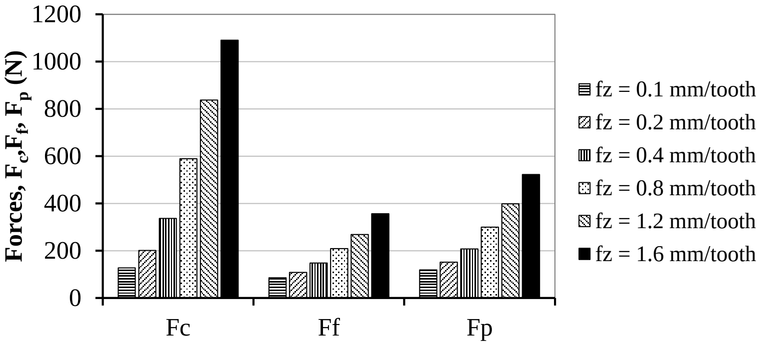

Figure 3 – Calculated cutting force components at different feed rates

From the figures, it can be observed that the value of all specific cutting force components decreases with increasing feed per tooth. Another characteristic of the diagrams is that in the case of f_z<0.4 mm/tooth, this decrease is exponential, while in the case of f_z>0.4 mm/tooth, it can be considered almost linear. Numerically, based on the diagrams, it was found, taking into account the minimum and maximum values of the test range, increasing the feed per tooth by a factor of 16 (from f_z=0.1 to 1.6 mm/tooth) decreased the specific force component k_x to 35% (from 2914 N/mm^2 to 1026 N/mm^2), the specific force component k_y to 48% (from 3677 N/mm^2 to 1777 N/mm^2), the specific force component k_z to 27% (from 2970 N/mm^2 to 816 N/mm^2), the specific force component k_c to 53% (from 3188 N/mm^2 to 1704 N/mm^2), the specific force component k_f to 26% (from 2145 N/mm^2 to 557 N/mm^2) and the specific force component k_p to 27% (from 2970 N/mm^2 to 816 N/mm^2). Also it was found that increasing the feed per tooth causes a decrease in the specific energy requirement. An additional advantage of increasing some cutting parameter values, e.g. the feed rate [14], results in the increasing productivity, which is the major objective of manufacturing processes in the automotive industry [15].

Using our previous research results [16], the effect of the change in the chip cross-section on the force components was examined. In our previous research, the chip cross-section could be determined according to the relation $A_c=a_p{\cdot}f_z=0.8{\cdot}f_z$, in our current research it is $A_c=a_p{\cdot}f_z=0.4{\cdot}f_z$. During the examination of the force components and the specific force components, a ratio number was created, which can be calculated as the ratio of the force values corresponding to the depth of cut a_p=0.8 mm and the force corresponding to the depth of cut a_p=0.4 mm. The results of the calculations are presented in Figures 6 and 7.

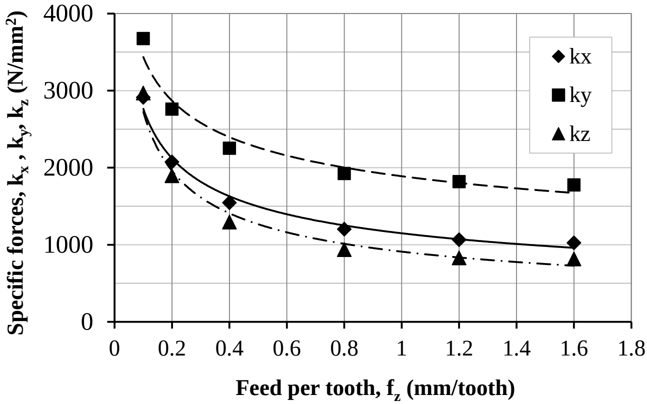

Figure 4 – Specific cutting forces k_x, k_y and k_z at different feed rates

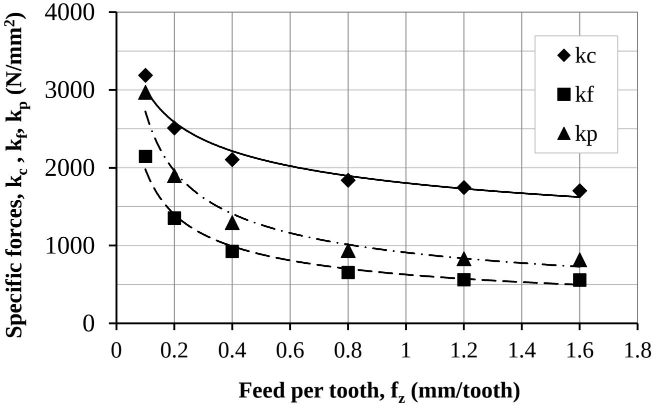

Figure 5 – Specific cutting forces k_c, k_f and k_p at different feed rates

The theoretical chip cross-section doubles are due to the double depth of cut; theoretically, the increase in force is also proportional to this. Based on the experiments, it was found that the ratio for the F_x, F_y and F_c force components is 166–188%, for the F_f force component it is approximately double (197–213%), and for the F_z (which is the same as F_p) force component it is significantly higher (257–304%). It was found that in the case of the tested feed per tooth values, F_x, F_y and F_c force components were 12–34% lower than the theoretical values, and the effect of feed per tooth is not significant. In the case of the ratio of the F_z force component, however, a significant increase was experienced, which decreases with the increase in feed per tooth. Examining the specific force components, higher values can also be observed in the case of the ratio of the k_z component (129–152%). An increase in feed per tooth caused a decrease in the ratio of the specific force component.

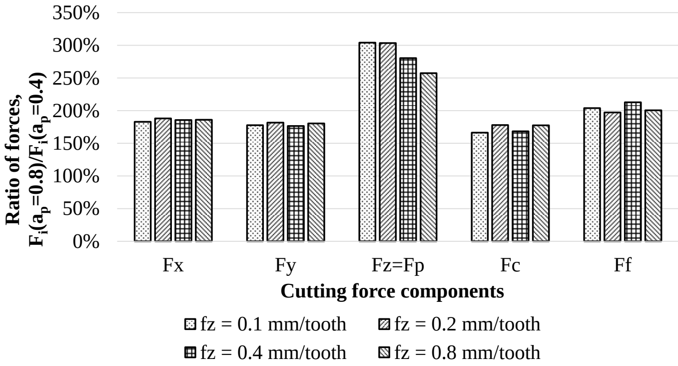

Figure 6 – Ratio of force components at different feed rates

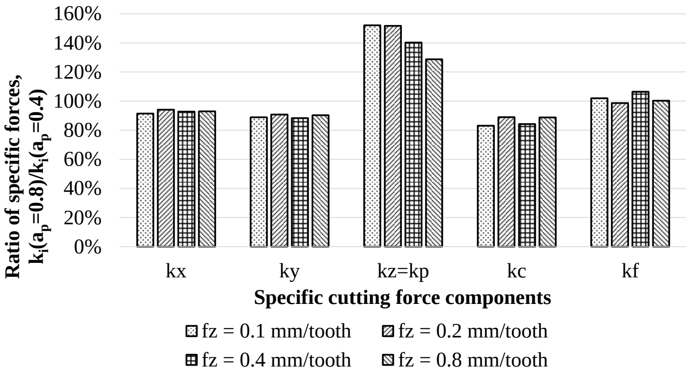

Figure 7 – Ratio of specific force components at different feed rates

4. CONCLUSIONS

In this study, a face milling experiment with an octagonal insert and its results were presented. Among the cutting data, only the feed per tooth was changed and six different values were set between 0.1 and 1.6 mm/tooth. After evaluating the experimental results, the following conclusions were made:

- By increasing the feed per tooth, the value of each force component increased.
- This increase is not directly proportional. Doubling the feed per tooth showed a smaller increase in each force component.
- The force components also changed differently compared to each other.
- Increasing the feed per tooth by 16-fold (from f_z=0.1 to 1.6 mm/tooth) caused a 4.2–8.6-fold increase in the force components.
- By increasing the feed per tooth, the value of the specific cutting force components decreased. This decrease is exponential in the case of f_z<0.4 mm/tooth, while it can be considered almost linear in the case of f_z>0.4 mm/tooth.
- Increasing the feed per tooth by 16-fold caused a decrease in the specific force components to 26–53%, that is, increasing the feed per tooth caused a decrease in the specific energy requirement.
- Using our previous research results, it was found in the test range that for the F_x, F_y and F_c force components, the values of the depth of cut were 12–34% smaller than the theoretical double values, and the effect of the feed per tooth is not significant. In the case of the ratio of the F_z force component, on the other hand, there was a significant increase, which decreased with the increase in feed per tooth. In terms of specific force components, a higher ratio (129-152%) in the case of the k_z component was also observed. An increase in feed per tooth caused a decrease in the ratio of the specific force component.

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ТОРЦЕВЕ ФРЕЗУВАННЯ СТАЛІ ВОСЬМИГРАННОЮ ПЛАСТИНОЮ

Анотація. *Торцеве фрезерування часто використовується для створення плоских поверхонь, тому що при використанні його в якості чистової обробки можна досягти відповідної шорсткості поверхні, виконавши зазначені вимоги до розмірів та допусків. Крім того, висока продуктивність може бути досягнута за рахунок вибору відповідних параметрів процесу різання. Режими різання також впливають на силу різання та знос інструменту, і ще одне міркування полягає в тому, що вібрації, що виникають, можуть погіршити мікрогеометрію поверхні. Для торцевого фрезерування доступні пластини кількох форм. Експерименти проводилися з фрезерною головкою, оснащеною одинарною восьмигранною пластиною-вставкою. Ефект збільшення подачі на зуб досліджувався через компоненти сили різання при фіксованих швидкості та глибині різання. Додаткові параметри налаштування, що впливають на силу різання (швидкість різання та глибина різання), задавалися постійними в діапазоні параметрів, рекомендованих виробником фрезерної пластини. З експериментів встановлено, що за рахунок збільшення подачі на зуб збільшувалося значення кожної складової зусилля. Це збільшення не є прямо пропорційним. Подвоєння подачі на зуб показало менше збільшення кожної складової зусилля. Складові сили по-різному змінювалися в порівнянні один з одним. Збільшення подачі на зуб у 16 разів (від f_z=0,1 до 1,6 мм/зуб) призвело до збільшення складових зусиль у 4,2–8,6 разів. При збільшенні подачі на зуб зменшувалась величина питомих складових сили різання. Це зменшення носить експоненційний характер у разі f_z<0,4 мм/зуб, тоді як у випадку f_z>0,4 мм/зуб його вважатимуться практично лінійним. Збільшення подачі на зуб у 16 разів спричинило зниження питомих складових сили до 26–53 %, тобто збільшення подачі на зуб спричинило зниження питомої енергоємності. Використовуючи результати попередніх досліджень, у діапазоні випробувань було встановлено, що для силових складових F_x, F_y та F_c значення глибини різання були на 12–34 % меншими від теоретичних подвійних значень, а вплив подачі на зуб значення не має. З іншого боку, у разі складової сили F_z спостерігалося значне збільшення, яке зменшувалося із збільшенням подачі на зуб. За питомою складовою сили також спостерігалося більш високе співвідношення (129-152 %) у разі k_z-складової. Збільшення подачі на зуб викликало зменшення відношення питомої складової сили різання.*

Ключові слова: *торцеве фрезерування; восьмикутна вставка; подача на зуб; сили різання; питомі сили різання.*