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## **INVESTIGATION OF CUTTING FORCE IN FACE MILLING**

*The increase of cutting applied in finishing processes can be achieved first of all by increasing the cutting speed and feed. In face milling, if feed  $f_z$  per tooth is increased and/or the shape of the chip cross section is changed, the load of the cutting edges changes and influences the cutting forces and the actual efficiency. In this paper, the cutting force arising in chip removal and changing under the influence of the increased feed is analysed.*

### **1. INTRODUCTION**

There are plane surfaces in almost all fields of the machine industry. A significant proportion of the surfaces of parts are plane surfaces, therefore the efficiency of their machining is of highlighted importance in the production process. Different milling variations have emerged that follow the versatility of workpiece geometry.

In producing parts – and also in the machining of plane surfaces – the main goals of manufacturers are to improve productivity, increase the accuracy and maintain/improve the surface quality. Nowadays the improvement in modern manufacturing technologies (turning, injection moulding, etc.) has a relevant role in Industry 4.0 because the satisfaction of the expanding and more unique customer needs requires the elaboration of new solutions [1, 2]. The timeliness of the feed investigation comes from the ever smaller allowance of pre-fabricants and the ever more frequent material removal in one clamp. In these cases, the increase of feed is an important factor in efficiency improvement.

Face milling is a widely used type of cutting machining [2]. The face milling cutter performs main rotational motion by peripheral speed  $v_c$ , its revolution axis is perpendicular to the machined surface. The collated motion is done by the workpiece, which is a rectilinear motion by feed rate  $v_f$ . As follows from kinematics, each point of the tool edge inscribed a looped epicycloid.

The chip cross sections change because of the joint influence of  $v_c$  and  $v_f$ . The removal is done by the major cutting edges on the plane surface, but also the minor cutting edges located in the face plane play a role in the forming of the machined surface.

Similarly to other cutting machining, the efficiency of the machining is analysed numerically by material removal rate  $Q_w$  ( $\text{mm}^3/\text{min}$ ) and surface rate  $A_w$  ( $\text{mm}^2/\text{min}$ ). An increase in surface rate, at a constant depth of cut, is possible by increasing cutting speed and feed.

In industrial practice, increasing cutting speed has its technical limits when considering economical tool life - machine tools have low reserves regarding the number of revolutions of the spindle. The increase of the feed rate is only made possible by suitable tool geometry.

With the increased feed rate the shape of the chip cross section ( $A_c$ ) also changes, which influences the cutting forces and the roughness of machined surface too. By increasing  $f_z$  feed per tooth – with constant depth of cut  $a_p$  –, the medium chip thickness  $h_m$  increases and changes the  $a_p/f_z$  ratio. As a consequence, several cutting technical parameters change, too, among them the cutting forces. Some researchers aim to reach feed increase of such a scale that the ratio  $a_p/f_z$  relation will be smaller than 1 (“inverse cutting”) [4, 5].

## 2. THE CHANGE OF CUTTING FORCE IN FACE MILLING

In the experiments, the measurement of cutting forces can be done by a force measuring platform connected either to the workpiece or to the tool.

The measured forces and their change (in a coordinate system attached to the workpiece) in one cutting period, that is during the removal of one single chip, can be seen in Figure 1a. The tool edge cuts during one rotation of the milling head, covering its route under the points 1 and 2. The figure shows the cutting force coordinate system in which the measured force components ( $F_x$ ,  $F_y$ ,  $F_z$ ) 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).

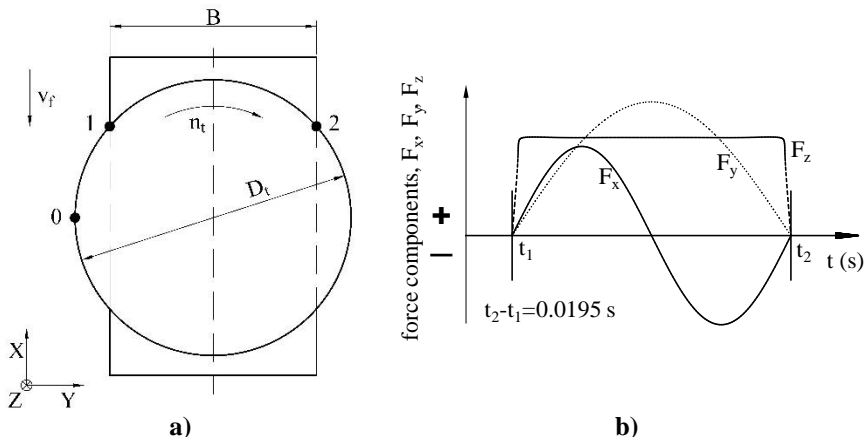


Figure 1 – Interpretation of the forces influencing the workpiece as a function of the swivel of the tool (a) and the theoretical characteristic curve of force components as a function of time (b) in the coordinate system of the dynamometer

The measured values – depending on the formation of the measuring system – are interpreted either in the coordinate system connected to the workpiece ( $F_x, F_y, F_z$ ), or in the coordinate system connected to the tool edge ( $F_c, F_f, F_p$ ). Therefore, these forces differ and are only equal in a determined, special case.

In our case the dynamometer corresponds with force components  $F_x, F_y$  and  $F_z$  (a coordinate system attached to the workpiece). Because the cutting force and its components are interpreted in a coordinate system attached to the tool edge, force components  $F_c, F_f$ , and  $F_p$  differ from the measured force components  $F_x, F_y, F_z$ . The conversion is given in Figure 2.

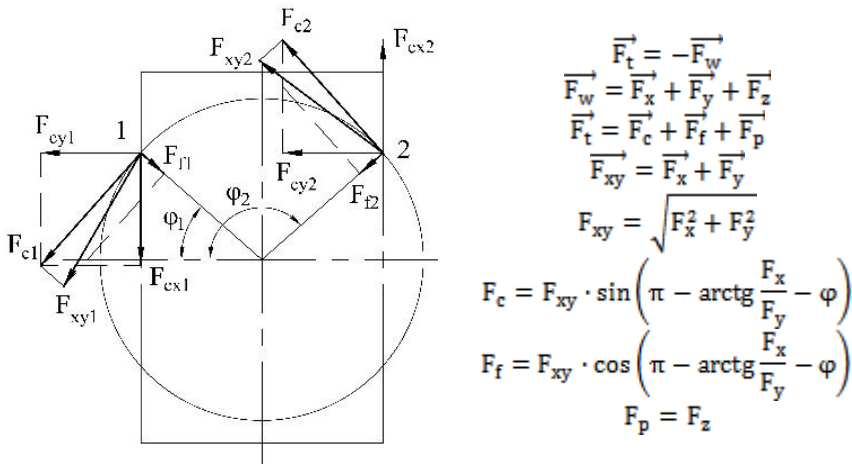


Figure 2 – The interpretation and conversion of cutting force components

### 3. EXPERIMENTS

The experiments focus on how the change of feed and the chip size ratio influences the cutting force components given a constant depth of cut.

#### 3.1. Experimental conditions

The experiments were done under the following conditions. The data of the workpieces: normalised C45 (1.0503) carbon steel, HB 180; width of the machined surface 58 mm; length: 50 mm. The type of the milling head: Sandvik R252.44-080027-15M face milling head,  $D_s=80$  mm. Insert: Sandvik R215.44-15T308M-WL GC4030 coated carbide insert.  $\kappa_r=90^\circ$ ;  $\gamma_o=0^\circ$ ;  $\alpha_o=11^\circ$ ;  $r_e=0.8$  mm. Machine tool: Perfect Jet MCV-M8 vertical machining centre.

One insert was clamped in the milling head. Five different values of feed  $f_z$  were set (Table 1), allowing the chip size ratio (shape of the chip cross section  $a_p/f_z$  ratio) to be changed, too, while keeping the depth of cut constant ( $a_p=0.4$ mm).

(width of cut  $b_w=58$  mm and depth of cut  $a_p=0.4$  mm are constants). The  $a_p/f_z$  ratio varied from 4 to 0.25 in 5 grades.

Table 1 – Data of cutting experiment

No	$v_c$ m/min	$a_p$ mm	$f_z$ mm/tooth	$a_p/f_z$ ratio	$A_c$ mm <sup>2</sup>	$v_f$ mm/min
1	200	0.4	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

During the machining, the force measurement was continuous (Figure 3), while recording the values of components  $F_x$ ,  $F_y$  and  $F_z$ .

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

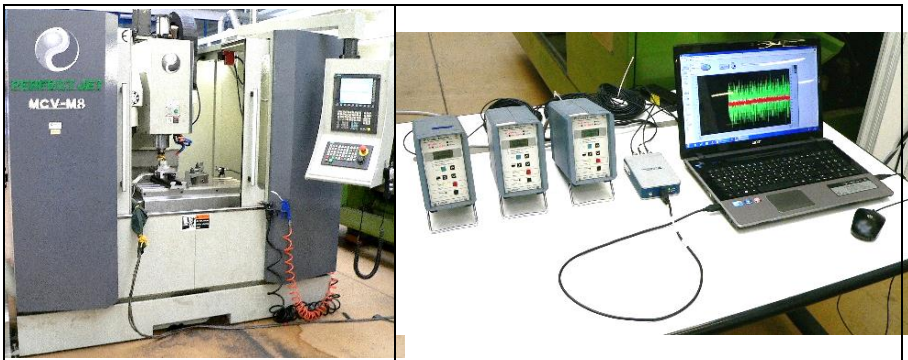


Figure 3 – Workplace for experiments

### 3.2. Results of experiments

Figures 4-5 show the results of measurement. Figure 4 gives the change of force during one roll of the milling head. It can be seen that the cutting during one roll, as a function of the width of the workpiece and also the diameter of the tool, takes a shorter time (on the basis of the sizes of the workpiece and the tool  $\varphi_1=43.53^\circ$  and  $\varphi_2=136.47^\circ$ ). Illustrating the curves in the angle of the turn, the character of its change is formed by the motion relation resulting in looped cycloid, the dynamics of the chip removal, etc.

The change in  $F_x$  is influenced mostly by the rotating motion of the insert. In direction  $x$ , in the feed direction of the tool shaft (in our case it is equal with the symmetry plane of the workpiece), the force components with  $x$  direction also change direction; therefore,  $F_x$  will have negative value too. Practically till the middle of the plane the milling goes in one direction and then the opposite direction.

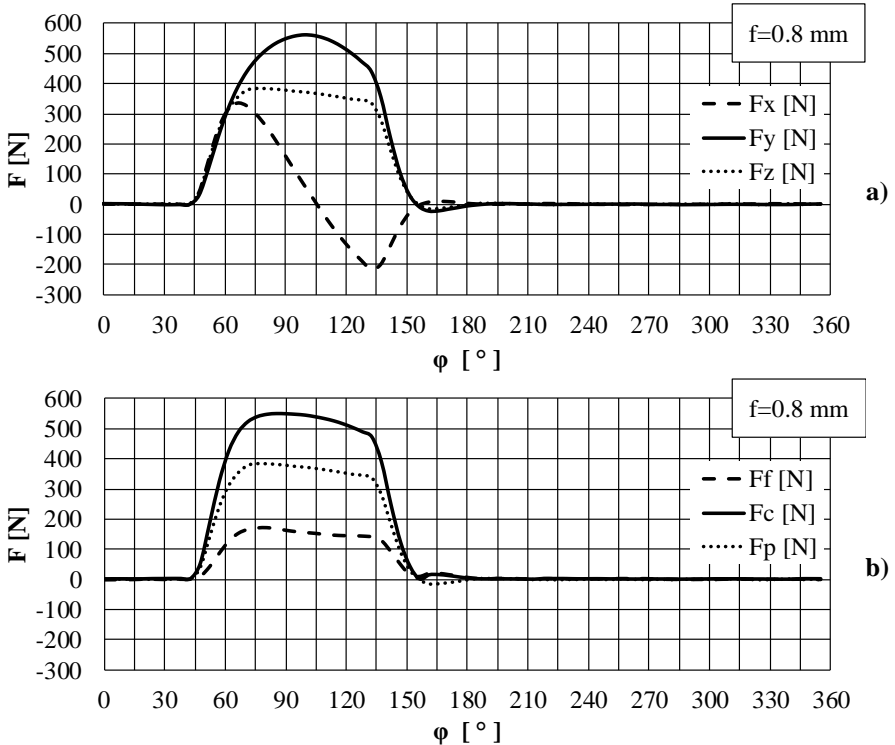
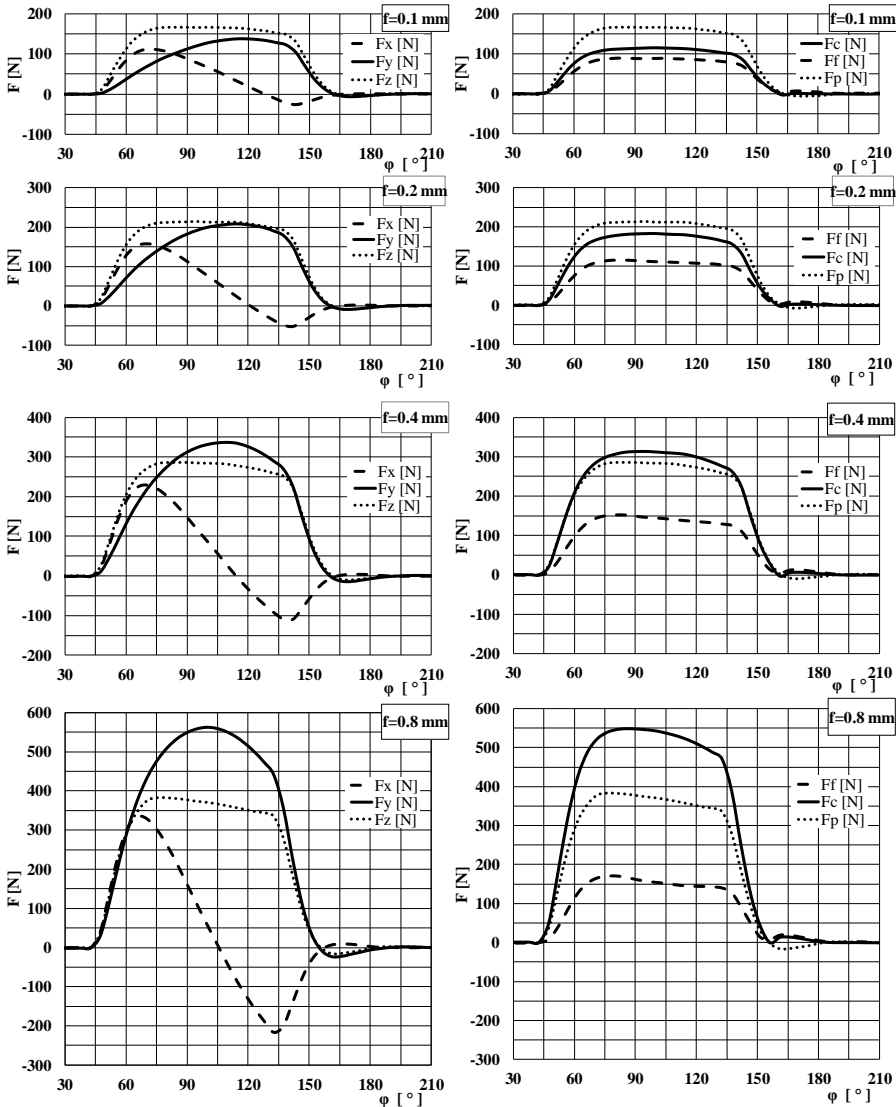


Figure 4 – Change of force components  $F_x$ ,  $F_y$ ,  $F_z$  (a) and cutting forces  $F_c$ ,  $F_f$ ,  $F_p$  (b) during one tool rotation around

In Figure 4b the cutting forces  $F_c$ ,  $F_f$  and  $F_p$  are demonstrated calculated from the measurements, and also their change as a function of the turn of the milling head.

The figure shows that the cutting forces change relatively little in the whole stage of the chip cross section removal. The changes that can be seen in Figure 4a and 4b are in connection with the kinematics of face milling.

In Figure 5 the cutting edge is demonstrated with different values of feed, as are the measured and calculated force values for the stage of the turn where the cutting edge does material removal.



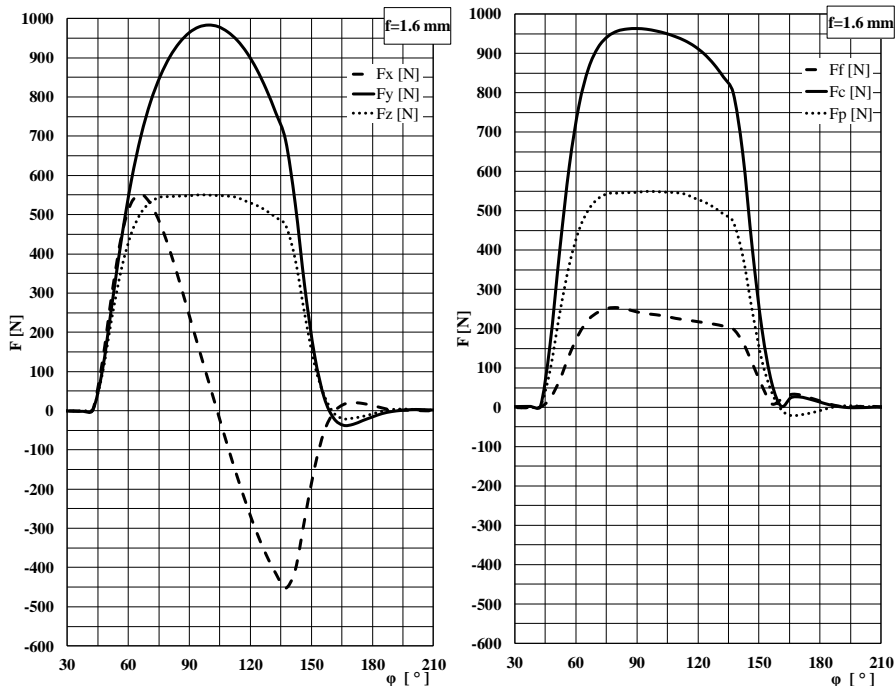


Figure 5 – Change of force components during one rotation of the tool

The character of the change of all three force components is the same in each feed, analysing the change of either  $F_x$ ,  $F_y$ ,  $F_z$  or  $F_c$ ,  $F_f$ ,  $F_p$ .

Among the three measured force components the values of  $F_z$  are the highest at the two smallest feed rates (with high ratio  $a_p/f_z$ ). Further increasing the feed, the values of  $F_y$  exceed the values of  $F_z$ . This difference grows almost to its two-fold with feed  $f=1.6$  mm. The value of  $F_z$  in a given domain is of an almost constant value with each feed. The value of  $F_z$  grows almost three-fold, from 165 N to 550 N, in the examined feed domain.  $F_y$  takes the local maximum value.

The change  $F_x$  is of negative value, because the components change direction in x direction. The extent of this latter domain of negative value and its values grow with the increase in the feed.

Values of  $F_c$ ,  $F_f$ ,  $F_p$  forces are nearly constant in the stage where the cutting edge removes a whole chip cross section. The cutting forces are only nearly constant because of the change of the motion track of the tool edge, also the momentum values of the resulting motion, and the chip cross section. The curve is not symmetrical with the middle plane.

The value of  $F_c$  grows proportionally with the increase of feed ( $8\times$  feed increase increases the value of  $F_c$  more than eight-fold);  $F_p$  has got the highest

value with the smallest feed value, the size of its increase is four-fold, while the value of  $F_f$  is the smallest with each feed and the size of the increase is also the smallest.

Analysing the maximum values of force components  $F_x$ ,  $F_y$ ,  $F_z$ , it was found that the maximal measured and calculated forces are equal. Under the influence of the feed increase the cutting forces increase nearly linearly. The machining time decreases to nearly 6 %, while force  $F_{c,max}$  needed to remove the cross section of a unit decreases by half. At the same time, the removed volume increases sixteen-fold, while the cutting force increases only 8.2-fold.

#### **4. CONCLUSION**

In this paper, the cutting forces characteristic of face milling are examined. The changes in their values are demonstrated in the process of chip removal as a function of the angle of the tool turn. The change is measured both in a coordinate system connected to the workpiece (also complying with the measuring system) and in a coordinate system connected to the tool edge.

It is ascertained that the maximum values of the forces interpreted in the two coordinate systems are nearly the same. By increasing the feed, the cutting forces increase and their ratio to each other also changes.

#### **ACKNOWLEDGEMENTS**

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