Effect of Cutting Feed and Chip Size Ratio on Cutting Force

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Abstract. In producing parts, besides increasing accuracy and maintaining/improving the cut surface quality, the main effort of the manufacturers is to improve the productivity/profit. In face milling this aim can be achieved first of all by increasing cutting speed and feed. The importance of feed impact analysis is justified by the general effort to prefabricate parts near net shape, if possible by one pass material removal. If the manufacturing is done by one pass, the surface rate (A_w, mm^2/min) can be increased by the increase of feed. It f_z feed is increased, the feed per tooth (keeping a_p at constant value) a_p/f_z ratio is changed and as a consequence also the load on cutting edges and the character of chip deformation. The increase in the feed and the change in the chip cross section shape influence the cutting forces and the efficiency. In this paper, the changes in the cutting force components with different feed rates are demonstrated, while the value of the feed is increased 16-fold.

Introduction

Face milling is a widely applied machining method with high efficiency [1, 2]. The rotation shaft of the tool is perpendicular to the machined surface and performs rotating motion at circumferential velocity v_c (m/min). The workpiece performs rectilinear feed motion at feed rate v_f (mm/min). As a result of this, each point of the tool edge describes a looped epicycloid. The chips forming under the influence of v_c and v_f have different chip cross sections; however, the difference is often small between the minimum and maximum (A_{cmin}, A_{cmax}) chip cross section. In general, it depends on the diameter of the milling tool and the width of the surface to be machined as well as on the positions of the "central lines" relative to each other (central line in identical position, large diameter, small width – nearly constant cross section).

The literature shows that face milling has not lost any of its importance [3]. The efficiency of machining – similarly to other types of cutting – is numerically expressed by the material removal rate Q_w (mm^3/min) and surface removal rate A_w (mm^2/min). An increase in efficiency can be achieved by increasing v_c and/or v_f. The cutting speed was continuously raised (high speed cutting), but its value is limited by the cost effectiv cutting speed. The increase of v_f also has limits depending on several factors, for example the positioning of the insert in the tool head, its edge geometry, ensuring the prescribed roughness, etc.

The investigation of the effect of the feed rate and feed per tooth f_z is important also because in case of a small allowance (near net shape) and one machining pass material removal – which is in ever higher demand – the surface removal rate A_w (mm^2/min) can be increased. By increasing f_z – with constant depth of cut a_p – co–medium chip thickness h_m increases and the a_p/f_z ratio changes. As a consequence, several cutting parameters significantly change and so do the cutting forces. Some researchers wish to achieve such a high increase in feed that a_p/f_z relation will be smaller than 1 ("inverse cutting") [4, 5].

Naturally, because of the multi-edge formation, the axial and radial run-out of insert [6] and their impact on stability is also an important question. The face milling of hardened steel by minimal cooling is discussed in [7], while the milling parameters optimal to minimum residual stresses are determined in [8]. The machining shortcomings of face milling are analysed in [9], while the deviation of milled surfaces from the plane is investigated in [10]. Tool wear from the point of view of tool-life and surface roughness is examined in [11].

Several recent studies deal with the simulation of forces emerging in face milling, e.g. [12]. On the basis of FEM simulation of forces emerging by throwaway inserts with different edge geometries, it was found that the geometrical relations of entry significantly affect the emerging forces and the dynamic relations of the process. The prevention of flash formation occurring in the milling of stainless steels has been analysed [13], while vibration phenomena emerging in the milling of discontinued surfaces is examined, and possible ways of avoidance are suggested in [14]. The milling of compound materials (integration of 2 or more different materials) is investigated in [15] The choice of the optimal tool for different materials is problematic.

It is clear from the works cited here that face milling has not lost any of its importance. Its output and parameters are investigated and studied in order to increase its efficiency and to improve its quality.

Experiments

The experiments were performed with radius insert by finish face milling. The aim was to examine how the change of the chip size ratio influences the components of cutting force. The experiments were done with 1 insert, applying 5 different feed per tooth f_z values (Table 1). Thus, the chip size ratio (the shape of the chip cross section, the a_p/f_z ratio) was changed, keeping the depth of cut constant (a_p=0.4 mm). The a_p/f_z ratio varied from 4 to 0.25 in 5 grades. Continuous force measurement was done while machining, and the values of components F_x, F_y and F_z were recorded.

Table 1 Feed values and chip size ratios during the experiments

Sequence number	f_z mm/tooth	a_p/f_z figure	a_p/f_z	A_c mm^2	v_f mm/min
1	0.1		4	0.04	79.58
2	0.2		2	0.08	159.15
3	0.4		1	0.16	318.31
4	0.8		0.5	0.32	636.62
5	1.6		0.25	0.64	1273.24

Machine tool: Perfect Jet MCV-M8 vertical machining centre

Tool: Sandvik R215.44-15T308M-WL GC4030 coated carbide insert. κ_r=90°; γ_o=0°; α_o=11°; r_ε=0.8 mm

Milling head type: Sandvik R252.44-080027-15M face milling head, D_s=80 mm

Workpiece: Normalised C45 (1.0503) carbon steel, HB 180; width of the machined surface 58 mm; length: 50 mm.

Cutting data:
cutting speed: v_c=200 m/min
rotation number: n_s=795.77 1/min
width of cut: b_w=58 mm
depth of cut: a_p=0.4 mm
feed per tooth: f_z=0.1-1.6 mm (Table 1)

Force measuring instrument and its accessories:
- 9257A dynamometer with 3 components, made by Kistler
- 5011A charge amplifier, made by Kistler, 3 pieces
- CompactDAQ-9171 data collector with 4 channels, made by National Instruments
- Measurement software, made by LabView programming language

Evaluation and Discussion

The forces arising in machining by rotating tools were measured in a coordinate system attached to the workpiece. Because the cutting forces are interpreted in a coordinate system attached to the tool edge, the forces diverge from F_c, F_f, F_p forces. The forces measured in milling – F_x, F_y and F_z – equal them only in determinated, special cases.

Results of force measurement experiments

Figure 1a demonstrates the cutting forces and their change in a cutting period that is in the removal of a single chip. On the basis of the sizes of the workpiece and the tool, $\varphi_1 = 43.53°$ and $\varphi_2 = 136.47°$.

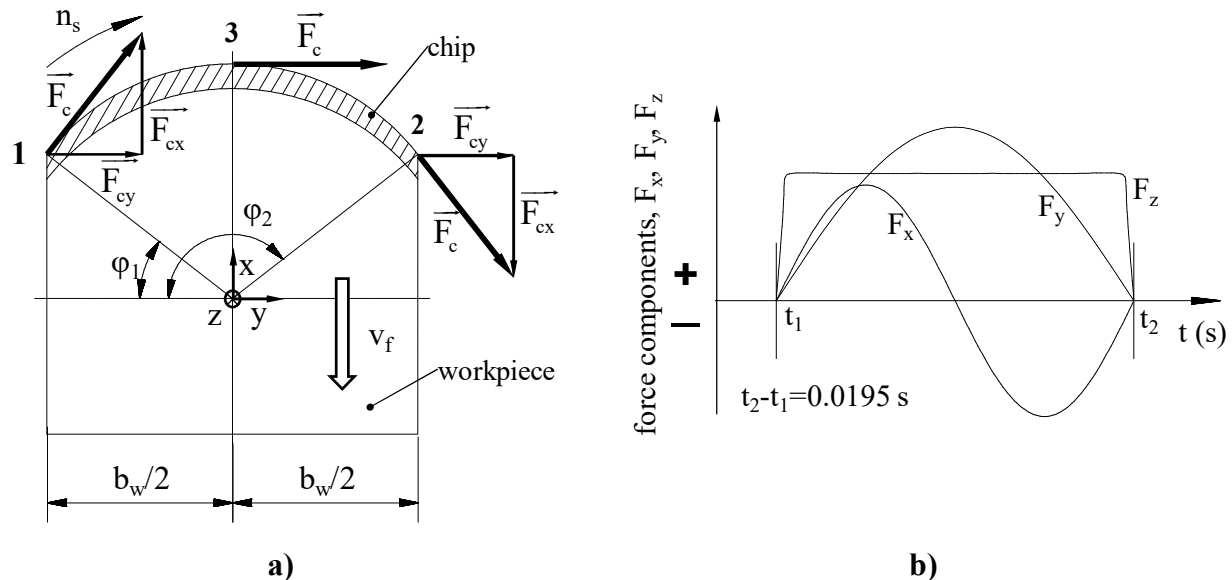a)   b)

Figure 1 Interpretation of the cutting forces: a) Change of components as function of the swivel of the tool and b)Theoretical characteristic curve of force components as a function of time

The coordinate system of the dynamometer is marked in Figure 1a where the measured force components are interpreted. On the basis of Figure 1a the theoretical scheme of the change of forces F_x, F_y, F_z can be drawn as a function of cutting time (Figure 1b).

During the experiments recordings were added as it can be seen in Figure 2. It is clearly visible that the cutting took a shorter time, during one rotation, as a function of only the width of the workpiece. The curves depicted in the angle of swivel are symmetrical, the character of their changes is formed by the motion relation resulting in a looped cycloid, the dynamics of the chip removal, the small chip cross section etc.

Figure 2 also demonstrates how the defined cutting forces change in the coordinate system attached (Figure 2b). Figure 3 represents the effect of feed changes on forces F_x, F_y, F_z. At the two smallest feeds (big a_p/f_z ratio) the values of F_z are the highest among the three measured force components.

Upon further increasing the feed the values of F_y exceed those of F_z. This difference grows nearly two-fold at $f=1.6$ mm feed. The value F_z is nearly constant in a given range at each feed. The value of F_z increased more than three-fold (550 N) from 165 N in the examined feed range. The value of F_y is the local maximum.
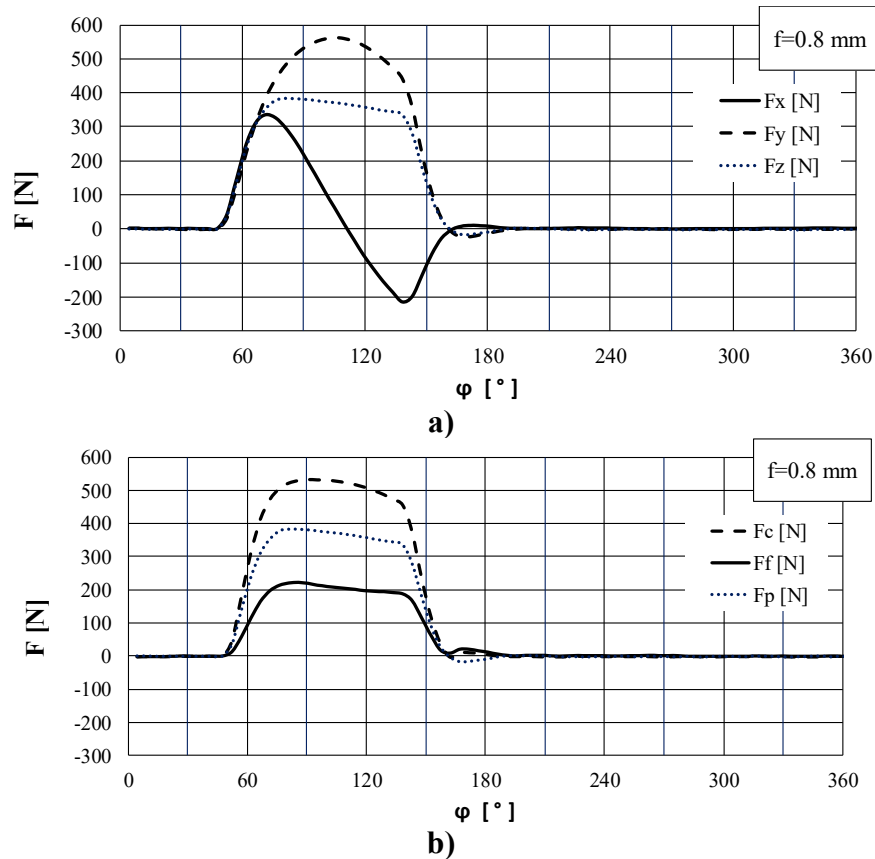
Figure 2 Change of force components during one tool rotation: a) in the coordinate system of the workpiece and b) in the coordinate system of the tool

The rotational motion of the insert has the strongest effect on F_x. Because in direction x the force components change direction, F_x also has negative values. The extension of this latter negative value range and its values grow with the increase of feed.

Figure 4 summarises the changes of maximum values of force components F_x, F_y, F_z. It can be stated that under the influence of feed increase, the cutting forces increase nearly linearly. The machining time decreases to nearly 6 %, while the force $F_{c,max}$ needed to remove a unit of cross section decreases to half. At the same time the removed volume increases 16-fold, while the cutting force increases only 8.2-fold.

Summary

By increasing the feed in the examined range the surface removal rate proportionally increased 16-fold. As the depth of cut was constant, with increasing f_z the ratio of a_p/f_z also proportionally decreased. As a consequence, the exploitation of the main and subsidiary edge changed. The cutting forces measured in the coordinate system of the workpiece increased, their relation to each other changed. Because their maximum value grew nearly linearly, the increase of feed requires a highly stiff machine tool if it is performed by a constant machining pass.
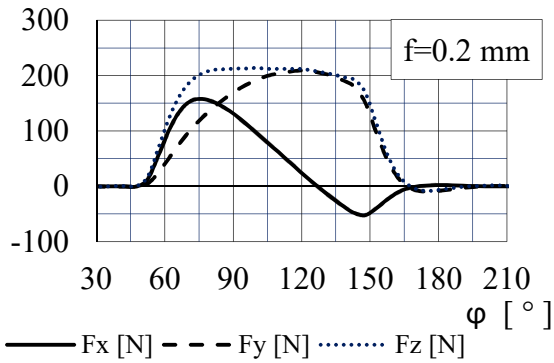Further investigation is planned to define the ratio of a_p/f_z with which a lower scale increase in cutting force and proportional efficiency proportional can be achieved.
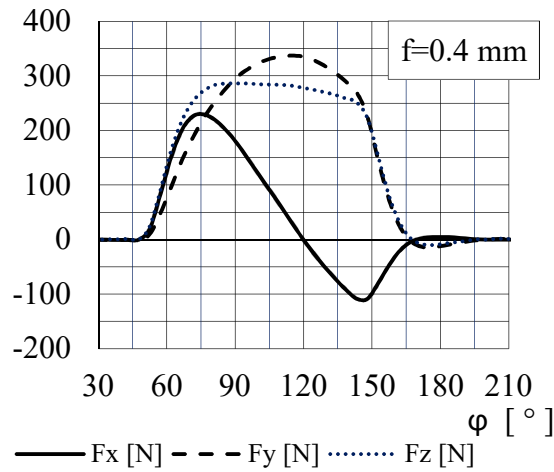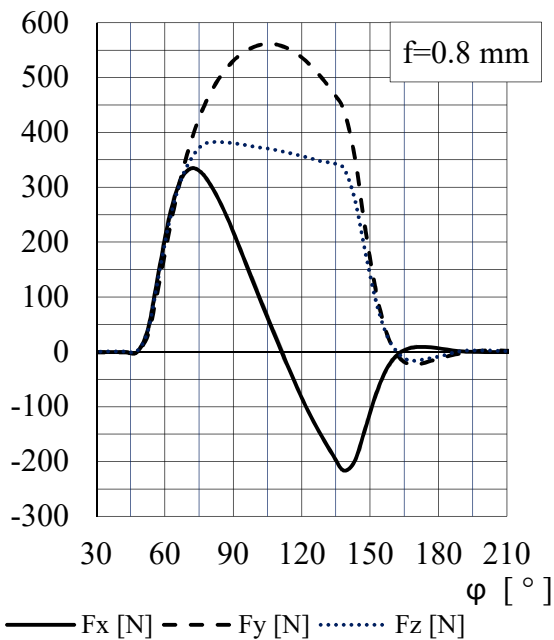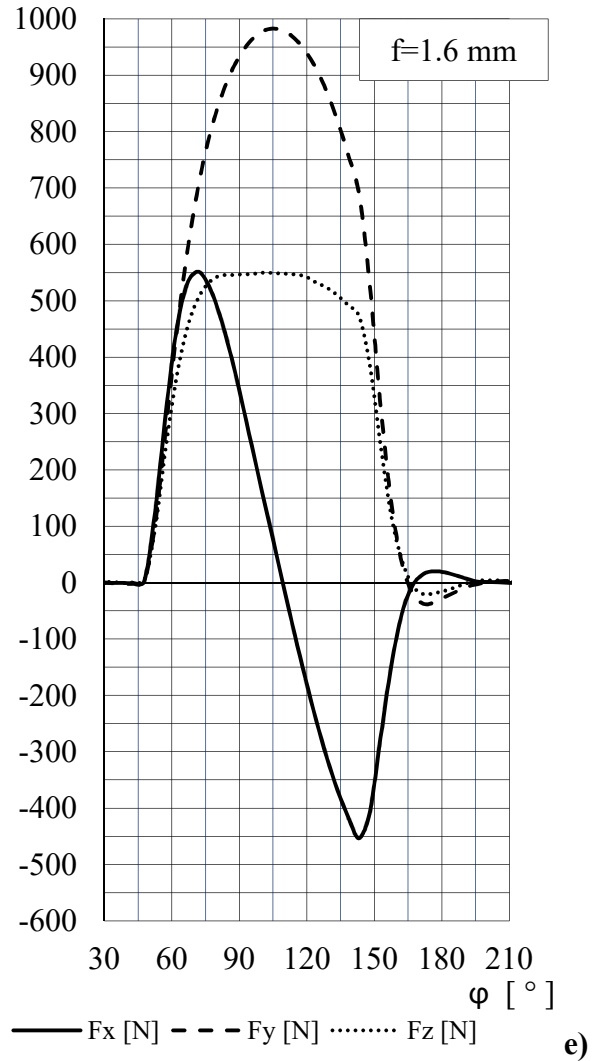
Acknowledgement
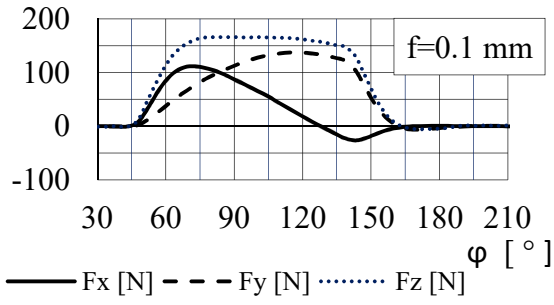
a)

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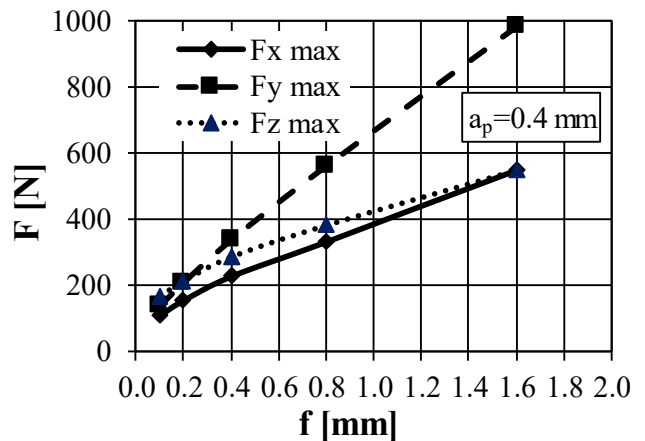**Figure 3** Changes in force components during one rotation of the tool

Figure 4 Changes in the maximum of force components as a function of feed

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