

Analysis of the Effect of Feed on Chip Size Ratio and Cutting Forces in Face Milling for Various Cutting Speeds

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Face milling is one of the most common machining processes used for the production of high quality flat surfaces. Another important feature of the process is the high material removal rate that can be achieved, or in the case of milling performed at one pass, the high surface rate. Surface rate is increased by increasing feed and cutting speed; both are bound by technological limitations and are limited to rather small variations, especially cutting speed. In finishing face milling, if feed per tooth is increased, subsequently the shape of the chip cross section is altered. This results in the change of the loads of the cutting edges, which influences the cutting forces and process efficiency. In this study, an experimental investigation is carried out in order to determine the influence of feed on chip size ratio. For this purpose, five different values of feed, at two different cutting speeds are tested for face milling. It is concluded that an increase in feed from 0.1 to 1.6 mm results in eight-fold increase of cutting force F_c while surface rate proportionally increases 16 times and specific cutting force only 0.5 times.

Keywords: face milling, cutting forces, feed rate, chip size ratio, force measurement, high speed machining, material removal rate, surface rate

1 Introduction

Manufacturing of high-end parts is usually accomplished through machining, in modern industry [1]. One of the most productive and effective processes for flat surfaces is face milling, due to its ability to remove material from the workpiece at high rates and at the same time achieve excellent quality of the machined part [2, 3]. Because of the aforementioned characteristics, face milling has been the main subject of many researches; the focal topics of research pertain to cutting forces estimation, surface roughness minimization and tool wear assessment [4, 5]. With the optimization of the process in mind, both theoretical and experimental works have enriched the relevant literature [6-8]. However, the complicated kinematics of face milling, in comparison to other manufacturing processes, e.g. turning, have rendered the studies more demanding [9, 10]. Experimental works pertain usually to the observation of the influence of cutting parameters on cutting forces and surface quality, tool wear being a common subject as well [4, 11-14].

A further bibliographic review reveals that modelling is commonly employed, either through mathematical or numerical models. Li et al. [7] used Oxley's theory to present mathematical models for the prediction of forces in face milling. Saï and Bouzid [15] also presented a mathematical model for the estimation of surface roughness in up-face milling. Franco et al. [16] employed a geometric model for face milling, while Hadad and Ramezani [17] used mathematical models to produce a Computer Aided Design (CAD) software that is able to evaluate the influence of different milling process parameters on pattern geometry. Soft computing methods are also used by many researchers for the analysis of milling, with the use of neural networks, genetic algorithm and particle swarm optimization techniques [18-21]. Most numerical models

on manufacturing processes in general [22, 23] and face milling in particular [24, 25] are realized through the use of the Finite Element Method (FEM). However, Gylieñ and Eidukynas [26] presented a three dimensional Smooth Particle Hydrodynamics (SPH) model of face milling. Most of the models are able to predict cutting forces and are validated by experimental results.

The analysis of face milling have shown that the parameters that significantly affect the process are the geometrical features of the tool, the tool and workpiece material properties and of course cutting conditions, including the depth of cut, feed rate and cutting speed. More particularly, the combination of high values for the latter parameters leads to high productivity, through the increase of the material removal rate Q_w [mm³/min], with an adverse effect on cutting forces and tool wear. However, with the adoption of near-net-shape manufacturing and the development of prefabrication technologies, the prescribed allowance can be removed by one pass and machining efficiency can be evaluated through the surface rate A_w [mm²/min] achieved; the increase of surface rate is possible at a constant depth of cut a_p [mm] by increasing of cutting speed and feed rate [27]. Note that, the increase of cutting speed has technological limitations in industrial practice. Furthermore, the ever smaller allowance of the pre-fabricants and the ever more frequent material removal in one clamp, qualifies feed rate increase as the most important factor in the efficiency improvement of the process.

Due to the joint influence of feed rate and cutting speed, the chip cross section changes. Material removal is performed by the major cutting edges on the plain surface, but in the forming of the machined surface also the minor cutting edges take part, located in the face plain; the role of these edges is altered, depending on the variation of the feed. It is important to examine the ratio of the

depth of cut and feed per tooth f_z [mm/tooth], i.e. chip size ratio, because by increasing the feed, the shape of the chip changes, and the role of the cutting edges in chip removal changes as well. In the case that $a_p/f_z \gg 1$, chip deformation is predominantly perpendicular to the edge on the outer surface, while in the case of $a_p/f_z \ll 1$, it is perpendicular to the edge on the face of the tool, see Figure 1. In this figure, the experimental procedure and calculations performed are shown; furthermore, the results of a finite element simulation with AdvantEdge software are briefly depicted for the two extreme cases of a_p/f_z in order to illustrate the chip formation variation.

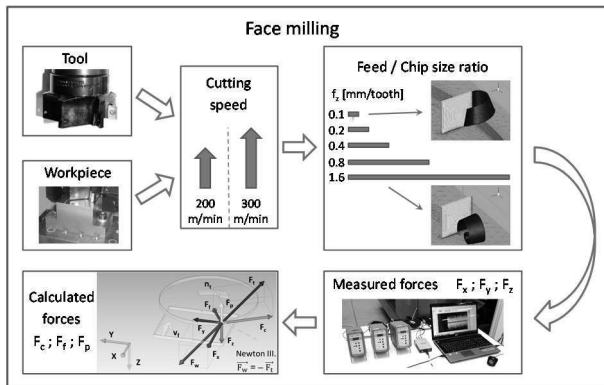


Fig. 1 Experimental work and calculations for face milling.

By increasing feed per tooth f_z , at constant depth of cut a_p , the medium chip thickness h_m increases and as a consequence, several cutting technical parameters change, too, among them the cutting forces. Kunderák and Felhő [28] and Kunderák et al. [8] have shown that the increase of feed rate and the variation of the chip cross-section shape influence the cutting forces and the roughness of the machined surface. In other works, Karpuschewski and Batt [29] and Karpuschewski et al. [30] seek to achieve such a high increase in feed that a_p/f_z ratio will be lower than 1, namely the case of “inverse cutting”.

From the published works found in the relative literature, there are only a few studies that investigate the influence of feed on chip size ratio, especially at different cutting speeds. In the present paper, experimental work is carried out for the evaluation of the effect of feed per tooth on chip size ratio and consequently on cutting forces, in face milling of steel. The analysis is carried out for the forces in the coordinate system attached to the

workpiece, as well as the coordinate system attached to the tool edge, by appropriate conversion between the two systems. As a novelty, the specific cutting forces, i.e. the cutting forces divided by the chip cross section, are considered and useful conclusions are drawn. Finally, the analysis is carried out for two different high cutting speeds, namely 200 m/min and 300 m/min and the results are compared.

2 Experimental work and results

For the realization of the analysis, several experiments were carried out. All the experiments were performed in a Perfect Jet MCV-M8 vertical machining center, supplied with a Sandvik R252.44-080027-15M face milling head of diameter $D_s=80$ mm. The workpiece material was normalized C45 (1.0503) carbon steel of hardness HB 180. Width and length of the machined surface were 58 mm and 50 mm, respectively.

The aim was to examine how the changes of the feed rate influence the components of cutting force, as more intensive cutting parameters lead to an increase in the cutting forces, in general. In other words, given that the depth of cut is constant, the focus of the experiments is the investigation of the influence of chip size ratio variation on cutting force components, at two different cutting speeds. It was chosen to use a milling head supplied with one insert, so that the effect of one cutting edge at the time is evaluated. For the experiments a Sandvik R215.44-15T308M-WL GC4030 coated carbide insert, with $\kappa_r=90^\circ$, $\gamma_o=0^\circ$, $\alpha_o=11^\circ$ and $r_e=0.8$ mm was used. Five different feeds per tooth, commonly used in practice for machining of steel, were selected. Table 1 contains the feeds per tooth, the corresponding chip size ratio, the chip cross-section A_c and feed rate v_f , for the two cutting speeds v_c . For depth of cut 0.4 mm, the chip size ratio decreases from 4 to 0.25, divided by 2 in each experiment.

Forces were measured by a Kistler 9257A dynamometer, with three components, connected to three 5011A charge amplifiers, one for each force component. Furthermore, a CompactDAQ-9171 data collector with 4 channels, by National Instruments was used and measurement software, made by LabView programming language, was employed. With the described configuration, continuous force measurement was possible at 10kHz sampling frequency while machining, and the values of F_x , F_y and F_z components were recorded, as depicted in Figure 2.

Tab. 1 Feed values and corresponding chip size ratios used in the experiments.

No.	f_z [mm/tooth]	a_p/f_z ratio	A_c [mm ²]	v_f [mm/min]	
				$v_c=200$ [m/min]	$v_c=300$ [m/min]
1	0.1	4	0.04	79.58	119.37
2	0.2	2	0.08	159.15	238.73
3	0.4	1	0.16	318.31	477.47
4	0.8	0.5	0.32	636.62	954.93
5	1.6	0.25	0.64	1273.24	1909.86

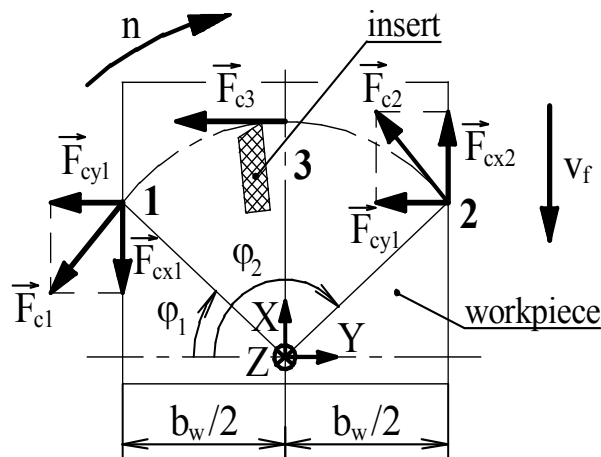


Fig. 2 Coordinate systems and cutting force components.

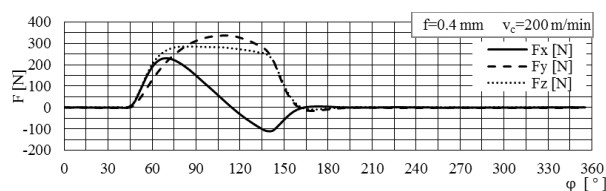
The xyz axes coordinate system is attached to the workpiece and can be measured by the dynamometer. However, cutting force components F_c , F_f and F_p referring to a coordinate system attached on the tool edge, are of particular interest. Due to the kinematics of the insert, the forces from the two coordinate systems are different. Nevertheless, geometrical considerations and analysis of the components of the latter system to axes parallel to the former system, can provide the conversion between the two, e.g. see the analysis of F_c in points 1 and 2, in Figure 2. However, there are specific points that forces of the two systems may coincide, e.g. F_c and F_y at point 3 of Figure 2. The force components for the coordinate system attached to the tool edge were calculated from the measured force components, through the following equations:

$$F_c = F_{xy} \cdot \sin\left(180^\circ - \arctg\frac{F_x}{F_y} - \varphi\right) \quad (1)$$

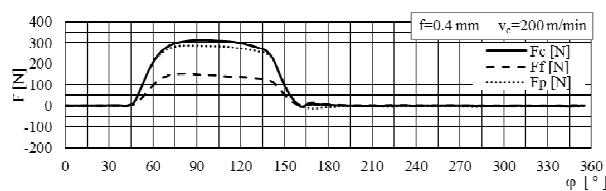
$$F_f = F_{xy} \cdot \cos\left(180^\circ - \arctg\frac{F_x}{F_y} - \varphi\right) \quad (2)$$

$$F_p = F_z \quad (3)$$

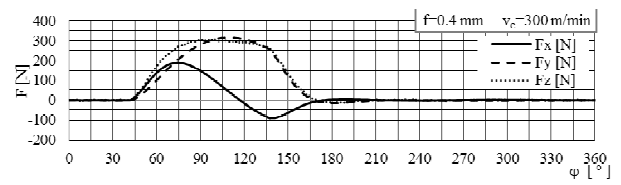
$$F_{xy} = \sqrt{F_x^2 + F_y^2} \quad (4)$$



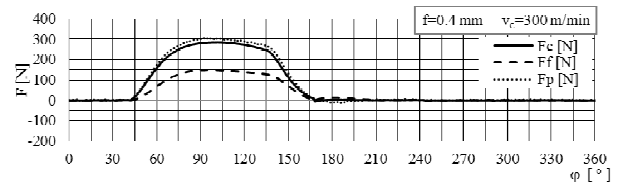
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b)



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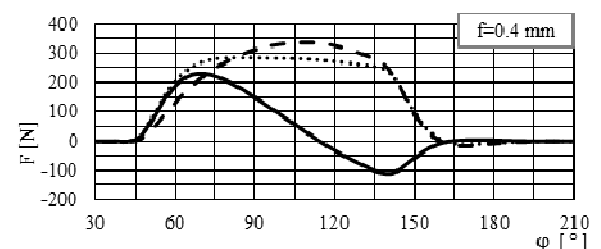
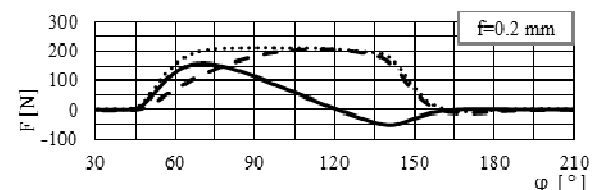
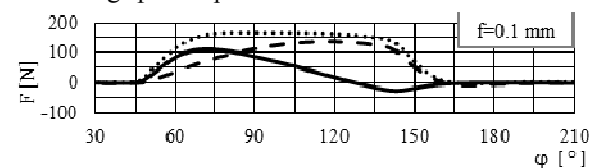


d)

Fig. 3 Cutting forces variation for $f=0.4$ mm/tooth, for a full rotation of the milling head and for coordination system attached to (a) workpiece and (b) tool edge for $v_c=200$ m/min and (c) workpiece and (d) tool edge for $v_c=300$ m/min.

Based on the geometrical characteristics of the experimental set-up, as described in the previous section and with reference to Figure 2, the insert engages the workpiece at angle $\varphi_1=43.53^\circ$ and exits at $\varphi_2=136.47^\circ$, which is also the period where cutting forces are recorded in a full rotation of 360° of the milling head. The variation of the cutting forces for a full rotation of the milling head, for feed 0.4 mm/tooth and cutting speed equal to 200 m/min, for the coordination system attached to the workpiece and the tool edge are shown in Figure 3a and 3b, respectively. The same, but for cutting speed of 300 m/min, is shown in Figure 3c and 3d.

Figure 4a and Figure 4b show the variation of the cutting forces, for cutting speed of 200 m/min and for all the feeds tested, for the coordination system attached to the workpiece and the tool edge, respectively. The graphs are shown in the range between 30° and 210° , as in the other degree ranges no cutting forces are recorded. The same kind of results are shown in Figure 5a and Figure 5b but for cutting speed equal to 300 m/min.



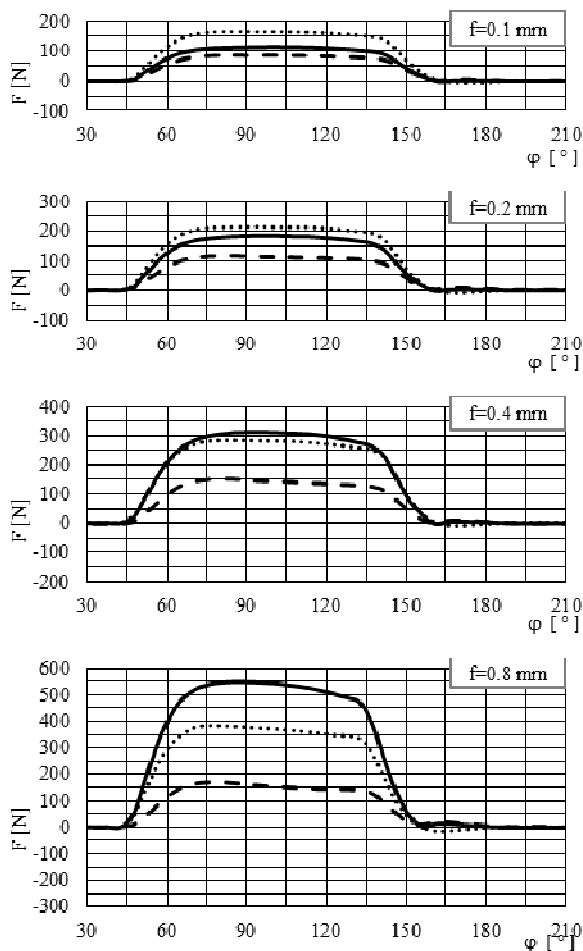
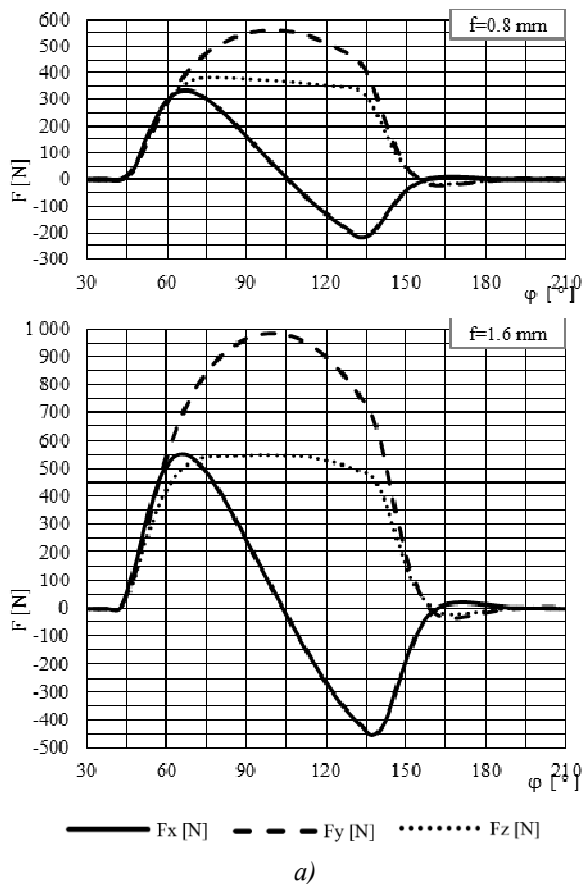
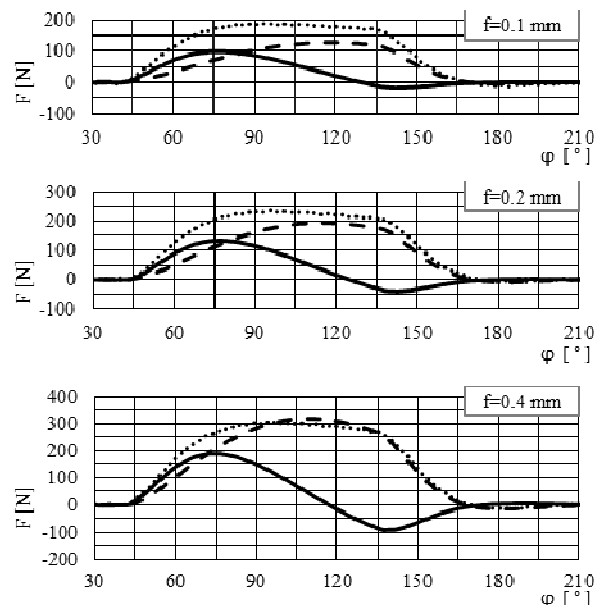


Fig. 4 Cutting forces variation for all tested feeds and $v_c=200$ m/min, for a full rotation of the milling head and for coordination system attached to (a) the workpiece and (b) tool edge.

3 Discussion

From Figures 4 and 5, some interesting discussions can be made. In general, the shape of the graphs for each force component are consistent with the kinematics of face milling and the range of the values are in good agreement with previous results [4]. It is worth noting the influence of the rotational motion of the insert on F_x ; in feed direction of the tool shaft, the force components with x-direction changes direction when passing the symmetry plain of the workpiece. The latter results in positive and negative values of F_x during the same pass, indicating that in the first half of the cutting action of the tool, milling goes in one direction and then in the opposite direction. Figures 4 and 5 indicate that F_c , F_f and F_p vary relatively little in the whole stage of the chip cross section removal. These changes are in connection with kinematics of face milling.



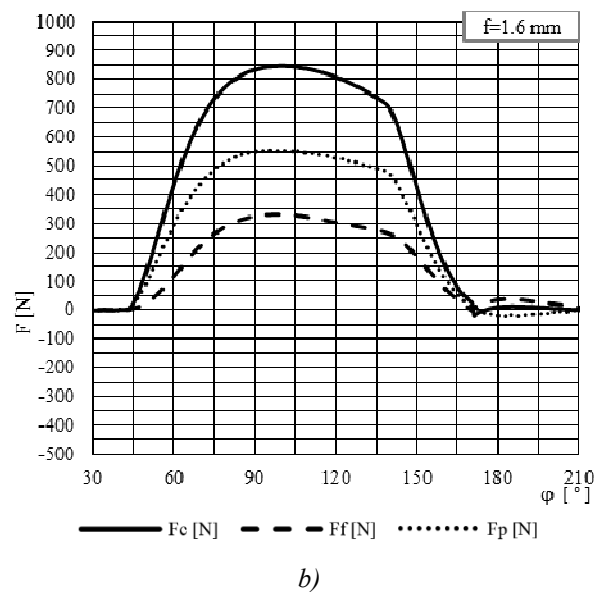
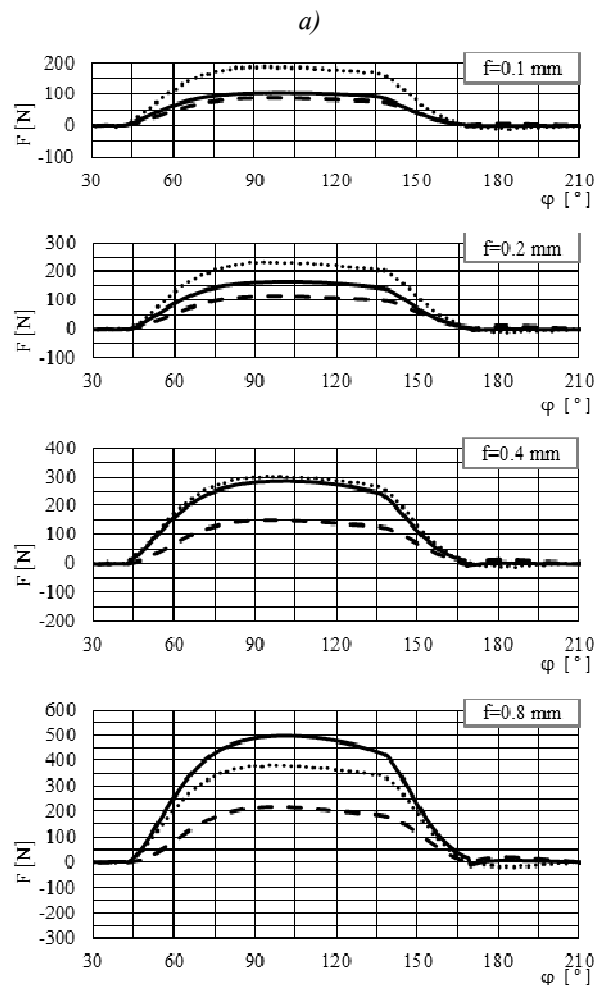
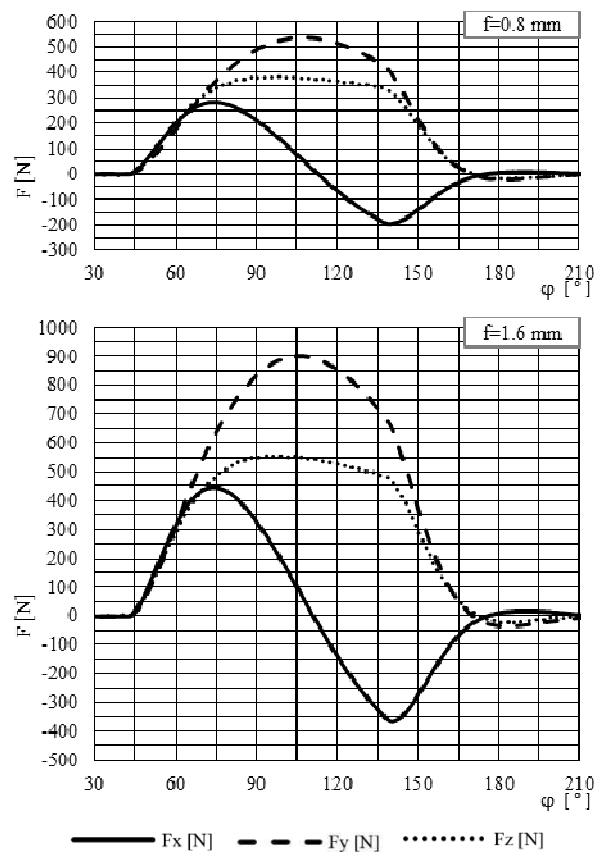
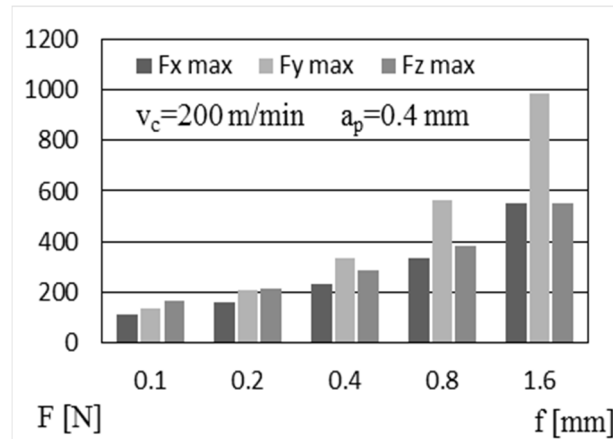


Fig. 5 Cutting forces variation for all tested feeds and $v_c=300$ m/min, for a full rotation of the milling head and for coordination system attached to (a) the workpiece and (b) tool edge.

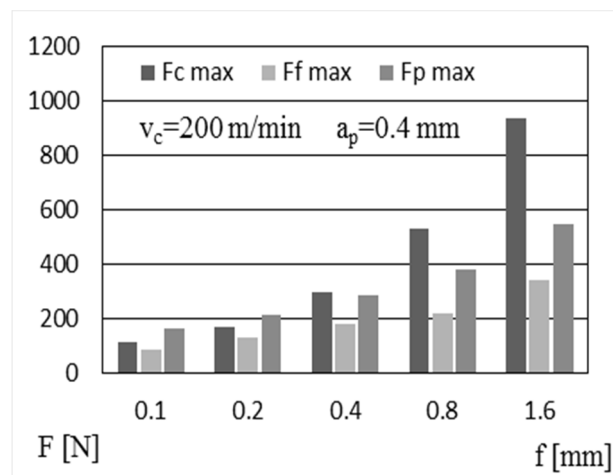
Figure 4a shows that among the three measured force components the values of F_z are the highest in the two lower feeds, i.e. with high ratio a_p/f_z . For further increase of the feed, the values of F_y exceed those of F_z . This is quite apparent at feed equal to 1.6 mm/tooth, where F_y is almost double the value of F_z . In general, for the feeds tested, F_z grows almost three times, namely from 165 N to 550 N, with increasing feed. Force component F_x also increases, as an absolute value, with increasing feed, as was expected. From Figure 4b, the analysis of F_c , F_f and F_p shows that their value is nearly constant, for no variation in feed, at the stage where cutting edge removes a whole chip cross section, forming a plateau at the graphs. The cutting forces are only nearly constant because of the change of the motion track of the tool edge, the momentum values of the resulting motion and the chip cross section; due to these attributes, the curve is not symmetrical with the middle plain. For varying feed, it is worth noting that F_c increases proportionally with the increase in feed. More specifically, an eight times increase in feed results in eight-fold increase of the force. Regarding F_p , it is higher than the other force components for the two lower feed values, with its value increasing four times with the increase in feed. Finally, F_f has the lowest value among the other two force components, for all experimental cases, showing the smallest increase with an increase in feed. The same trends may be observed for the force components in Figure 5a and Figure 5b, referring to higher cutting speed.

Figure 6 contains the maximum values for each force component, for cutting speeds of 200 m/min and 300 m/min. Analyzing the maximum values of force components F_x , F_y , F_z and F_c , F_f , F_p it can be stated that under the influence of the feed increase, the cutting forces increase nearly linearly. With the increase in feed, machining time decreases by almost 6% while the maximum F_c needed to remove the cross section of a unit, decreases to

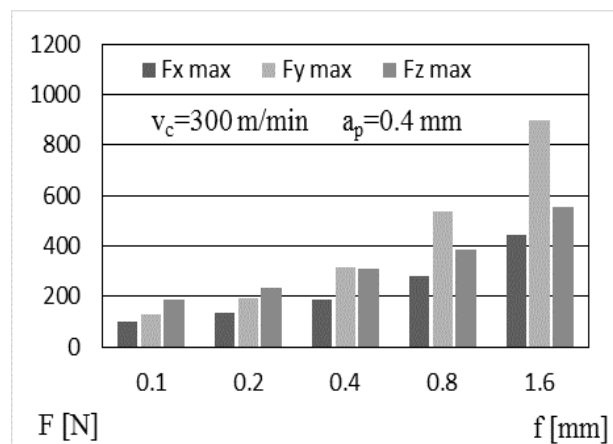
its half. At the same time, the removed volume increases sixteen-fold, while the cutting force increases only by 8.2 times. Furthermore, it is of particular interest that the maximum forces are lower for the higher cutting speed of 300 m/min, in comparison to the ones in the cutting speed of 200 m/min. Although it is quite interesting to observe the variation of the cutting forces in connection to feed variation, it is also useful to analyze the cutting forces per chip cross section, i.e. the specific cutting forces, and the influence of feed on them.



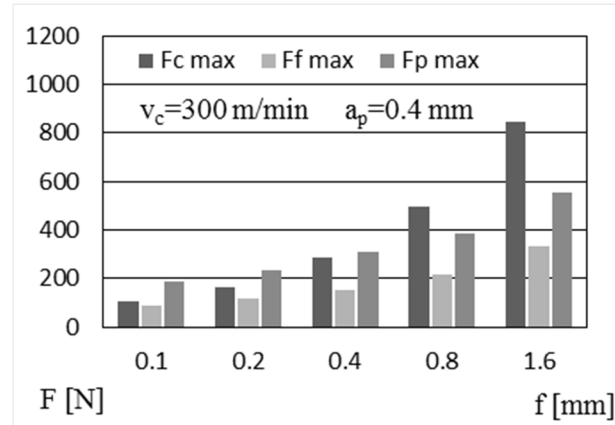
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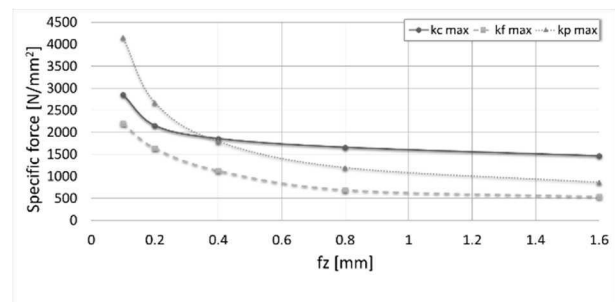
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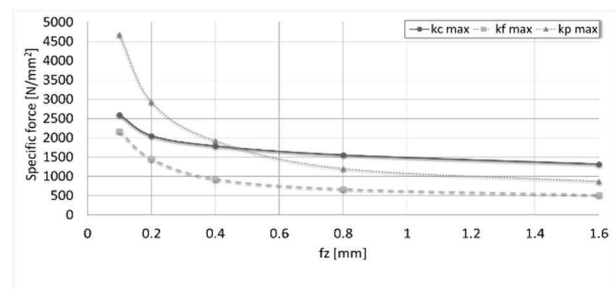
d)

Fig. 6 Maximum values of the force components for $v_c=300$ m/min for coordination system attached to (a) workpiece and (b) tool edge for $v_c=200$ m/min and (c) workpiece and (d) tool edge for $v_c=300$ m/min.

In Figure 7, the maximum specific cutting forces, for all the feeds and cutting speeds are shown. The specific forces are denoted with the letter k , with subscript that corresponds to the force component that was used for its calculation. A closer observation of the data contained in Figures 5 to 7 indicates that indeed more intensive cutting conditions, namely higher feed, lead to an increase in cutting forces. However, a higher feed, increases chip cross section, which leads to a significant decrease of the specific cutting forces. In Figure 7, it can be clearly seen that specific cutting forces for all force components decrease significantly with the increase in feed. Although the cutting forces are higher, the load on the cutting insert is lower.



a)



b)

Fig. 7 Specific cutting forces for cutting speed (a) $v_c=200$ m/min and (b) $v_c=300$ m/min.

4 Conclusions

In this paper, the characteristic cutting forces of face milling are examined. The change of their values is demonstrated in the process of chip removal as function of the angle of the tool rotation. The variation of forces is measured both in a coordinate system attached to the workpiece, also complying with the measuring system used in the experimental procedure, and calculated in a coordinate system attached to the tool edge.

By increasing the feed in the examined range, the surface rate proportionally increased 16 times. As the depth of cut was constant, with increasing f_z the ratio a_p/f_z 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 and their relation to each other changed. It is of special interest, though, that the values of specific forces decreased. This is an indication that the overall loading of the cutting insert is low, even though the feed increased. Regarding maximum force values, it may be observed that for higher cutting speed, lower cutting forces were measured.

Because the maximum value of the cutting forces grew nearly linearly, the increase of feed requires a highly stiff machine tool. Further investigation is planned to define the chip size ratio a_p/f_z with which a lower scale increase in cutting force and proportional efficiency can be achieved.

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