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INVESTIGATING THE IMPACT OF FEED AND CUTTING SPEED ON CUTTING FORCES FOR THE INCREASE OF SURFACE REMOVAL RATE IN FACE MILLING

Face milling is used for the manufacturing of engineering surfaces. A significant part of the produced surfaces pertains to flat surfaces with high quality. Surface quality, in turn, is connected to the machining conditions used in the process. In this paper, the influence of feed and cutting speed on cutting forces is experimentally investigated, with a view to increase surface removal rate A_w (mm^2/min) of the process. The experimental results are treated with ANOVA, indicate a high influence of the feed on all components of the cutting force. With the analysis, optimum conditions may be obtained with the aim of lower cutting forces.

1. INTRODUCTION

In modern industrial practise, metal cutting is one of the most important and widely used manufacturing processes. Investigations on metal cutting technology pertain mostly to the features of tools, workpiece materials and cutting conditions; these parameters have an impact on process efficiency and final product quality. Selection of optimal machining conditions is a key factor in achieving the latter [1, 2]. Milling is one of the commonly used machining operations and especially face milling is used for machining and structuring of flat surfaces.

In the relevant literature of metal cutting, cutting forces, surface quality and workpiece integrity are commonly experimentally and theoretically investigated [3, 4]. Additionally, modelling is also considered, either through mathematical or numerical models; modelling of milling, where the use of a multipoint tool is required, is more demanding than in turning. Li et al. [5] used Oxley's theory to present mathematical models for the prediction of forces in face milling. Tapoglou and Antoniadis [6] developed a simulation model embedded in a commercial CAD environment to simulate tool kinematics, considering tool geometry, for the prediction of surface roughness. Hadad and Ramezani [7] used mathematical models to produce a CAD software that is able to evaluate the influence of different milling process parameters on pattern geometry. Regarding numerical modelling, Gylienė and Eidukynas [8] presented a three dimensional Smooth Particle Hydrodynamics model and Zhang et al. [9] a Finite Element model for the simulation of face milling. Nowadays the improvement of the up to date manufacturing technologies, including machining, through modelling methods and techniques, has a relevant role in the Industry 4.0 concept. The latter statement is true because the satisfaction of the increasingly more unique customer needs requires elaboration of new solutions [10, 11].

Regarding the efficiency of milling, expressed in a similar way to other machining operations, material removal rate Q_w (mm^3/min) may be used. However, the modern applied approach, considers milling with constant depth of cut, i.e. at one machining pass. Thus, a new indicator, namely surface removal rate A_w (mm^2/min) is used [12]. In this case, an increase in efficiency is a result of an increase of the feed and/or the cutting speed. Increase of the cutting speed has technical limitations at the industrial practice, connected to tool life. Feed increase can only be efficient with the use of proper tool geometry. It is worth noting that increase of the feed and alteration of the chip cross section shape influence the cutting forces and the machined surface roughness. Furthermore, the investigation of feed is important because in the case of higher demand milling, e.g. near net shape manufacturing at one pass, the surface removal rate can be increased. As a result, important cutting parameters, including the cutting forces, are significantly influenced [13].

The aim of this work is to present the influence of feed and cutting speed on cutting forces, under various cutting conditions. It is possible to determine the extent to which the surface removal rate can be increased without resulting to exaggerating cutting forces in face milling. For this reason, experiments were carried out with three different feeds per tooth and three different cutting speeds. For each combination of the aforementioned cutting conditions, the cutting forces were registered and processed. The results, were then treated by the Analysis of Variance (ANOVA) method and useful conclusions were drawn.

2. EXPERIMENTAL

For the cutting forces measurements in the experimental procedure, one insert was mounted on the milling head, as can be seen in Figure 1. For feed per tooth, three different values, namely, 0.2, 0.9 and 1.6 mm were used. Similarly, three different cutting speeds, i.e. 50, 225 and 400 m/min were employed. In all cases, the depth of cut was constant at 0.4 mm. In Table 1, the experimental conditions and the equipment used are tabulated.

Figure 1 – Machine tool and milling head with one insert

Forces measurements were taken by a Kistler 9257A dynamometer with 3 components. Furthermore, three Kistler 5011A charge amplifiers and a CompactDAQ-9171 data collector with 4 channels, made by National Instruments were employed. All measurements were fed into the measurement software, prepared by LabView programming language.

Table 1 – Experimental equipment and conditions

Machine tool:	Perfect Jet MCV-M8 vertical machining centre
Tool:	Sandvik R215.44-15T308M-WL GC4030 coated carbide insert. κ_r=90°; γ_o=0°; α_o=11°; r_ε=0.8 mm
Milling head type:	Sandvik R252.44-080027-15M face milling head, D_s=80 mm
Workpiece:	Normalised C45 (1.0503) carbon steel, HB 180; width of the machined surface 58 mm; length: 50 mm.
Cutting data**:**	cutting speed: v_c=50, 225, 400 m/min width of cut: b_w=58 mm depth of cut: a_p=0.4 mm feed per tooth: fz=0.2, 0.9, 1.6 mm

The forces in machining by rotating tools are measured in a coordinate system attached to the workpiece. Due to the fact that the cutting forces are interpreted in a coordinate system attached to the tool edge, the forces diverge from F_c, F_f, F_p forces system. The forces measured in milling, namely F_x, F_y and F_z, are equal to the previous ones only in specific orientations. Figure 2(a) depicts the cutting forces and their variation in a cutting period that is in the removal of a single chip. The dynamometer coordinate system can also be seen in the same Figure. Based on the theory shown in Figure 2(a), the theoretical scheme of the F_x, F_y, F_z variation versus time, can be drawn in Figure 2(b).

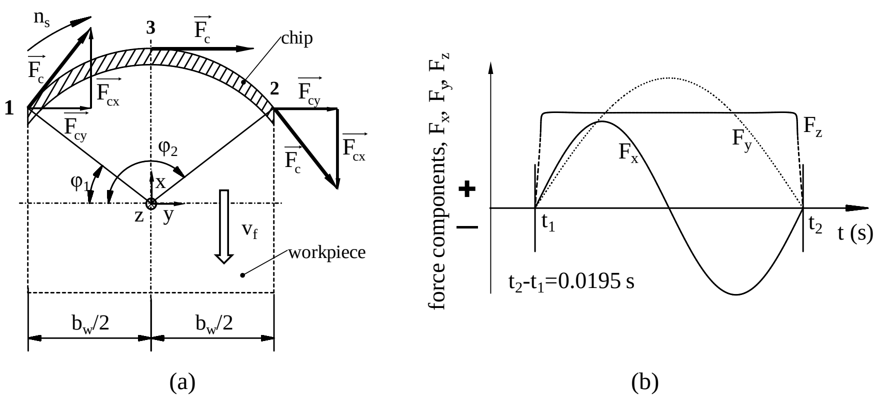


Figure 2 – Change of force components during one tool rotation: a) in the coordinate system of the workpiece and b) in the coordinate system of the tool [12]

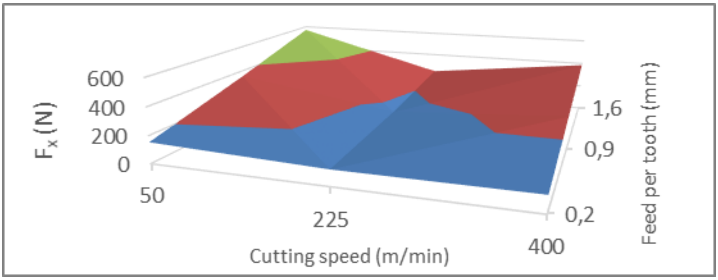
Table 2 contains the maximum forces obtained from the described procedure.

Table 2 – Maximum cutting forces

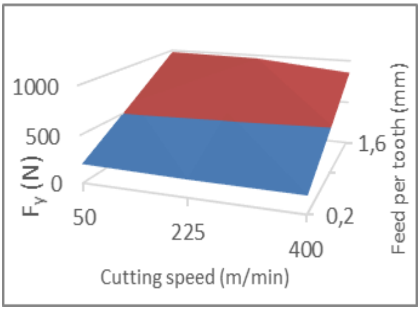
Run No.	Feed per tooth (mm)	Cutting speed (m/min)	Maximum cutting forces (N)		
			F_x	F_y	F_z
1	0.2	50	153.89	200.20	172.00
2		225	113.34	182.87	212.63
3		400	117.34	180.23	223.32
4	0.9	50	353.62	586.61	421.00
5		225	161.37	548.44	376.89
6		400	245.38	508.03	382.68
7	1.6	50	569.72	980.63	613.96
8		225	243.35	963.18	547.31
9		400	385.72	858.20	547.14

3. RESULTS AND DISCUSSION

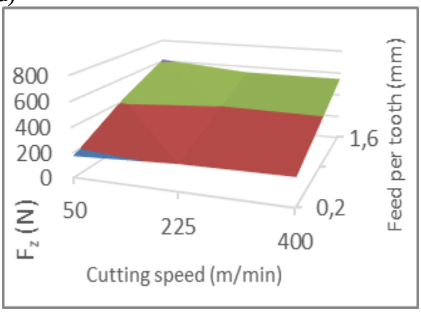
Figures 3 (a) to (c) show the dependence of the three cutting force components on feed and cutting speed.



(a)



(b)

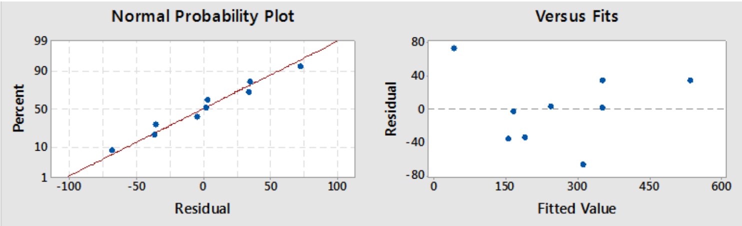


(c)

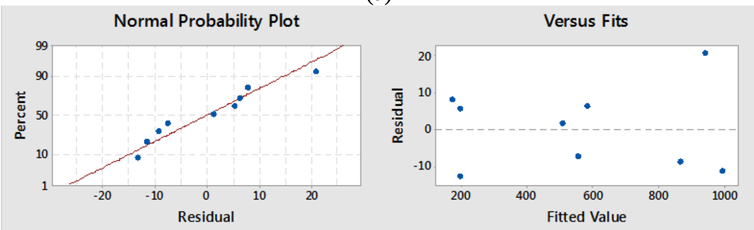
Figure 3 – F_x, (b) F_y and (c) F_z versus feed per tooth and cutting speed

From Table 2 and Figure 3 some useful results may be obtained. In the examined domain cutting force component F_x is the highest among all cutting force components, with the smallest cutting speed and the highest feed values. The value of F_x exceeds 400 N when the cutting speed is under 100 m/min and feed is 1 mm. If the cutting speed is increased above 200 m/min and the feed is chosen lower than 0.9 mm, the maximum value of force does not exceed 200N.

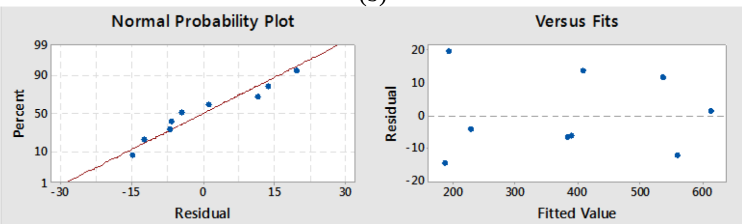
Furthermore, the maximum value of F_y changes little; it is practically constant. However, with the increase of feed it increases 5-fold. Additionally, the maximum value of F_z increases a little with low values of feed and when increasing the speed, for feed equal to 0.9 mm, it decreases a little.



(a)



(b)

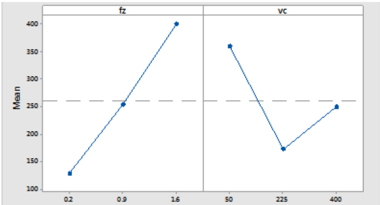


(c)

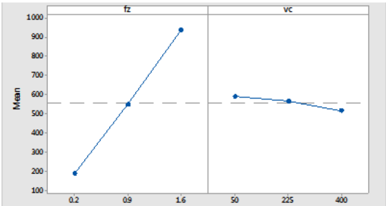
Figure 4 – Residual plots for (a) F_x, (b) F_y and (c) F_z force component.

For the experimental results an ANOVA procedure was followed. The analysis was performed separately for each force component. The R^2 for F_x, F_y and F_z component was 91.82%, 99.88% and 99.42%, respectively. All three values are close to 100%, indicating an acceptable value. In Figure 4 (a)-(c) the residual plots can be seen, for each force component. It can be observed from the normal probability plots that the residuals generally fall on a straight line implying that the errors are dispersed normally. Furthermore, versus fits do not follow any pattern.

Figure 5 shows the main effects plots for the three force components. It may be seen that feed per tooth has a high influence on the force results and its optimum value is 0.2 mm for all force components. On the other hand, the influence of cutting speed greatly affects F_x, with optimum value 225 m/min. The other two force components are lightly affected by the cutting speed.



(a)



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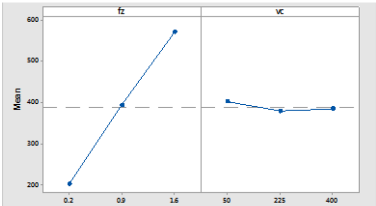

(c)

Figure 5
Main effects plot for (a) F_x, (b) F_y and (c) F_z force component.

4. SUMMARY

The surface removal rate (A_w) in cutting, having constant cross section, is influenced by the values of cutting force and feed. In this paper the results of the investigations are presented in which the experimental data are chosen so that the value of A_w is increases 64-fold. The goal of the examination was to investigate in this case to what extant the maximum values of forces F_x, F_y and F_z measured in cutting, increased having different combinations of feed and cutting speed. It is ascertained that the ratio of the highest and the lowest values of the measured forces are $F_{xmax}/F_{xmin} = 5$, $F_{ymax}/F_{ymin} = 5.5$ and $F_{zmax}/F_{zmin} = 2.9$, therefore, none of them achieved even 10% of the value of A_w increase. Varying the values of cutting speed and feed it can be stated that by the increase of speed, the maximum values of the measured forces decrease having either low or high values of feed.

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