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Productivity analysis of machining milled surfaces

J Kundrák[1], **V Molnár**[2*], **I Deszpoth**[1]

[1] Institute of Manufacturing Science, University of Miskolc, Hungary
[2] Institute of Management Science, University of Miskolc, Hungary

*szvmv@uni-miskolc.hu

Abstract. Milling is a widely applied procedure because its kinematic versions and applied tools allow the machining of several surfaces and surface combinations. In this study the efficiency of material removal performed by face milling was analyzed when machining aluminum alloys by diamond tools. The analyzed material is the material of an automotive industrial component that is produced in large scale. When producing components in large scale the analysis of material removal efficiency and profitability of machining is particularly important. The efficiency of material removal has a direct impact on the time parameters characterizing the production. The focus of the paper is how the productivity can be increased by the selection of technological data that reduce the machining time of the procedure or increase the values of material removal rate or surface rate. Experiments and analyses were carried out for machining prismatic components among operating conditions. It is found that in a given workpiece-gadget-machine-tool system, a significant reduction in production time and therefore cost savings can be reached by appropriately chosen cutting data while the geometric accuracy and surface quality of the component remain as specified in the part drawing.

1. Introduction

Super hard tools such as diamond tools allow efficient chip removal owing to their special characteristics. Artificial diamond tools have a polycrystalline material structure; therefore, damage (e.g. cracks) from the load and stress do not affect the whole diamond volume. Among the tool materials, diamond is among the hardest and has high wear-resistance, a low friction coefficient and high heat conduction capacity. These characteristics, mainly the heat resistance and chemical activity, determine the chip removal process. The friction coefficient of the diamond tool is extremely low and is independent of the cutting speed. The extent of chip deformation is low, there is no secondary chip deformation and the friction within the chip is negligibly low. Owing to the lower heat production which is the consequence of these properties, and to the high heat conduction capacity of the tool, the cutting temperature is low. Therefore cutting by diamond tool is also called ‘cold cutting’. Tool wear is mechanical wear and independent of the cutting speed because of the hardness and the low temperature, depending only on the machined path (area of the machined surface). This means that at different cutting speeds the same surface area can be machined. In machining soft and non-ferrous metals and their alloys, in contrary to the changes experienced in cutting by carbide tools, increasing the cutting speed produces essentially no differences in chip deformation, the friction coefficient, cutting forces, the machined length and the surface roughness, all of which remain almost constant. Owing to this the speed can be increased to the extent that is allowed by the rigidity of the system of machine-tool / gadget / tool. In our experiments analyses were carried out for cutting of aluminum alloy by diamond coated insert. The excellent properties of diamond tool can be utilized in cutting non-ferrous metals if they are considered in the technology design. The effects of alteration of cutting data are analyzed from an economical point of view in this paper. While there are several calculation methods for economic efficiency. In our research the efficiency of material removal was analyzed.

To calculate the theoretical value of material removal rate (MRR, Q_w) the most typical method is to consider cutting data and the dimension of the parameter is given in mm^3/min. Mukherjee et al. carried out experiments for turning mild steel in order to determine the optimum value of MRR on the basis of cutting data [1]. Zhong et al. carried out turning experiments and calculated the theoretical MRR values for carbide steel. In their paper MRR served as a decision parameter for minimizing the energy consumption of machining [2]. Mia et al. optimized the MRR on the basis of cutting data in their hard turning experiments with the Taguchi method [3]. Satyanatayana et al. applied a genetic algorithm in their analyses when turning super alloys [4].

Table 1. Application possibilities of MRR.

Procedure	MRR calculation	Dimension of MRR	Application of MRR, workpiece material, source
Turning	Theoretical formula	cm^3/min	Optimization of cutting data on the basis of MRR (Ni-alloy) [9], [10]. Tool life analysis on the basis of MRR (Heat resistant super alloy [11]
Turning	Mass and density of removed material	mm^3/min	Effect of cutting data on MRR (AL-alloy) [12]
Turning	Specific change in workpiece volume (machining time considered)	mm^3/s	Simulation and experiment for determining MRR (Inconel) [13]
Turning	Removed mass	g/min	Multi-attribute optimization of cutting data (EN353 alloy) [14]
Milling	Theoretical formula	mm/min	Cutting data selection [15]
Milling	Theoretical formula, modified by cycle time	mm^3/min	Effect of cutting data on MRR (En19) [5]
Milling	Change in mass and density of workpiece	mm^3/min	Determination of optimum MRR, relational analysis coupled with fuzzy logic (Al-alloy) [16]
Micro milling	Theoretical formula	mm^3/min	Effect of cutting data on MRR (Al-alloy) [17]
Plasma cutting	Mass difference before and after machining	g/s	Optimization of cutting data on the basis of MRR [18]
Honing	Removed volume, total area of honing stones, honing time	cm^3/min	Effect of cutting data on MRR (steel) [19]
Polishing	Luo-Dornfeld model for abrasive machining	-	Construction of a theoretical model [20]

Table 1 summarizes further results beyond turning for milling and other procedures. Among these, the research of Parashar and Purotrit is particularly relevant; they considered the cycle time of machining in calculation of the material removal rate [5]. In efficiency analyses of machining the

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surface quality [6] and accuracy [7] are important limiting factors of cutting because these requirements have to be fulfilled by the surfaces among every circumstance. The efficiency of machining was described by the practical parameter of material removal rate. In the practical parameter not only the cutting data but also the time data characterizing the machining are considered [8].

2. Methodology

One method for efficiency analysis of machining procedures is the comparison on the basis of efficiency parameters (material removal rate, Q_w [mm^3/s]; surface rate, A_w [mm^2/s]). These parameters provide information about the intensity of cutting technology. The parameter Q_w provides information about the specific material volume removed and A_w about the specific surface removed with a certain procedure. The theoretical values of these parameters can be calculated on the basis of the cutting data characterizing the procedure. For face milling Q_w and A_w can be calculated as:

$$Q_w = a_p \cdot a_e \cdot v_f \text{ (mm}^3\text{/s)}, \quad (1)$$

$$A_w = a_e \cdot v_f \text{ (mm}^2\text{/min)}, \quad (2)$$

where a_p is depth of cut [mm]; a_e is width of cut [mm]; v_f is feed rate [mm/min].

From the formulas of Q_w and A_w it can be seen that the calculation of the two parameters differs only in the consideration of depth-of-cut (DoC). In our case DoC is considered basically as fixed, therefore it is enough to analyze only the factors influencing surface rate. In machining the plain surfaces of a given prismatic workpiece the length of the tool path remain the same even if the cutting data change. Therefore, in machining these types of workpieces the material removal rate (thus the efficiency of machining) is basically determined by the v_f feed rate. Calculation of feed rate in face milling is:

$$v_f = f_z \cdot z_s \cdot n_s \text{ (mm/min)}, \quad (3)$$

where f_z is feed per edge [mm/edge]; z_s is number of edges [-]; n_s is revolution per minute (rpm) of the tool [1/min].

From equation (3) it is clear that an increase in the material removal rate when machining the analyzed prismatic workpiece can be obtained by increasing three parameters:

1. Increasing the f_z feed per edge;
2. Increasing the rpm (thus the cutting speed) of the tool;
3. Increasing the number of teeth (cutting edges).

In this research the first two parameters were chosen for increasing the efficiency. The first parameter (f_z) is determined on the basis of literature results and experiments. The increase of rpm of the tool (n_s) should be selected on the basis of the cutting characteristics of the diamond tool when cutting aluminum alloys, considering of the limits of the machine tool in use. The increase of teeth number (z_s) can be ensured by the increase of tool diameter when a given tool construction is applied. The number of teeth is considered as fixed in the experiment described in this paper. The theoretical material removal rate provides information about the efficiency of the physical material removal, namely when the tool is cutting (other necessary movements of tool such as approach of the workpiece or positioning to another surface is not considered). Therefore it does not provide information about the whole machining process. That is why it is necessary to introduce a practical parameter that allows the measurement of the operation by both the different time parameters connected to the machining (e.g. machining time, base time, piece time, operation time, etc.) and the parameters characterizing the efficiency of material removal. In our research the value of the practical material removal rate is analyzed by considering the machining time and then the base time in the formula.

The introduced parameter can be calculated as [21]):

$$Q_w \sim L \cdot v_f / T_x \text{ [mm}^3\text{/min]}, \quad (4)$$

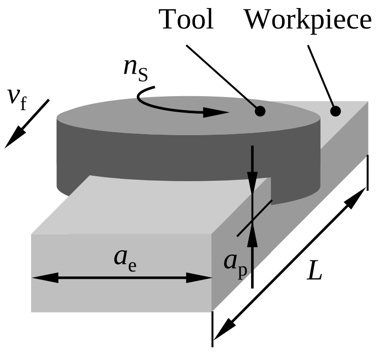
where T_x is the time characterizing the machining (machining time, base time).

3. Experiment design

The goal of the experiments was to determine the efficiency of the face milling operation. The machining time and the base time of the operation element were measured. The objective of this was to determine the values of the practical material removal rate taking these time values into account. The experiments were carried out in the plant where the analyzed component is produced in large-scale; therefore, the applied cutting data correspond to the technological circumstances of the manufacturing. In the experiments the effects of the change in the feed per tooth and the rpm of the tool were analyzed. Based on these we chose the feed rate, which is an additional factor (besides depth-of-cut and width-of-cut) that directly determines the machining time.

The milling experiments of the prismatic component (gearbox housing) were carried out on a DMG MORI DMC 60 H linear type horizontal machining center. The milling tool is the Lach Diamant MB-X3-063-08-Z12/P type face milling head (soldered diamond insert). The diameter of the milling head is D_s=63 mm. Number of teeth is z_s=12; tool cutting edge angle is κ_r=90°. Workpiece material is AlSi9Cu3(Fe). The cutting data applied in the experiments are summarized in table 2. In the table the fixed and the variable data are also included.

Table 2. Cutting data.



a_p [mm][a]	1.5				
a_e [mm]a	35				
n_s [1/min]	12000	12500	13000	13500	14000
v_c [m/min]	2375	2474	2573	2672	2771
f_z [mm/edge]	feed rate, v_f [mm/min]				
0.12	17280	18000	18720	19440	20160
0.13	18720	19500	20280	21060	21840
0.14	20160	21000	21840	22680	23520
0.15	21600	22500	23400	24300	25200
0.16	23040	24000	24960	25920	26880

[a] Average values

4. Discussion

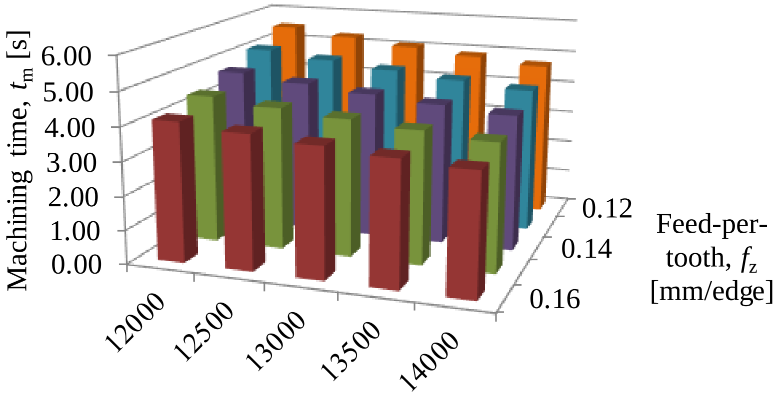
The machining time and base time of machining were calculated. The machining time describes the time during which the tool is cutting, while the base time includes the supplementary times. In the experiments these supplementary times were the time of tool change, workpiece approach and overrun. The machining time varied between 3.54 and 5.50 s at different feed per teeth and feed rates (figure 1). The decreases in machining time compared to the highest value are summarized in table 3.

The base times are summarized in figure 2. The difference between the highest (19.38 s) and the lowest (17.43 s) values is greater than that of the machining times. The reason for that is the presence of the constant supplementary time. In table 4 the rates are summarized compared to the highest value.

We believe that the practical parameter of the material removal rate is more useful than the theoretical version because the other times connected to the machining are also considered in it when analyzing the efficiency. The theoretical values are summarized in table 5 and figure 3.

The machining operation element (face milling) is characterized in the most appropriate way by the base time (table 6 and figure 4).

The practical material removal rate values calculated by the base time are significantly lower than the values of the theoretical parameter when the feed per tooth (f_z) and the feed rate (v_f) combinations are the same. The reason for this is that the base times are 3.53-4.92-times higher than the machining times. The values of the theoretical parameter vary between 15120 and 23520 mm^3/s (table 5). The values of the practical parameter calculated with the base time vary between 4288 and 4768 mm^3/s (table 7). In the case of the theoretical parameter the highest value is 1.56 times higher than the lowest one, while it is 1.11 for the practical parameter. The rates of material removal rate are summarized in figures 3 and 4. While the lowest value of the theoretical parameter is 64% of the highest one, the difference in the practical parameter is smaller (90%).



	12000	12500	13000	13500	14000
0.16	4.12	3.96	3.81	3.66	3.54
0.15	4.40	4.22	4.06	3.91	3.77
0.14	4.71	4.52	4.35	4.19	4.04
0.13	5.07	4.87	4.68	4.51	4.35
0.12	5.50	5.28	5.07	4.89	4.71

rpm of main spindle, n_s

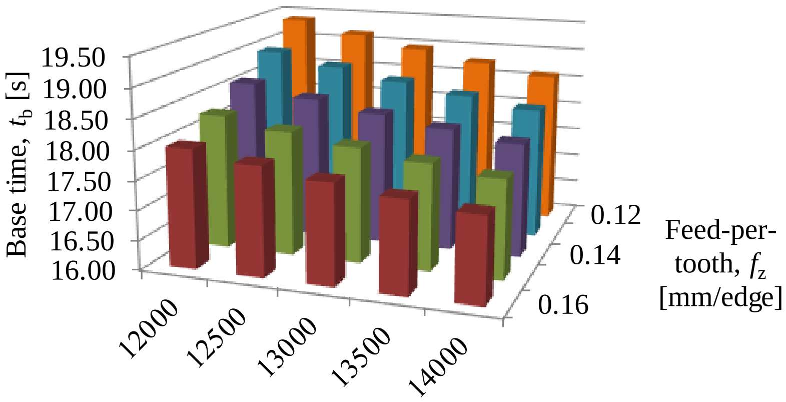
Figure 1. Machining times at different rpm and feed-per-tooth values.

Table 3. Decrease in machining times; basis: n_s=12000 1/min and f_z=0.12 mm/edge.

% t_m		rpm of main spindle, n_s [1/min]				
		12000	12500	13000	13500	14000
Feed-per-tooth, f_z [mm/edge]	0.12	0%	-4%	-8%	-11%	-14%
	0.13	-8%	-11%	-15%	-18%	-21%
	0.14	-14%	-18%	-21%	-24%	-27%
	0.15	-20%	-23%	-26%	-29%	-31%
	0.16	-25%	-28%	-31%	-33%	-36%

The efficiency of machining can also be expressed by the times connected to the machining / production (tables 3 and 4). When analyzing these values it is important to consider the time as the basis of the analysis that expresses mostly the main goal of the analysis. In the face milling operation of machining prismatic components that contain complex surfaces, this specific time is the base time that includes the supplementary times of machining beyond machining time. We have found that this time is significantly higher than the machining time.

To extend the efficiency analysis the material removal rate proved also to be appropriate, but its theoretical value, which is used widely in literature, does not characterize the machining in a very accurate manner. The parameter was modified by including the base time and thus describes the milling operation more exactly. This new parameter is named practical material removal rate. By applying it, we can gain a clearer picture about the efficiency of material removal of the operation. This practical parameter was analyzed by different feed per tooth and rpm of main spindle values. We demonstrated how the theoretical material removal rate and the base time-based practical parameter change when increasing the above mentioned cutting data (figures 3 and 4).



	12000	12500	13000	13500	14000
0.16	18.01	17.84	17.69	17.55	17.43
0.15	18.28	18.11	17.95	17.80	17.66
0.14	18.60	18.41	18.24	18.07	17.93
0.13	18.96	18.76	18.57	18.40	18.24
0.12	19.38	19.16	18.96	18.77	18.60

rpm of main spindle, n_s

Figure 2. Base times at different rpm and feed-per-tooth values.

Table 4. Decrease in base times; basis: n_s=12000 1/min and f_z=0.12 mm/edge.

% t_b		rpm of main spindle, n_s [1/min]				
		12000	12500	13000	13500	14000
Feed-per-tooth, f_z [mm/edge]	0.12	0%	-1%	-2%	-3%	-4%
	0.13	-2%	-3%	-4%	-5%	-6%
	0.14	-4%	-5%	-6%	-7%	-8%
	0.15	-6%	-7%	-7%	-8%	-9%
	0.16	-7%	-8%	-9%	-9%	-10%

Table 5. Values of theoretical material removal rates.

Theoretical material removal rate, Q_w [mm^3/s]		rpm of main spindle, n_s [1/min]				
		12000	12500	13000	13500	14000
Feed-per-tooth, f_z [mm/edge]	0.12	15120	15750	16380	17010	17640
	0.13	16380	17063	17745	18428	19110
	0.14	17640	18375	19110	19845	20580
	0.15	18900	19688	20475	21263	22050
	0.16	20160	21000	21840	22680	23520

%Q_w		f_z [mm/edge]				
		0.12	0.13	0.14	0.15	0.16
n_s [1/min]	12000	0	8	17	25	33
	12500	4	13	22	30	39
	13000	8	17	26	35	44
	13500	13	22	31	41	50
	14000	17	26	36	46	56

Figure 3. Increase in theoretical material removal rates at different rpm and feed-per-tooth values; basis: n_s=12000 mm/min and f_z=0.12 mm/edge.

Table 6. Values of practical material removal rates.

Practical material removal rate, $Q_{wp,b}$ [mm^3/s]]		rpm of main spindle, n_s [1/min]				
		12000	12500	13000	13500	14000
Feed-per-tooth, f_z [mm/edge]	0.12	4288	4337	4383	4427	4469
	0.13	4383	4431	4475	4517	4557
	0.14	4469	4514	4557	4598	4636
	0.15	4545	4589	4631	4670	4707
	0.16	4615	4657	4697	4735	4768

%$Q_{wp,b}$		f_z [mm/edge]				
		0.12	0.13	0.14	0.15	0.16
n_s [1/min]	12000	0	2.2	4.2	6.0	7.6
	12500	1.1	3.3	5.3	7.0	8.6
	13000	2.2	4.4	6.3	8.0	9.6
	13500	3.3	5.4	7.2	8.9	10.4
	14000	4.2	6.3	8.1	9.8	11.2

Figure 4. Increase in practical material removal rates at different rpm and feed-per-tooth values; basis: n_s=12000 mm/min and f_z=0.12 mm/edge.

5. Summary

The efficiency analysis of face milling operation element of plain surfaces of prismatic components that contains many surfaces was carried out by the calculation of times necessary for the machining. The cutting data for machining aluminum material with diamond tool were determined by the material removal characteristics of diamond cutting. On the basis of this the possible ways (strategies) of economically efficient cutting were designated and specified in the experimental setup. The possible extent of base time reduction was analyzed when increasing the feed and the feed rate. In our analyses the practical material removal rate was calculated on the basis of the base time of machining, which characterized the milling operation appropriately. This strategy proved to be efficient because it was found that in the practical value of material removal rate a 3.3-4.2% and 6.6-7.6% increase in efficiency can be reached, respectively. Considering the parallel change in the two cutting data, an 11% efficiency increase is reached. In further research aimed at increasing efficiency we plan to analyze the effects of increasing the number of tool teeth on the efficiency of material removal.

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