Theoretical and Experimental Analysis of the Effect of Chip Size Ratio on Cutting Forces in Face Milling of Steel

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Abstract: - In this paper, the effect of chip size ratio on the cutting forces in face milling of steel is investigated with both geometrical analysis and experimental work pertaining to the testing of various cutting conditions. More specifically, the focus is on the increase of the amount of material being removed in one pass at high cutting speed, in connection to the increase of the cutting forces; the former increase should be maximum while the latter should be kept to a minimum. For this purpose, five different values of feed are tested and cutting forces are measured by a dynamometer, on a xyz axes coordinate system attached to the workpiece. Furthermore, cutting force components, referring to a coordinate system attached on the tool edge, can be calculated through geometrical assumptions and mathematical formulation. It is concluded that an eight times increase in feed results in eight-fold increase of cutting force F_c while material removal is much higher.

Key-Words: - face milling, cutting forces, feed rate, chip size ratio, material removal rate, surface removal rate

1 Introduction

Face milling is one of the most common machining processes used for the production of high quality flat surfaces [1, 2]. Another important feature of the process is the high material removal rate that can be achieved, or in case of milling performed at a single pass, the high surface removal rate, given that the process is performed at a constant depth of cut. The use of a single pass is not unusual in contemporary industry, thus this is the case that will be investigated in this work [3]. Surface removal rate is increased by increasing feed and cutting speed; the combination of high values for the latter parameters leads to high productivity [4]. Because of this, face milling has been the main subject of many researches. The works found in the relevant literature focus on cutting forces estimation, surface roughness minimization and tool wear assessment [5, 6]. However, both cutting parameters, namely cutting speed and feed, are bound by technological limitations.

The increase of cutting speed has an upper bound in industrial practice, because besides tool life and surface integrity considerations, machine tools usually have a low margin of increasing spindle speed. On the other hand, increasing of the feed rate can only be feasible with the use of proper tool geometry and positioning of the insert on the tool head. Increasing feed per tooth f_z, at constant depth of cut a_p, the medium chip thickness h_m increases and a_p/f_z ratio, also referred as chip size ratio, changes.

As a consequence, several cutting technical parameters change, too, among them the cutting forces. It can be 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 [7], and a high increase in feed, so that a_p/f_z ratio will be lower than one, leads to favorable conditions and output [8, 9].

A bibliographic review in the relevant literature reveals that both theoretical and experimental works can be found, mainly concerning the optimization of the process [10, 11]. However, it is a fact that the kinematics of face milling are more complicated in comparison to other manufacturing processes, e.g. turning, thus rendering the studies more demanding [12, 13]. Experimental works usually refer to the observation of the influence of cutting parameters on cutting forces, tool wear and surface quality [14-17].

Besides experimental works, modelling is commonly employed, either through mathematical or numerical models. Saï and Bouzid [18] presented a mathematical model for the estimation of surface roughness in up-face milling, while Hadad and Ramezani [19] 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. Furthermore, a geometric model for face milling was presented by Franco et al. [20].

Numerical modelling is popular for the analysis and evaluation of manufacturing processes in general [21-25] and face milling in particular [26, 27], usually through the use of the Finite Element Method (FEM). However, a three dimensional Smooth Particle Hydrodynamics (SPH) model of face milling can also be found [28]. Most of the models are able to predict cutting forces and are validated by experimental results.

Many researchers employ soft computing methods for the analysis of milling, with the use of artificial intelligence methods, namely neural networks or genetic algorithms, and statistical methods and optimization techniques, e.g. Taguchi analysis, grey relational analysis and particle swarm optimization [29-32].

Only a few studies from the already published works can be found that investigate the influence of feed on chip size ratio and surface removal rate. In the present paper, experimental work is carried out for the evaluation of the effect of feed on chip size ratio and consequently on cutting forces, in face milling of steel.

The analysis is carried out for the forces measured 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, and the results are compared, allowing the extraction of useful conclusions.

2 Experimental Procedure

The aim of the investigation is to examine the influence of various feed rates on the components of cutting force. Assuming that the depth of cut is constant and equal to 0.4 mm, the focus of the experiments is the investigation of the influence of chip size ratio variation on cutting force components.

All experiments were performed in a Perfect Jet MCV-M8 vertical machining center. It was mounted with a Sandvik R252.44-080027-15M face milling head with diameter D_s=80 mm.

The milling head is supplied with one insert, as can be seen in Fig. 1, 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 κ_r=90°, γ_o=0°, α_o=11° and r_ε=0.8 mm was used.

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 cutting speed is set at 200 m/min for all the experiments.

Forces were measured by a Kistler 9257A dynamometer, as can be seen in Fig. 1, with three components. They are connected to three 5011A charge amplifiers, so that one amplifier is assigned to each force component.

Fig. 1 Milling head with one insert and the workpiece, which is mounted on the dynamometer

Furthermore, a CompactDAQ-9171 data collector with 4 channels, by National Instruments was used and measurement software, made by LabView programming language, was employed, as depicted in Fig. 2.

Fig. 2 Data acquisition of the experimental procedure

With the described configuration, continuous force measurement was possible while machining, and the values of F_x, F_y and F_z components were recorded. 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. However, 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, as can be seen in Fig. 3. It is worth noting, that there are specific points that forces of the two systems may coincide [9].

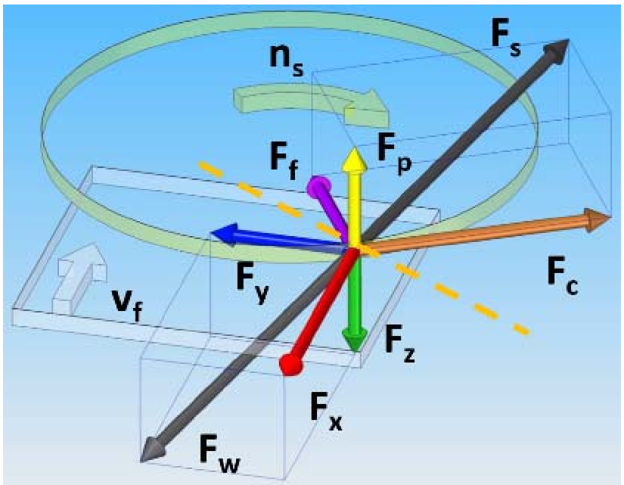


Fig. 3 Force components

Five different feeds per tooth, commonly used in practice for machining of steel, were selected. Table 1 contains the feed per tooth, the corresponding chip size ratio and the chip cross-section A_c. Chip size ratio decreases from 4 to 0.25, divided by 2 in each experiment.

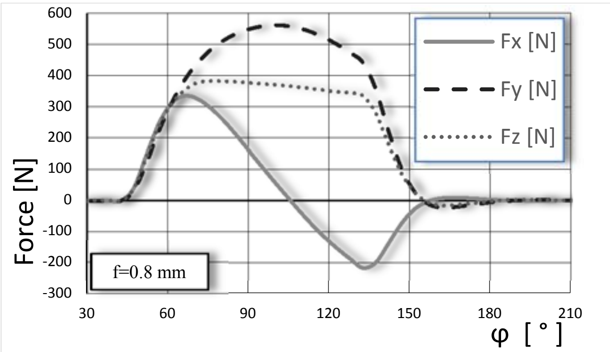
Table 1. Feed per tooth, chip size ratio and chip cross section for the various experiments performed

No. of Experiment	Feed per tooth f_z [mm/tooth]	a_p/f_z	Chip cross section 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

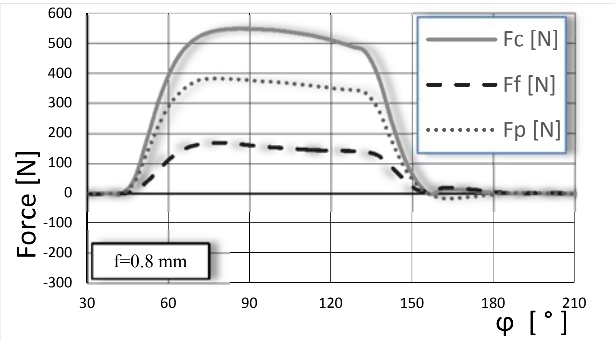
5	1.6	0.25	0.64

3 Results and Discussion

In Fig. 4, the variation of the cutting forces, for feed equal to 0.8 mm is shown. From the dimensions of the workpiece and the milling head, it may be calculated that the insert engages the workpiece at angle $\varphi_1=43.53^o$ and exits at $\varphi_2=136.47^o$, which is also the period where cutting forces are recorded in a full rotation of 360^o of the milling head. Thus, it is enough if the graphs are shown in the range between 30^o and 210^o, as in the other degree ranges no cutting forces are observed.



(a)



(b)

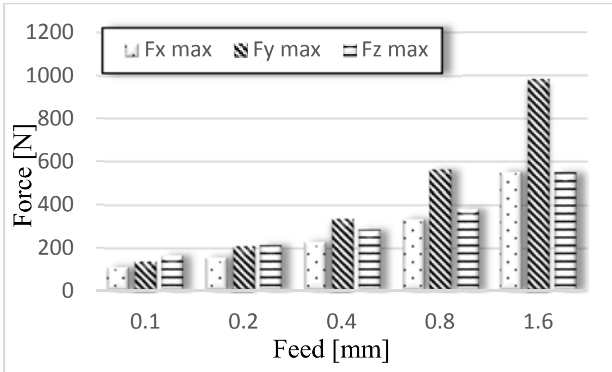
Fig. 4 Cutting forces variation for feed 0.8 mm, for coordination system attached to (a) the workpiece and (b) tool edge

In these graphs, the measured forces for the coordination system attached to the workpiece and the calculated forces for the coordination system attached to the tool edge are shown in Fig. 4(a) and Fig. 4(b), respectively.

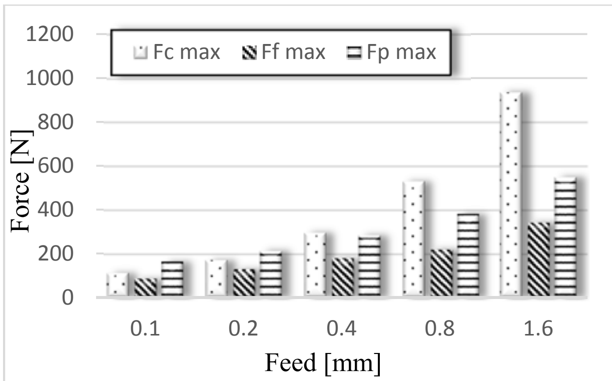
From these Figures, some interesting conclusions may be drawn. In general, the shape of the graphs for each force component are consistent with the kinematics of face milling. It is worth noting the influence of the rotational motion of the insert on F_x force components, in Fig. 4(a). In feed direction of the tool shaft, the force components with x-direction changes orientation when passing the symmetry plain of the workpiece, which has as a result the positive and negative values of F_x during the same pass. It is an indication that in the first half of the cutting action of the tool, milling goes in one direction and then in the opposite direction.

Fig. 4(b) shows that F_c, F_f and F_p components change little in the whole stage of the chip cross section removal; more specifically they tend to reduce in size, slightly. These changes are in connection with kinematics of face milling, i.e. the change of the motion track of the tool edge, the momentum values of the resulting motion and the chip cross section. Because of these phenomena, the curve is not symmetrical with the middle plain.

Fig. 5 contains the maximum values for each force component, for all the experiments. The range of the values are in good agreement with previous results from other similar investigations [5].



(a)



(b)

Fig. 5 Maximum values of the force components for coordination system attached to (a) the workpiece and (b) tool edge

Fig. 5(a) indicates that among the three measured force components, F_z is the highest for high ratio a_p/f_z, for lower feeds. However, for further increase of the feed, F_z is surpassed by the values of F_y. This is more obvious at feed equal to 1.6 mm, 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.

In Fig. 5(b), it may be seen that F_c increases almost linearly 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.

An analysis of the maximum values of force components F_x, F_y, F_z and F_c, F_f, F_p brings to light that under the influence of an increase in feed, the cutting forces increase nearly linearly.

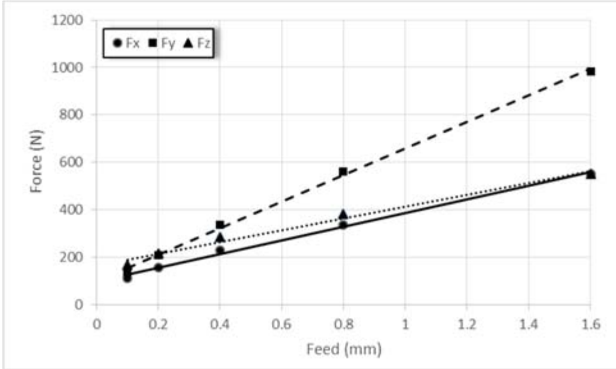
With the increase in feed, machining time decreases by almost 6% while the maximum F_c needed to remove the cross section of a unit, decreases to 50% of the initial value. At the same time, the removed volume increases sixteen-fold, while the cutting force increases only by 8.2 times.

Table 2. Maximum forces for all force components, for all feeds

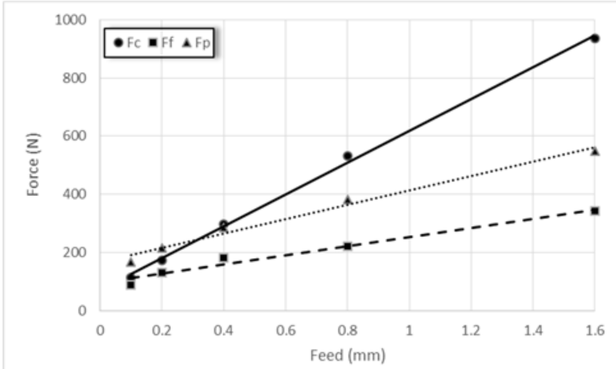
f_z [mm]	0.1	0.2	0.4	0.8	1.6
F_x max [N]	112	158	229	335	552
F_y max [N]	137	209	337	562	983
F_z max [N]	166	214	286	382	550
F_c max [N]	114	172	297	531	935
F_f max [N]	88	131	181	221	343
F_p max [N]	166	214	286	382	550

In Table 2, the values of the maximum forces for all force components, for all the feeds used in the experiments are tabulated. Fig. 6 contains the data of Table 2, showing the almost linear increase of cutting forces.

In Fig. 6(a), the maximum forces for coordination system attached to the workpiece are shown, while in Fig. 6(b) for coordination system attached to the tool edge are depicted.



(a)



(b)

Fig 6. Maximum values of the various force components versus feeds used in the experiments for coordination system attached to (a) the workpiece and (b) tool edge

5 Conclusion

The aim of the paper was to examine the influence of chip size ratio, in one pass face milling of steel, on cutting forces. The change of their values is demonstrated at 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 in a coordinate system attached to the tool edge.

An increase in feed results in a proportional increase of the surface removal rate. With increasing f_z, given that depth of cut is constant, the ratio a_p/f_z proportionally decreased. As a consequence the exploitation of the main and subsidiary edge of the cutting tool changes. The cutting forces measured in the coordinate system of the workpiece increased and their relation to each other changed.

Because the maximum value of the cutting forces grew nearly linearly, the increase of feed requires a highly stiff machine tool, if it is performed by a constant depth of cut. Further investigation will be sought later in order to examine the surface quality of the machined workpieces.

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