The Examination of Cutting Force as Function of Depth of Cut in Cases with Constant and Changing Chip Cross Section

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Abstract. For the achievement of highly productive and efficient manufacturing of flat surfaces, face milling is often the best choice in industrial practice. Process conditions should be selected with care in order to be able to reduce the machining time without increasing cutting forces excessively. For that reason, it is necessary to investigate the relationship between process parameters and cutting forces in various face milling cases. In the present study, various face milling experiments on steel workpieces are conducted in order to investigate the effect of depth of cut in cases with both constant and changing chip cross section values, with a view to determine its importance in face milling.

Keywords: Face milling · Cutting forces · Specific cutting forces · Depth of cut · Chip cross section

1 Introduction

Nowadays, the need of manufacturing of high quality flat surfaces for industries such as automotive and aerospace industry is still existent and usually it is achieved by face milling. With regard to maintaining high productivity and efficiency but at the same time avoid unfavorable issues caused by high cutting forces such as reduced tool life or increased power consumption, the process parameters should be selected appropriately. For that reason, it is required to investigate the relationship between the various process parameters and the outcome of face milling. Due to the fact that face milling is long established, considerable amount of work has been conducted on various aspects of this process, such as surface quality [1, 2], cutting forces prediction and tool wear assessment [3, 4]. Research work regarding face milling is not limited on experimental work, but also numerical models have been developed, as there is definitely need to be able to predict the outcome of the process under various conditions. A model for the theoretical prediction of cutting forces in face milling was developed by Li et al. [5], based on Oxley's theory. A CAD model was used by Hadad and Ramezani in order to

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assess the effect of milling parameters on surface topography. Moreover, FEM and soft computing methods are also employed to study face milling [6–10].

During face milling, the parameters which have an impact on the process include the tool and workpiece material properties, tool geometry, as well as the milling conditions, namely feed rate, depth of cut and cutting speed. Productivity during face milling can be increased with increased values of milling conditions, but this leads to excessive cutting forces, tool wear and power consumption. Apart from the aforementioned process conditions, combinations of some of them are also important. For example, the chip cross section defined as the product of feed rate and depth of cut is found to have an impact on the face milling outcome, as well as the ratio of the depth of cut to the feed per tooth value, denoted as chip size ratio, which affects directly the way which machining chip is formed.

From the experimental work conducted in the relevant literature, the effect of depth of cut and cutting speed on the cutting forces can be determined. Regarding cutting speed, it is usually stated that an increase of cutting speed leads to a decrease of cutting forces [11–17]. More specifically, the decrease of cutting forces is noticed for all force components with F_x and F_y components being most affected by the variation of cutting speed [12, 13]. Moreover, this decrease is evident even at high speed machining cases, at least up to 3000 m/min [13, 15]. However, it us still disputed whether the influence of cutting speed on cutting forces is significant or not; the majority of researchers agree that this effect is not as significant as the effect of feed rate or depth of cut [11, 18, 19]. The reduction of the value of cutting force components with an increase of cutting speed is often related to the increase of temperature, which results in workpiece material softening [13].

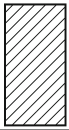
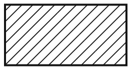
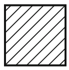
The influence of depth of cut on cutting forces is undisputable, as in all cases its increase results in an increase of cutting force components [12, 14–19]. It is also shown that this influence is more evident in the case of F_x and F_y force components, while F_z force component is less affected [12]. Most researchers agree that the depth of cut is one the most important parameters in face milling, regarding cutting forces, along with feed rate [14, 18, 19]. The increase of cutting forces value when depth of cut is increase can be related to an increase of tool-workpiece contact length [13] and the increase of cross-sectional area of uncut chip [12].

Although the relationship between depth of cut, cutting speed and cutting forces is already been studied, the variation of cutting forces in respect to other face milling parameters, such as the undeformed chip cross section (A_c) is rarely studied. Thus, in the present work it is attempted to determine and explain the influence of depth of cut on cutting forces during face milling for cases with constant and changing A_c values. Thus, three sets of experiments are conducted for cases with the same and different A_c values at various cutting speed values. Then, analysis is carried out, not only for cutting forces but also for specific cutting forces, and also analysis is conducted on cutting forces graphs in both workpiece and cutting insert coordinate systems. From the comparison of results between cases with different A_c values, useful conclusions are drawn.

2 Experimental Conditions

For the determination of the effect of depth of cut on cutting forces and specific cutting forces, face milling experiments with a milling head with a single rectangular-shaped cutting insert were conducted. The milling conditions are summarized in Table 1.

Table 1. Machining conditions for the face milling experiments.

A					
No.	v_c [m/min]	a_p/f_z [-]	a_p [mm]	f_z [mm]	A_c = 0.32 mm^2
1	100	2	0.8	0.4	
2	200				
3	300				
4	400				
B					
No.	v_c [m/min]	a_p/f_z [-]	a_p [mm]	f_z [mm]	A_c = 0.32 mm^2
1	100	0.5	0.4	0.8	
2	200				
3	300				
4	400				
C					
No.	v_c [m/min]	a_p/f_z [-]	a_p [mm]	f_z [mm]	A_c = 0.16 mm^2
1	100	1	0.4	0.4	
2	200				
3	300				
4	400				

Workpiece material was normalized C45 carbon steel (1.0503) with a hardness value of HB180. All the experiments were performed on a PerfectJet MCV-M8 vertical machining center under dry machining conditions. In these tables the following abbreviations are employed for various quantities related to face milling: v_c denotes the cutting speed [m/min], a_p denotes the depth of cut [mm], f_z denotes feed per tooth [mm/tooth]; A_c denotes the undeformed chip cross section [mm^2], a_p/f_z represents the chip size ratio and v_f represents the feed rate [mm/min]. More specifically, it was chosen that two of the three sets of experiments, namely A and B are performed under constant chip cross section conditions and the last set was conducted with a different chip cross section value. Cutting speed was varied in the range of 100–400 m/min, feed per tooth was 0.4 and 0.8 mm/tooth and depth of cut was 0.4 and 0.8 mm.

During the experiments, all three cutting force components, namely F_x, F_y, F_z were measured with a Kirstler 9257A dynamometer in a coordinate system relative to the workpiece and then amplified by three Kirstler 5011A charge amplifiers before being recorded in the PC using a CompactDAQ-9171 data collector by National Instruments company. These data were processed on the PC using a special software prepared in the LabView programming language.

Finally, other machining conditions for the experiments include:

- Cutting insert: Sandvik R215.44-15T308M-WL GC4030 coated carbide insert ($\kappa_r = 90°$; $\gamma_o = 0°$; $\alpha_o = 11°$; $r_\varepsilon = 0.8$ mm)
- Milling head type: Sandvik R252.44-080027-15M face milling head ($D_s = 80$)
- Workpiece dimensions: Width: 58 mm, Length: 50 mm.

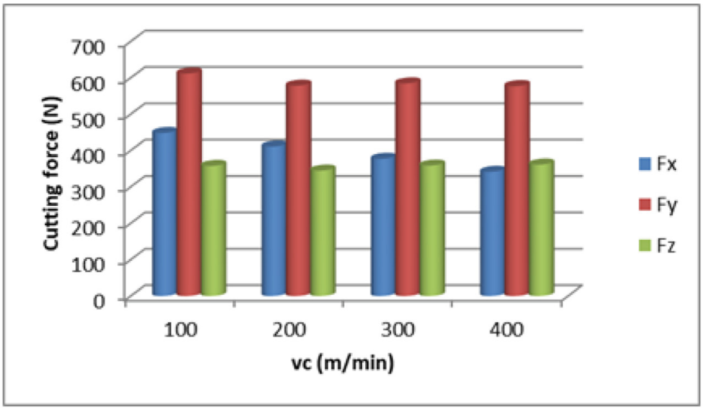
3 Results and Discussion

At first, the results regarding cutting forces will be discussed. In Fig. 1, the maximum forces for the experiments pertinent to cases A, B and C as described in Table 1, are presented. By comparing the cutting force components between cases with the same A_c value but different depth of cut value, namely A and B, it is apparent that especially F_x and F_y components of force have higher values in the cases with a larger depth of cut (A). More specifically, F_x component has a considerable difference between these cases, whereas F_y has a lower difference and for F_z a slightly opposite trend is observed. Furthermore it is observed that, in every case, F_y component has the largest values. As for the influence of cutting speed, cutting force components are reduced with an increase of cutting speed and especially F_x is more affected from variations of cutting speed than the other components. The differences between the experimental results in cases A and B can be attributed to the difference of depth of cut as in both cases, the chip cross section is the same.

By comparing the cutting force components between cases with different A_c value, namely cases A and C, it can be clearly observed that cutting forces are larger in cases A where A_c has the largest value. F_x component is slightly more influenced by the change of A_c and values of both F_x and F_y increase almost 2-fold whereas the change for F_z is less significant. When cases B and C are also compared, the same conclusions can be drawn; however the difference of cutting forces values in lower between cases B and C than between cases A and C.

After the results regarding maximum cutting forces values are discussed, it is considered important to investigate the variations of specific cutting force values. Specific cutting forces are obtained by dividing the cutting force component values by A_c and are denoted with the symbol K_c and the relevant coordinate axis namely x, y and z. Consequently, the trends observed when comparing specific cutting forces between cases A and B are the same with the trends observed when comparing cutting forces values due to constant A_c value in these cases. What is considered particularly important is that, when comparing the specific cutting force values between cases A and C, the latter cases exhibit higher values in most cases, except for K_{cx} at cutting speeds over 300 m/min. The same conclusion can be drawn when comparing cases B and C but the difference between specific cutting forces values in these cases is smaller (Fig. 2).

Apart from the analysis regarding cutting force and specific cutting force values, it is also important to analyze the results regarding the cutting forces graphs between cases with constant or different A_c values at the same cutting speed value, namely 300 m/min. The cutting forces graphs are displayed for a full rotation of the milling



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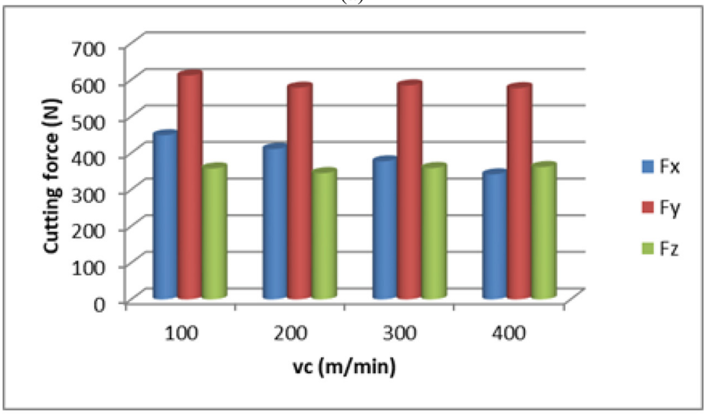

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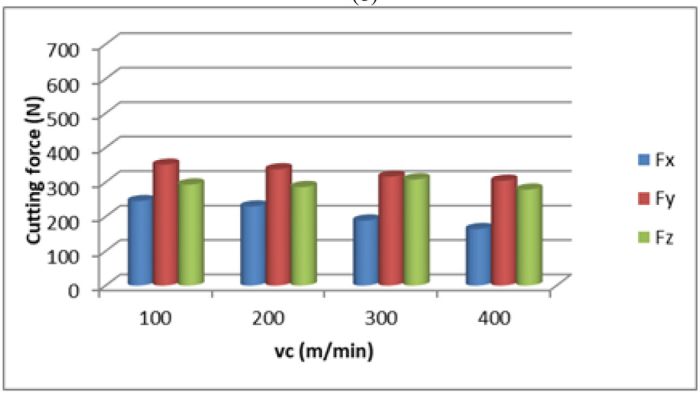

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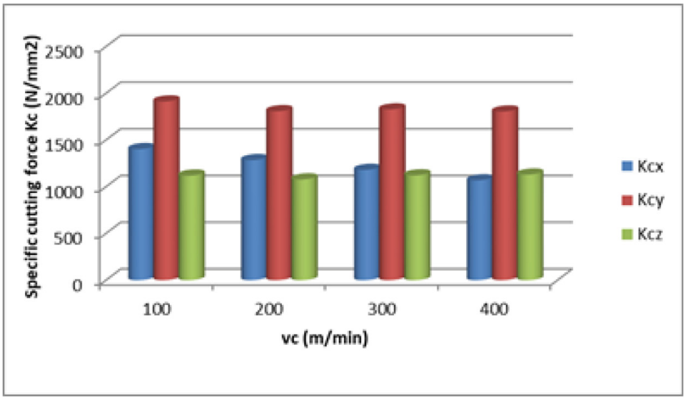
Fig. 1. Maximum cutting force components values for the three sets of experiments conducted in the present work.



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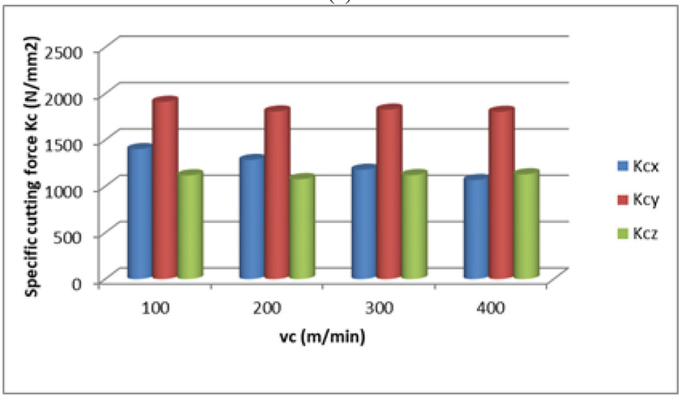

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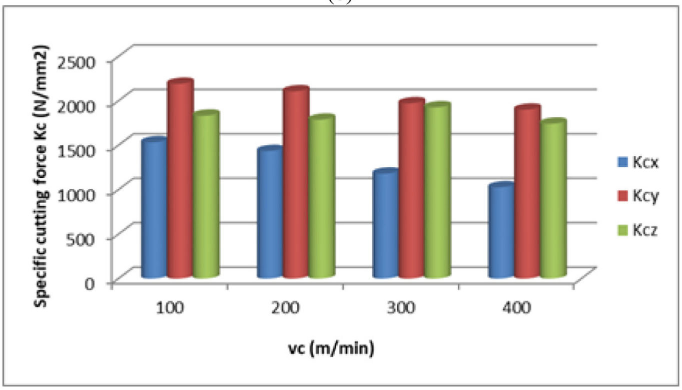

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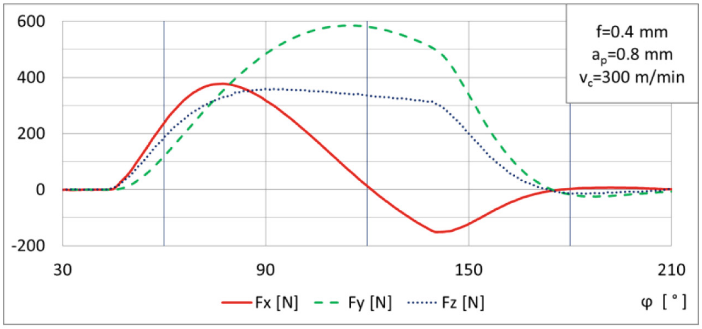
Fig. 2. Maximum specific cutting force components values for the three sets of experiments conducted in the present work.

head in two different coordinate systems; the first one is corresponding to the coordinate system of the dynamometer (xyz) with which the cutting forces were recorded and thus represents the coordinate system for the workpiece, whereas the second one is corresponding to the coordinate system of the cutting tool, which means that it represents the coordinate system of the cutting insert. Cutting forces graphs in the workpiece coordinate system are presented in Fig. 3. The shape of the graph of each force component is almost the same in each case (A, B or C). F_y and F_z components of force have always positive force values, gradually increasing to a maximum value when the cutting insert comes in contact with the workpiece and then gradually decreasing when the cutting insert reaches the exit side of the workpiece. Although F_y and F_z have only positive values, F_x exhibits both positive and negative values; when the cutting insert reaches the entrance side of the workpiece and is in contact with it large positive values are observed and when it reaches the symmetric plane of the workpiece and moves towards the exit side, F_x values become negative and afterwards they become gradually zero. These observations are consistent with the kinematics of face milling; F_x, which is measured on the feed direction of the tool is actually more influenced from the rotational motion of the tool and its values change direction when the insert passes from the symmetric plane towards the exit side, indicating that at the first half of the milling process, the cutting action goes in one direction and at the second half, it goes in the opposite direction [20, 21].

From Fig. 3, it can be observed that, between cases with constant chip cross section, namely A and B, there is an evident change in F_x curve, a lower change in F_y curve but F_z is remains almost unchanged.

As it was noted in the analysis of maximum force values, F_x and F_y values become lower with a decrease of depth of cut and eventually, F_x becomes lower than F_z in the region where the positive values of F_x are occurring. Furthermore, it is observed that the graph is not symmetric with the middle plane. Between cases A and C, there is an obvious change in the magnitude of all cutting forces components, mainly due to the smaller chip cross section value in case C. The largest decrease of cutting forces is observed in the cases of F_x and F_y and it is noted that although the shape of F_x and F_z curves remain almost the same, regarding F_y curve, there is a shift of the region with the maximum force value to the right side, which means that the maximum value of force occurs almost after the cutting insert reached the symmetric plane while moving towards the exit side. The same trends are apparent when comparing the graphs of cases B and C, although the change of cutting force values is lower than the one occurring in between cases A and C.

Finally, after the variation of cutting force components relative to the workpiece coordinate system was analyzed, the variation of cutting force components relative to the cutting tool coordinate system will be examined. In order to calculate the cutting force components values relative to the cutting tool coordinate system, namely F_f, F_p and F_c, special formulas are employed for the transformation of forces between the two coordinate systems, derived from geometrical considerations and analysis of the force components. After the transformation is conducted, F_f, F_p and F_c graphs are presented in Fig. 4. Cutting force components relative to the cutting insert have almost the same shape and their values are always positive. Their values are increasing when the cutting insert is at the entrance side and moves towards the symmetric plane, they reach a



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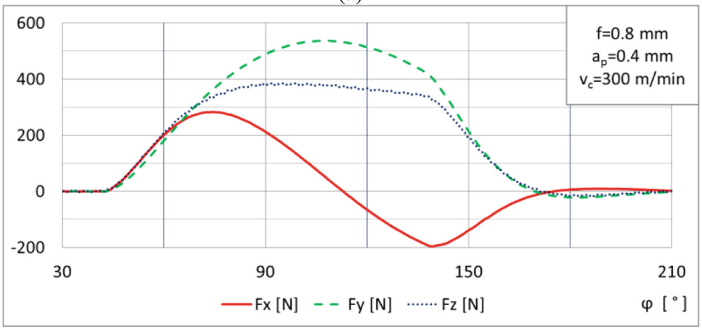

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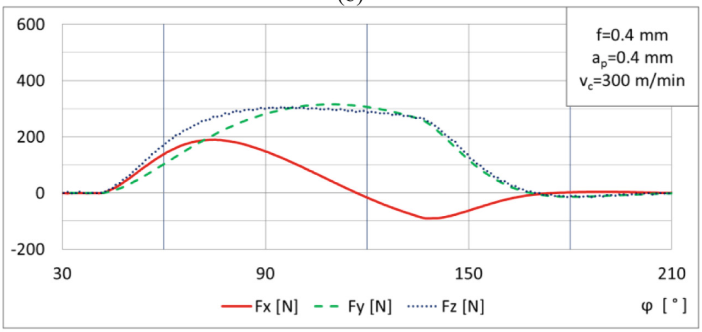

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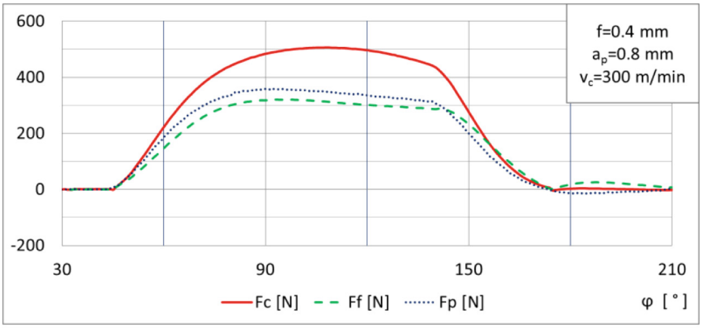
Fig. 3. Variation of cutting force components values for the three sets of experiments measured at a coordinate system relative to the workpiece.

region with maximum force value and are reduced to zero when the cutting insert is close to the exit side of the workpiece. Although generally, the force values in the two coordinate systems are not the same, there are cases where forces of the two coordinate systems may coincide, such as F_c and F_y when the insert is exactly on the symmetric plane. As in the case of F_x, F_y and F_z, the graphs are not symmetric with the middle plane, due to several reasons such as the change of the motion track of the tool edge, the momentum values of the resulting motion and the chip cross section. As it was seen with F_x, F_y and F_z components of force, these observations are again consistent with the kinematics of face milling [20, 21].

By comparing the graphs between cases with constant Ac value, namely A and B, it can be seen that F_c values remain almost the same, F_p values increase and F_f values exhibit a considerable decrease at case B, in which depth of cut is lower. F_c component has the largest values among the three components, followed by F_p and F_f; however the difference between the two latter is larger in case B where the depth of cut is lower. When comparing cases with different A_c value, namely A and C, there is a considerable change regarding F_c force component as well as F_f but F_p is the least affected by the change of chip cross section value. In every case it is again confirmed that the magnitude of all force components is reduced with a decrease of A_c value. Furthermore, similar trends are observed when comparing cases B and C.



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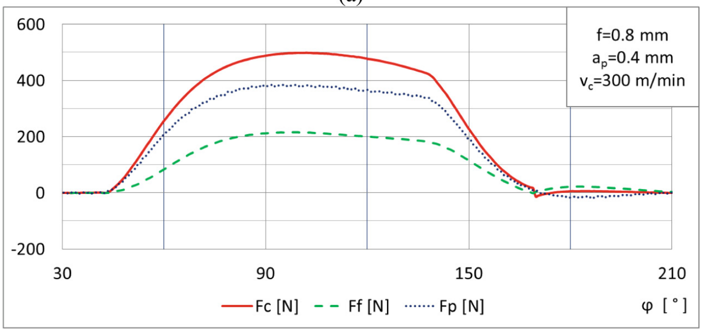

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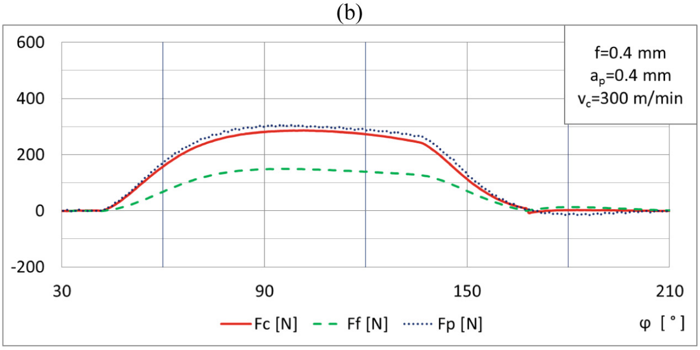

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Fig. 4. Variation of cutting force components values for the three sets of experiments measured at a coordinate system relative to the cutting insert.

4 Conclusions

In the present work, the influence of depth of cut on cutting forces during face milling of steel is examined. Cutting forces are obtained for cases with different depths of cut at various cutting speed values and cases with either constant or different chip cross section (A_c) are considered. Apart from cutting forces, specific cutting forces are also calculated and studied as well as the variation of cutting forces during a single revolution of the milling head both in a coordinate system relative to the workpiece and the cutting insert. Several conclusions are drawn:

- In cases with constant A_c, where the same chip cross section is removed in one pass, it was found that an increase of depth of cut resulted in larger cutting forces, especially for F_x and F_y components. In these cases, the variation of cutting speed resulted in a decrease of cutting forces, as it was anticipated, especially for the F_x component of force. Similar trends were noted for the specific cutting forces.
- In cases with different A_c, a clear increase of cutting force components was observed when A_c was increased. In fact, a 2-fold increase of A_c by doubling the depth of cut at constant feed rate resulted in an almost 2-fold increase of F_x and F_y force components. In the case of 2-fold increase of A_c by doubling the feed rate at constant depth of cut, an increase of forces was also noted, but to a lesser extent. Furthermore, it was observed that specific cutting forces decreased with an increase of A_c in all cases.
- Analysis of cutting forces graphs confirmed the aforementioned findings for the cutting force components both in the coordinate system attached to the workpiece and the cutting tool.

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