Correlation Between Chip Ratio and Specific Forces with Increasing Feed per Tooth and Cutting Speed in Face Milling of Steel

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Abstract: - In this paper, the influence of feed per tooth and cutting speed on cutting forces is investigated. More specifically, various values of the ratio of depth of cut to feed per tooth, namely chip ratio, are investigated, at 200, 300 and 400 m/min and the cutting forces at a coordination system attached to the workpiece are measured. These are translated into a coordination system attached to the tool edge and then, specific cutting forces are calculated for each case. It is of special interest the area where chip ratio receives values lower than 1, in the so-called inverse cutting area. The results indicate that under these circumstances machining efficiency is increased and at the same time load on cutting tools is decreased.

Key-Words: - Face milling, chip ratio, surface rate, machining efficiency, specific cutting forces, inverse cutting,

1 Introduction

Machining efficiency of surfaces with various shapes and good quality plays a significant role in contemporary industry. This is particularly true in the automotive industry, in recent years, due to the fact that the number of machined parts produced in great volumes increased significantly. Note that the total annual revenue and profit of a company can significantly increase by an infinitesimal decrease in the machining time of one workpiece, when mass production of machined parts is considered. If an improvement in the manufacturing procedure leads to a decrease in machining time of a component or a lot, then the production of more or other components can be undertaken in the gained extra time. If the goal is not volume increase, then the production cost of the fixed number components can be decreased, which also facilitates an increase in profit. Of course, a necessary condition is that changes in the machining strategy must not negatively affect the surface quality and accuracy specifications of the component [1, 2]

One of the most productive and effective processes for flat surfaces, in everyday practice, 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 [3, 4]. 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 [5-7]. With the optimization of the process in mind, both theoretical and experimental works have enriched the relevant literature [2, 8, 9]. However, the complicated kinematics of face milling, in comparison to other manufacturing processes, e.g. turning, have rendered the studies more demanding [10, 11]. 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 [5, 12, 13].

In the relevant literature it may be concluded that geometrical features of the tool, tool and workpiece material properties and, more commonly, cutting conditions, including depth of cut, feed rate and cutting speed are the parameters that significantly affect the process. Process efficiency is quantified through material removal rate Q_w [mm^3/s] or surface rate A_w [mm^2/s]. The former expresses how many units of material can be cut during one unit of time and the latter expresses how many units of surface area can be finished during one unit of time with a given procedure. More particularly, the combination of high values of the milling conditions leads to higher productivity, 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 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 [14].

Although the impact of high cutting speeds on cutting performance, in general, and in cutting forces, in particular, has been investigated in the past, the effect of increased feed rate is not adequately discussed. High speed machining is an established practice in metal machining; however, the increase of cutting speed beyond a certain limit, depending mostly on the machinability of the material and other technological limitations, is impossible [15, 16]. 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.

In this paper, a novel approach for the investigation of the effect of feed rate on face milling is adopted. Firstly, the ratio of the depth of cut and feed per tooth f_z [mm/tooth], namely chip size ratio a_p/f_z, is introduced. By suitably altering depth of cut and feed per tooth, the cross section of the chip may be preserved at the same value, however, the material removal mechanism changes significantly. If depth of cut is held constant and feed per tooth is increased, the chip cross section is increased leading to higher surface rate and thus higher process efficiency. At the same time, chip ratio decreases, to values lower than 1; if a strategy of small chip ratio is realized, then the cutting process is entering a completely new as well as unexplored field of milling, where a lot of cutting parameters and mechanisms invert; it can be referred as inverse cutting technology. The border area of the inverse to the conventional chip formation is a_p/f_z=1, and it will be shown that there are important discrepancies between the two set-ups.

From the published works found in the relative literature, there are only a few studies that investigate the influence of the increase of feed per tooth on chip size ratio, especially at different cutting speeds. By increasing feed per tooth, at constant depth of cut, the medium chip thickness h_m increases and as a consequence, several cutting technical parameters change, too, among them the cutting forces. Kundrák and Felhő [17] and Kundrák et al. [10] 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 [18] and Karpuschewski et al. [19] investigate cases where $a_p/f_z<<1$, and evaluate the resulting cutting forces and dynamic phenomena.

Secondly, besides the cutting forces, specific cutting forces, i.e. cutting forces per chip cross section are investigated. There are works that specific cutting forces are considered in the case of face milling [20, 21] in order to evaluate the load of the chip, but also the load on the cutting insert, which is of special interest.

Finally, the provided data pertain to various cutting speeds, so the combined influence of cutting speed and feed per tooth may be observed and useful conclusions may be drawn from the comparison of the experimental data.

In the next section, the experimental procedure and the resulting data are described. Then, with the aid of graphs and tables, important parameters that are either measured or calculated are presented and discussed. In the last section, the most important conclusions are presented.

2 Experimental

2.1 Focus of the experimental procedure

The aim of the experimental procedure is to exhibit the role of feed per tooth on the cutting forces and specific cutting forces, with various cutting speeds, but under reverse machining conditions. In this case, material removal is not performed by the major cutting edges on the plain surface, but the minor cutting edges take part in the forming of the machined surface, 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, i.e. chip size ratio. In the case that $a_p/f_z >> 1$, chip deformation is predominantly perpendicular to the edge on the outer surface, while in the case of $a_p/f_z << 1$, it is perpendicular to the edge on the face of the tool, see Figure 1. In this figure, an illustration of the different chip formation mechanisms is included for regular and cases of a_p/f_z are depicted in order to illustrate the chip formation variation.

With the measuring equipment that was used for the experimental work, namely a dynamometer located under the workpiece, the cutting force components F_x, F_y and F_z that correspond to a coordinate system attached to the workpiece, are measured. However, it is possible, with the suitable kinematics of milling considerations to calculate cutting force components F_c, F_f and F_p referring to a coordinate system attached on the tool edge, which are of particular interest; it is from these forces that specific forces will be calculated at a later step. The

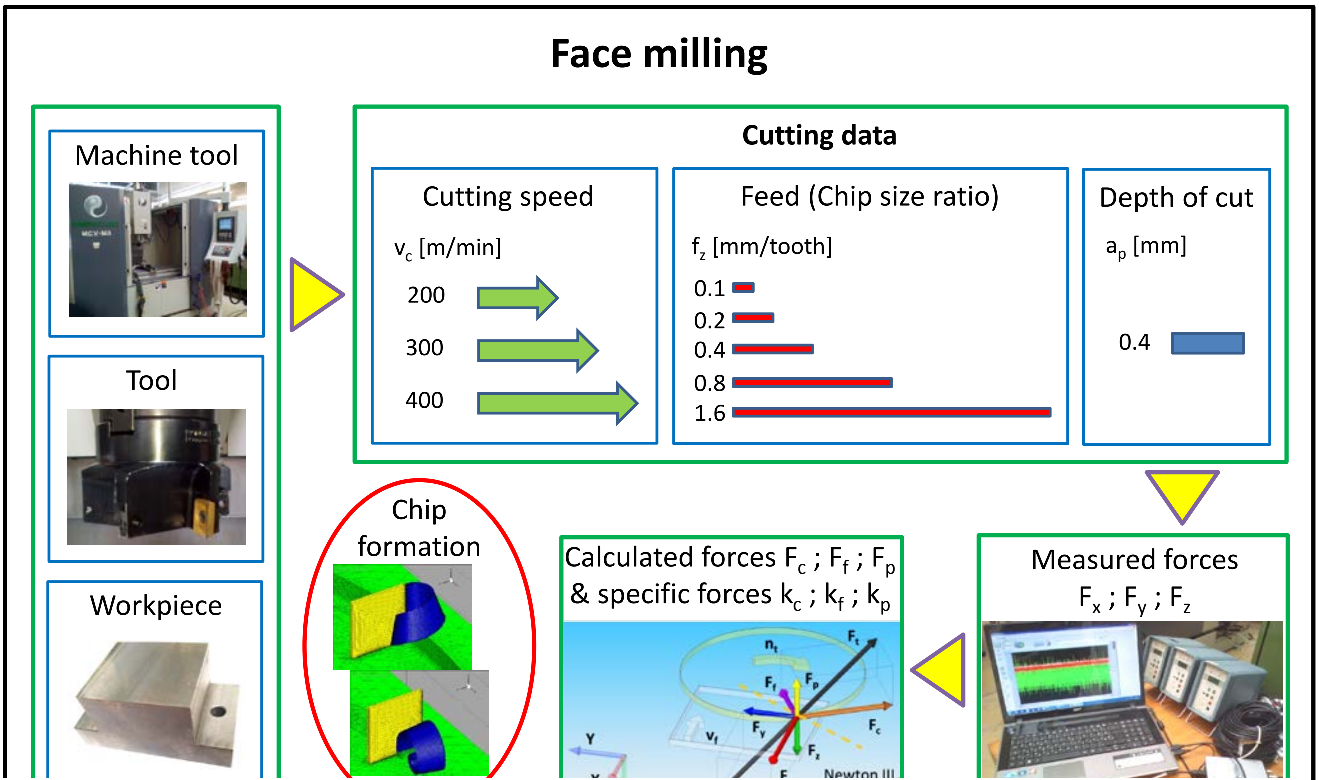


Fig. 1 Experimental work and calculations for face milling.

force components for the coordinate system attached to the tool edge are calculated from the measured force components, through the following equations:

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

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

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

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

2.2 Experimental method

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.

In order to measure the effect of only one cutting edge during the process, the milling head was mounted with only one cutting insert, as can be seen in Figure 1.

Table 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]
1	0.1	4	0.04
2	0.2	2	0.08
3	0.4	1	0.16
4	0.8	0.5	0.32
5	1.6	0.25	0.64

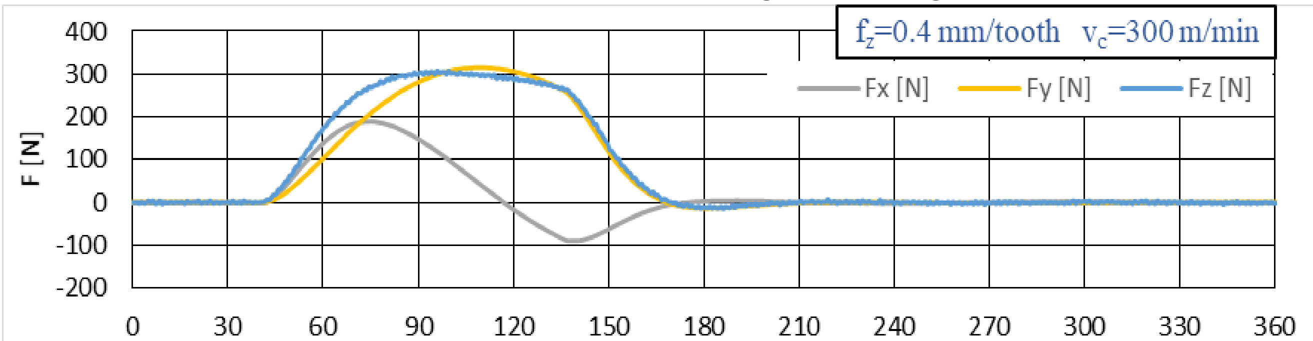
The specifications of the insert are the following: Sandvik R215.44-15T308M-WL GC4030 coated carbide insert, with κ_r=90°, γ_o=0°, α_o=11° and r_ε=0.8 mm. Five different feeds per tooth, commonly used in practice for machining of steel, were selected. Table 1 contains the feeds per tooth, the corresponding chip size ratio and the chip cross-section A_c. For depth of cut 0.4 mm, the chip size ratio decreases from 4 to 0.25, divided by 2 in each experiment. The experiments were repeated for cutting speeds equal to 200, 300 and 400 m/min.

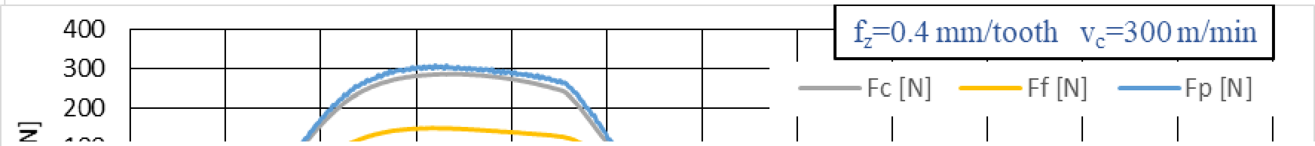
Forces were measured by a Kistler 9257A dynamometer, as can also be seen in Figure 1, with three components, connected to three 5011A charge amplifiers, one for each force component. Furthermore, a CompactDAQ-9171 data collector with 4 channels, by National Instruments was used and measurement software, made by LabView programming language, was employed. With the described configuration, continuous force measurement was possible at 10 kHz sampling frequency while machining, and the values of F_x, F_y and F_z components were recorded.

2.3 Experimental results

Based on the geometrical characteristics of the experimental set-up, the dimensions of the workpiece and the milling head and with reference to Figure 2, the insert engages the workpiece at angle φ_1=43.53° and exits at φ_2=136.47°, 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 300 m/min, for the coordination system attached to the workpiece and the tool edge are shown in Figure 2a and 2b, respectively. The graphs for other cutting speeds and feeds per tooth are of similar trends, differing only in their extreme points.

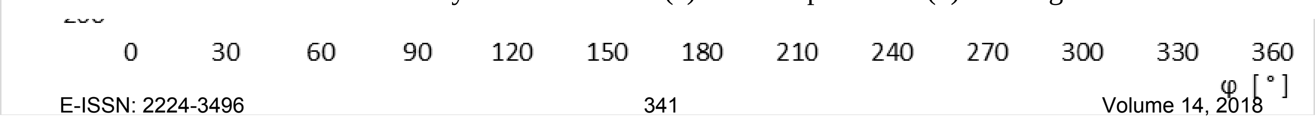
Figure 3a and Figure 3b show the variation of the





(b)

Fig. 2 Cutting forces variation for f=0.4 mm/tooth, 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.



cutting forces, for cutting speed of 400 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^o and 210^o, as in the other degree ranges no cutting forces are recorded. Again, the graphs for the other cutting speeds are of similar trend, with different extreme points.

In Table 2, all the results for the calculated maximum force components, as well as the corresponding specific forces are gathered. The specific forces are denoted with the letter k, with subscript that corresponds to the force component that was used for its calculation.

3 Evaluation and discussion of the results

In this section, the measured and calculated results are evaluated and discussed. From Figures 2 and 3, some interesting discussions can be made. In general, the shape of the graphs, for each force component, is consistent with the kinematics of face milling and the range of the values is in good agreement with previous results [5]. It is worth noting the influence of the rotational motion of the insert on force component F_x. More specifically, the force components on axis x, changes direction when passing the symmetry plain of the workpiece, in the feed direction of the tool shaft. This results in positive and negative values of F_x during the same pass; in the first half of the cutting action of the tool, milling moves towards one direction and then in the opposite direction. Figures 2 and 3 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.

Figure 3a 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 feed increase, 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.

Table 2 Calculated results.

f_z [mm/tooth]	0.1	0.2	0.4	0.8	1.6
a_p/f_z ratio	4	2	1	0.5	0.25
A_c [mm^2]	0.04	0.08	0.16	0.32	0.64
v_c=200 m/min					
$F_{c\ max}$ [N]	114	172	297	531	935
$F_{f\ max}$ [N]	88	131	181	221	343
$F_{p\ max}$ [N]	166	214	286	382	550
$k_{c\ max}$ [N/mm^2]	2853	2154	1857	1659	1462
$k_{f\ max}$ [N/mm^2]	2201	1641	1129	691	536
$k_{p\ max}$ [N/mm^2]	4152	2673	1787	1195	859
v_c=300 m/min					
$F_{c\ max}$ [N]	104	165	286	499	846
$F_{f\ max}$ [N]	87	117	150	216	334
$F_{p\ max}$ [N]	187	235	308	385	557
$k_{c\ max}$ [N/mm^2]	2596	2057	1790	1558	1322
$k_{f\ max}$ [N/mm^2]	2177	1461	936	674	522
$k_{p\ max}$ [N/mm^2]	4679	2933	1924	1202	871
v_c=400 m/min					
$F_{c\ max}$ [N]	144	259	465	813	814
$F_{f\ max}$ [N]	128	170	251	423	399
$F_{p\ max}$ [N]	222	279	366	536	532
$k_{c\ max}$ [N/mm^2]	3608	3233	2908	2541	1271
$k_{f\ max}$ [N/mm^2]	3208	2123	1566	1322	624
$k_{p\ max}$ [N/mm^2]	5543	3483	2288	1674	831

Force component F_x also increases, as an absolute value, with increasing feed, as was expected. From Figure 3b, 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, as can also be seen from Table 2. 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

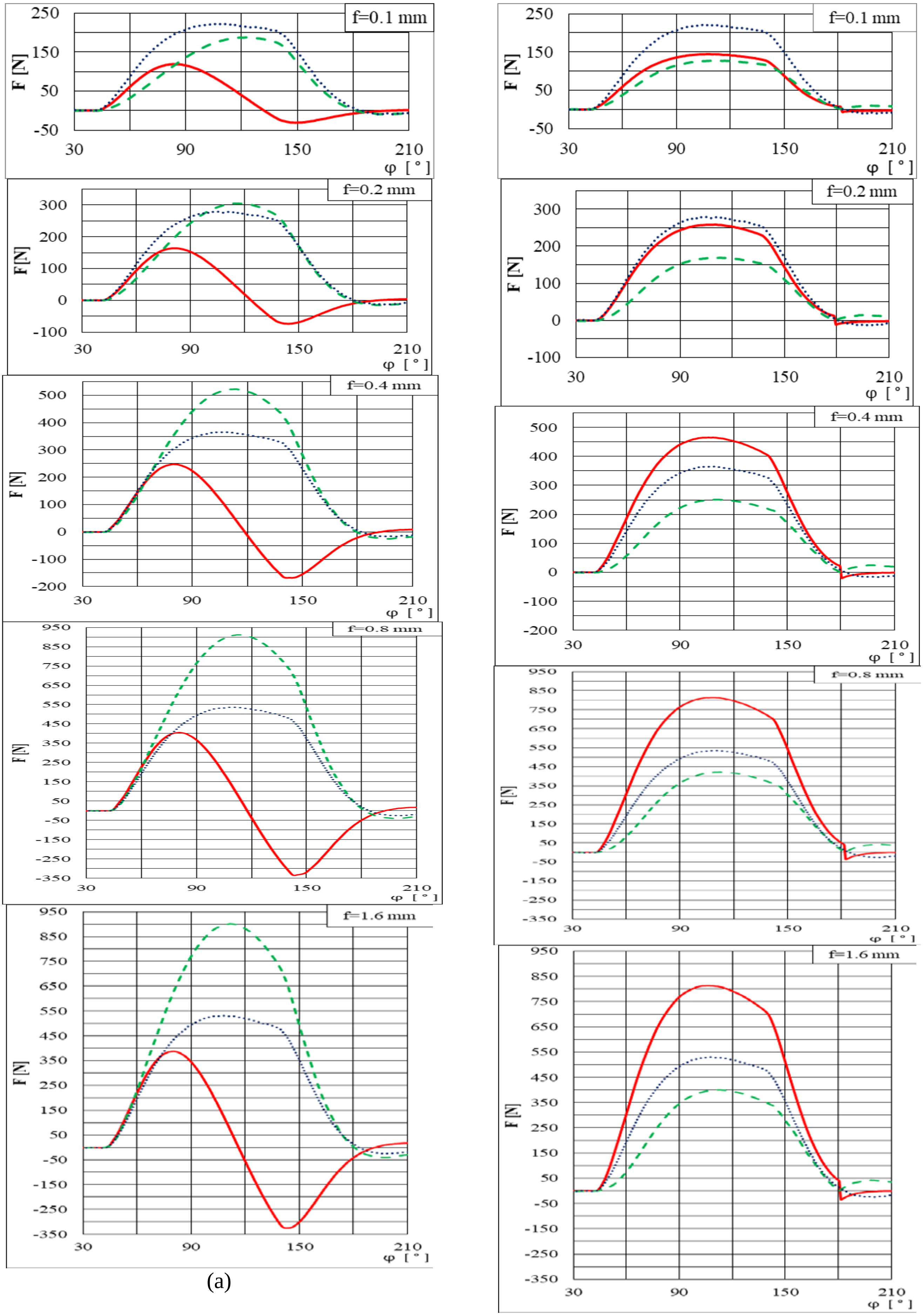
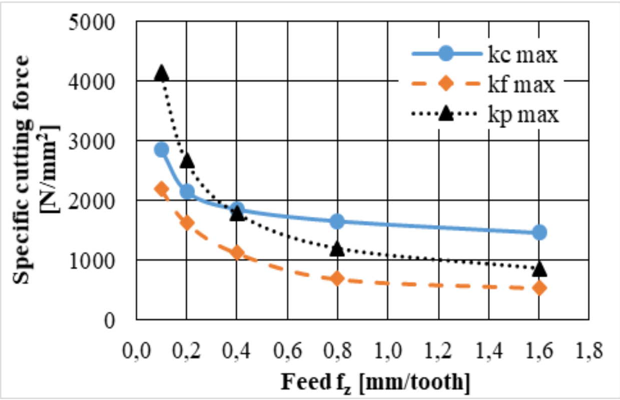


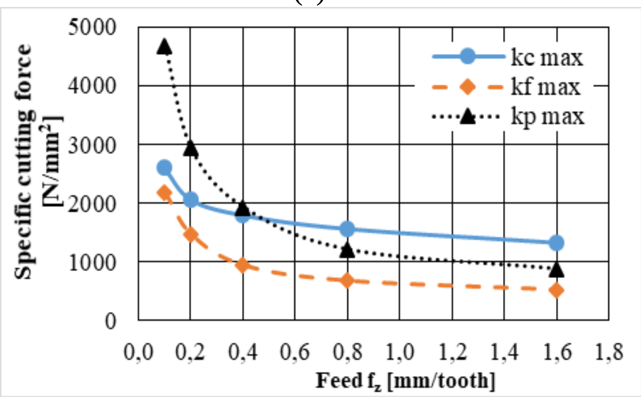
Fig. 3 Cutting forces variation for all tested feeds and v_c=400 m/min, for a full rotation of the milling head and for coordination system attached to (a) the workpiece and (b) tool edge.

(b)

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.



(a)



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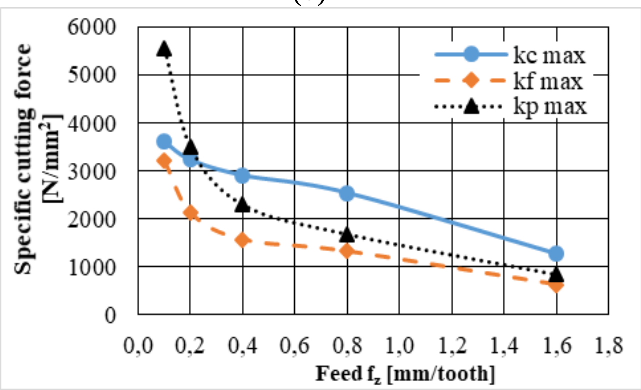

(c)

Fig. 4 Specific cutting forces for cutting speed (a) v_c=200 m/min, (b) v_c=300 m/min and (c) v_c=400 m/min.

In another approach, it is useful to observe and analyze the cutting forces per chip cross section, i.e. the specific cutting forces, and the manner they are affected by the increase of feed per tooth. A closer observation of the data contained in Table 2 indicates that indeed more intensive cutting conditions, namely higher feed, lead to an increase in cutting forces. However, a higher feed per tooth, increases chip cross section, which leads to a significant decrease of the specific cutting forces. The latter is graphically shown in Figure 4 a-c for cutting speed 200 m/min, 300 m/min and 400 m/min, respectively.

Table 3 Feed, chip size ratio, chip cross section, forces and specific forces ratio between maximum and minimum feed, for all cutting speeds.

	v_c=200 m/min		
			Ratio
f_z [mm/tooth]	0.1	1.6	16.00
a_p/f_z ratio	4	0.25	0.06
A_c [mm^2]	0.04	0.64	16.00
$F_{c\ max}$ [N]	114	935	8.20
$F_{f\ max}$ [N]	88	343	3.90
$F_{p\ max}$ [N]	166	550	3.31
$k_{c\ max}$ [N/mm^2]	2853	1462	0.51
$k_{f\ max}$ [N/mm^2]	2201	536	0.24
$k_{p\ max}$ [N/mm^2]	4152	859	0.21
	v_c=300 m/min		
			Ratio
f_z [mm/tooth]	0.1	1.6	16.00
a_p/f_z ratio	4	0.25	0.06
A_c [mm^2]	0.04	0.64	16.00
$F_{c\ max}$ [N]	104	846	8.13
$F_{f\ max}$ [N]	87	334	3.84
$F_{p\ max}$ [N]	187	557	2.98
$k_{c\ max}$ [N/mm^2]	2596	1322	0.51
$k_{f\ max}$ [N/mm^2]	2177	522	0.24
$k_{p\ max}$ [N/mm^2]	4679	871	0.19
	v_c=400 m/min		
			Ratio
f_z [mm/tooth]	0.1	1.6	16.00
a_p/f_z ratio	4	0.25	0.06
A_c [mm^2]	0.04	0.64	16.00
$F_{c\ max}$ [N]	144	814	5.65
$F_{f\ max}$ [N]	128	399	3.12
$F_{p\ max}$ [N]	222	532	2.40
$k_{c\ max}$ [N/mm^2]	3608	1271	0.35
$k_{f\ max}$ [N/mm^2]	3208	624	0.19
$k_{p\ max}$ [N/mm^2]	5543	831	0.15

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. By observing all three graphs of Figure 4, it can be seen that for feed per tooth equal to 0.4 mm/tooth the inclination of the angles changes significantly. This value coincides with the value of chip size ratio equal to 1, indicating a limit point on the graph. For values lower that this limit, specific cutting forces decrease steeply, while their change, after the limit point is significantly smoother. Furthermore, it is worth noting that chip size ratio lower than 1, k_p is higher than k_c; this trend reverts for chip size ratio higher than 1.

Some interesting conclusions may be also drawn from the data of Table 3. In this Table, calculated cutting force components and the respective specific forces, for the lower and the higher feed used in the experiments and the corresponding chip size ratio and chip cross section are gathered, for both cutting speeds. Furthermore, the ratio of the maximum to the minimum value for each parameter is cited.

The results indicate that an increase of 16 times to the feed, leads to an increase of about 8 times of the maximum cutting force F_c, for the two lower cutting speeds and an increase of 5.65 times for the higher cutting speed. At the same time, for the corresponding specific forces, the ratio is 0.51 and 0.35 for the first two and the third cutting speeds, respectively, exhibiting a significant decrease in their value.

4 Conclusion

The purpose of this paper was to examine the influence of feed, cutting speed and chip size ratio, in one pass face milling of steel, on cutting forces and specific forces. Thus, 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, i.e. experimental results, but also in a coordinate system attached to the tool edge, i.e. calculated results. It is ascertained that the maximum values of the forces interpreted in the two coordinate systems are nearly the same.

The change in cutting speed and feed per tooth resulted in interesting results. By increasing the feed in the examined range, the surface rate proportionally increased up to 16 times; the same trend is valid for cutting forces that increase up to 8 times. However, if the specific cutting forces are examined, this trend is reversed. The point that this reversion takes place is the condition where $a_p=f_z$, which coincides with chip size ratio equal to 1. The descent of the specific cutting forces before and after this point also presents significant variation. Furthermore, it was observed that k_p is higher than k_c for chip size ration lower than 1 and the opposite is seen for values of $a_p/f_c>1$.

Of course, as the depth of cut was constant, with increasing f_z the ratio a_p/f_z proportionally decreased. This is important because the load on the cutting edges also changes, with an effect on stresses and dynamic phenomena on the cutting insert.

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