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ENERGY CONSUMPTION ANALYSIS AND PARAMETER OPTIMIZATION IN HIGH-FEED MILLING OPERATION

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A B S T R A C T

Improving the performance, efficiency and productivity of the machining, reducing energy consumption and establishing control over the machining process are the main goals of the production technologies development. This paper provides the basis for establishing of a process management and determining of optimal conditions for performing high-feed milling, as a special machining method. An experimental study of the analysis of the influence of process parameters, namely depth of cut and feed rate, on the output parameters of high-feed milling were carried out. As output indicators of the performance of the high-feed milling, namely the energy efficiency of the machine tool and the productivity of the machining process were analysed. Based on experimental data, analysis and modelling of the material removal rate per unit of time and electrical energy consumption were carried out. A workpiece made from aluminium was machined on a three-axis machining centre. By using the boundaries of the domain of process parameters and the optimization objective function, the optimization of the values of the process parameters was carried out. As an optimal solution, the following process parameters were obtained: cutting depth $a_p = 2$ *mm and feed rate* $v_f = 1500$ *mm/min.*

1. INTRODUCTION

The modern market constantly demands better quality of the product, its improved functionality, low cost of the product and delivery in the shortest possible time interval. Consequently, manufacturers are forced to shorten the time from order to delivery, and reduced costs related to production, by reducing the number of engaged production means and process operations (Gresik, 2008).

The manufacturer's responds, which was based on the use of advanced machining processes, is impossible to imagine without the use of special, unconventional and hybrid processes. Continuous improvement of the

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performance of the processes is a basic task in production technologies, which requires an ever wider application of advanced machining processes, as well as concepts of sustainable production (Davim, 2017). Attention is focused to special machining methods, and especially to highly efficient methods whose performance enables efficiently fulfillment of quality and accuracy requirements, as well as significant time and cost savings during machining process. Special machining methods are developed in order to increase productivity, quality and accuracy of machining, as also cost and time reduction. High-efficiency and high-performance machining methods are based on a significant change in some of the geometric or process parameters. These changes refer to their significant increasing or decreasing; and the most common are: increasing of cutting speed, increasing of cutting depth, increasing of feed rate, decreasing the contact on the cutting tool edge, etc.

2. HIGH-FEEED MILLING

High-feed milling (HFM) is used in roughing and semi-finishing processes, where the main goal is to remove as much material from the workpiece as possible in the shortest possible time, with maximum preservation of the cutting tool edge. HFM can be considered as type of highly efficient machining, where large values of feed rate per tooth f_z or feed rate v_f are used, which results in a high degree of material removal from workpiece. This leads to reduction in machining time and a maximization of the material removal rate per time unit (*MRR*).

The mechanism of high-feed milling is based on the so-called "chip ticking" effect. It is the effect of chip thinning or its retention at the recommended value. If the effect of reducing the entering angle is observed, while keeping the chip thickness constant, a significant increase in the value of the feed rate per tooth can be achieved (Figure 1).

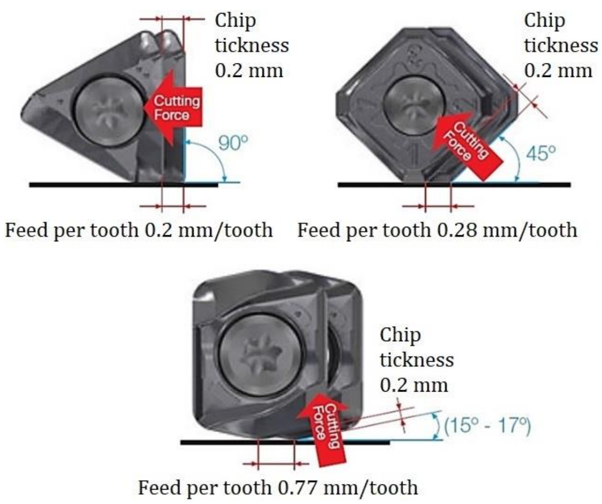

Figure 1. Influence of the entering angle on feed rate per tooth

Small values of the entering angle of the cutting tool lead to the directing of the resultant cutting force in the direction of the tool axis (Figure 2). This results in stable machining because the cutting tool has much greater rigidity in the axial direction than in the radial direction. Orientation in the radial direction leads to a greater deformation of the tool and thus to a higher machining error. Smaller cutting depth and the directing of the resultant cutting force in the direction of the tool axis, enables increasing of the cutting width. This results also in increasing of material removal rate and enables more efficient cooling and lubrication.

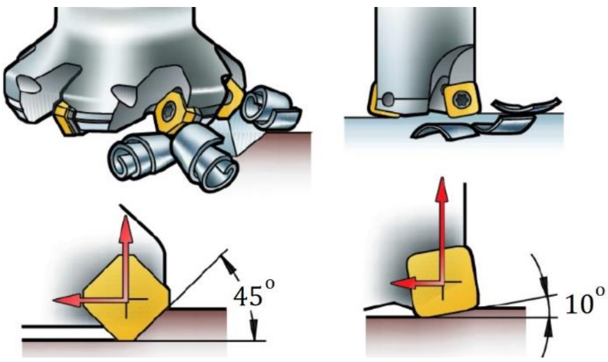

Figure 2. Influence of the entering angle on cutting force resultant

High-efficiency milling processes primarily include high-feed milling, which is accompanied by the appearance of negative effects such as tool deflection, intense tool wear, high cutting forces, vibrations, and similar (Zhao et al, 2022). Zhu et al. (Zhao et al, 2021) investigated the influence of cutting parameters and tool geometry on cutting forces and tool wear during high-feed milling with ceramic inserts. The possibilities of high-feed milling during machining titanium super-alloy Ti6Al4V with PCD tools is analysed in (Araujo et al, 2020). Jiang et al. (Jiang et al, 2023) developed a model for identification and analyses of tool wear and tool vibration during high-feed milling. In order to enable the maintenance of a constant cutting force, researches (Saikumar et al., 2012) developed feed rate adaptation control systems for high-speed milling of hardened EN24 steel. From the point of view of energy consumption, high-feed milling is an energy-efficient machining process. Zhang et al. (Zhang et al., 2020) investigated the energy efficiency in high-feed milling and concluded that with an increase in the feed rate, there is an improvement in the energy efficiency of the milling process.

3. EXPERIMENTAL SETUP

The experiment was performed on a three-axis machining centre EMCO Concept Mill 450, which was equipped with a control unit Sinumerik 810D/840D (Figure 3). The available power of the machine is 11 [kW], while the maximum spindle speed is 12000 [rpm]. As a cutting tool, a face mill with circular inserts by Sandvik R300-1240M was used; the material designation of the inserts is GC4230. The designation of the face mill is R300-050Q22-12M. The nominal diameter of the face mill is D_c = 50 (mm), and the effective diameter of the face mill is D_e = 38 (mm). The face mill has Z_n = 4 circular inserts, mechanically fixed with a screw to the body of the face mill.

Figure 3. Experimental setup

A face mill with circular inserts was chosen for application in high-feed milling in order to analyse its possibilities during exploitation. Due to the characteristic geometry of the workpiece, there is a variable value of the entering angle, which depends on the insert diameter D_t (mm) and the cutting depth a_p (mm). The feed rate per tooth depends on the thickness of the chip, i.e. the maximum thickness of the cutting layer, as well as on the cutting depth and the diameter of the insert. The material of the workpiece, which was used to perform the experimental research, was aluminum. Due to its low density, it is often used in cases where it is necessary to reduce the weight, especially for parts of the aviation and automotive industry, but also for other functional parts of mechanisms in machines.

A full orthogonal design of the engineering experiment was used, whereby all variations of variable parameters were combined with each other, which gave an experiment plan of nine combinations (Table 1). Cooling and lubricating fluids were not used during the high-feed milling. During the entire experiment, the spindle speed n was constant with value of n = 3000 (rpm), so the cutting speed was constant. The milling width was also constant with value of a_e = 30 (mm).

A 3-phase MAVOWATT 30 analyser was used to measure power and energy consumption during the experiment. This device support standards EN50160, EN61000-4-7 and EN61000-4-15, which are relevant for measuring power supply quality, and EN61000-4-30, which specifies measuring voltage quality procedures. The software used to analyse the experimental results was *DesignExpert* 7.1.5 through which a mathematical model of the behaviour of the output machining parameters were generated. The software was intended for experiment planning, modelling, analysis of model accuracy, determination of the significance of individual parameters, as well as optimization of results, and graphical presentation.

Table 1. Experiment plan

Experiment number	**Cuting parameters variations**	
	Cutting depth a_p [mm]	Feed rate v_f [mm/min]
1	2.0	1500
2	2.0	1000
3	2.0	500
4	1.5	1500
5	1.5	1000
6	1.5	500
7	1.0	1500
8	1.0	1000
9	1.0	500

4. RESULTS AND DISSCUSION

Data processing and analysis of the results obtained by practical measurements was performed based on experimental measurements. The data analysis, statistical processing and modelling of energy consumption during high-feed milling were presented below. The analysis of the measured results was carried out using the statistical method of analysis of variance (ANOVA). In addition to measuring of the electrical energy consumption, for the purpose of analysing the observed process, the components of the cutting force were also measured. At higher values of the cutting depth, the cutting force F_x has a higher value than the cutting force in the direction of the axis of the cutting tool F_z. As the value of the cutting depth decreases, the opposite happens, and the value of cutting force F_z becomes greater than the value of cutting force F_x (Figure 4).

Using smaller values of the cutting depth, a smaller entering angle was obtained, so that the resultant of the cutting force was closer to the axis of the tool, which coincides with the previous theoretical settings. Smaller cutting depth and approaching the resulting cutting force to the direction of the tool axis, allows increasing of the cutting width in terms of keeping the resulting cutting force within certain limits.

The basic indicator of the energy efficiency of the machining process or the machining system during this experiment, the electrical energy consumption E (kWh) during high-feed milling was measured and analysed. With a change of the milling parameters, there is also a change in the energy efficiency of the machine tool, i.e. parameters such as the required power and the total consumed electrical energy.

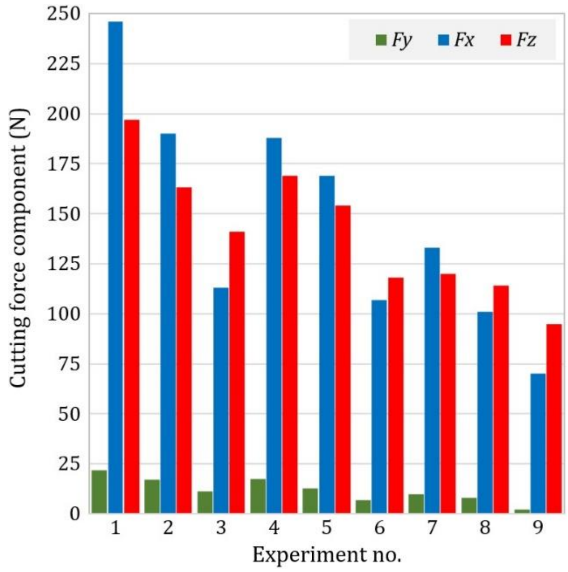

Figure 4. Measured cutting forces in axis directions

In the next table, calculated data of the productivity of the milling operation, which was represented by the degree of material removal rate per time unit, was obtain as a multiplication of the feed rate, the cutting depth and the cutting width, was added (Table 2).

Table 2. Experiment plan

Exp. no.	a_p (mm)	v_f (mm/min)	*MRR* (mm³/min)	*E* (kWh)
1	2.0	1500	90000	0.00512
2	2.0	1000	60000	0.00525
3	2.0	500	30000	0.01105
4	1.5	1500	67500	0.00434
5	1.5	1000	45000	0.00529
6	1.5	500	22500	0.00854
7	1.0	1500	45000	0.00402
8	1.0	1000	30000	0.00457
9	1.0	500	15000	0.00905

From the Table 2 can be concluded that the highest value of total consumed electrical energy E = 0.01105 kWh was obtained by applying the following parameters a_p = 2.0 mm and v_f = 500 mm/min, while the smallest value of consumed electrical energy E = 0.00402 kWh was obtained by using the process parameters a_p = 1.0 mm and v_f = 1500 mm/min. The lowest value of total consumed electrical energy during observed milling process occurs at the lowest cutting depth and at the highest feed-rate, and vice versa (Figure 5).

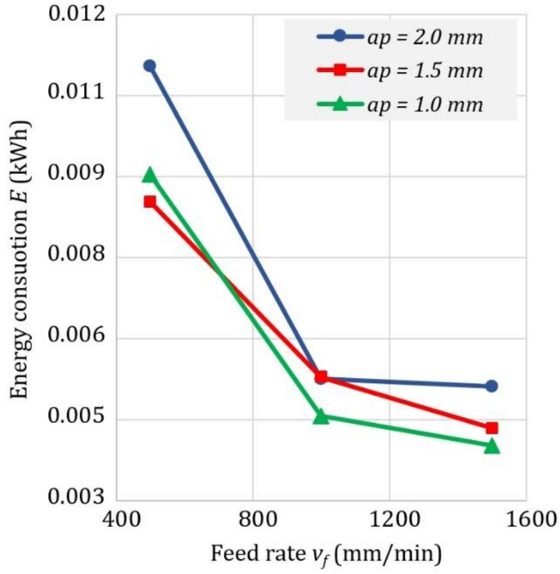

Figure 5. Influence of feed rate and cutting depth on the total energy consumption

In order to form a mathematical description of the changing of the total electrical energy consumption during the milling process based on the least squares method, a linear model was proposed and selected as opposed to a model with parameter interaction (Quadratic vs 2FI). After the variance analysis, the results shown in Table 3 were obtained. Based on the values of the F and P parameters, it can be concluded that the model was significant.

Table 3. Results of the ANOVA

Source	Adj SS	Adj MS	F parameter	Source
Model	$4.9\cdot10^{-5}$	$1.22\cdot10^{-5}$	28.88083	0.0033
A - a_p	$2.38\cdot10^{-6}$	$2.38\cdot10^{-6}$	5.618571	0.0768
B - v_f	$3.83\cdot10^{-5}$	$3.83\cdot10^{-5}$	90.37341	0.0007
A²	$4.11\cdot10^{-7}$	$4.11\cdot10^{-7}$	0.969748	0.3805
B²	$7.87\cdot10^{-6}$	7.87·10-^{6}	18.56158	0.0126
Residue	$1.7\cdot10^{-6}$	$4.24\cdot10^{-7}$		
Total	$5.07\cdot10^{-5}$			

Statistically, the mean value of the consumed electrical energy $\bar{x}$ = 0.0064 was obtained, with a standard deviation of the SD = 0.00065, with the value of the signal-to-noise ratio S/N = 13.1. The regression coefficient was R^2 = 0.97, which proves the alignment of the measured and modelled data. Based on the above mentioned data, it can be concluded that the model is adequate. The mathematical dependence between the consumed electrical energy and the process parameters, the cutting depth a_p and the feed rate v_f, was given on the basis of the following formula:

$$E = 0.02 - 0.0042 \cdot a_p - 2.1 \cdot 10^{-5} \cdot v_f + 0.008 \cdot a_p^{\ 2} + 7.93 \cdot 10^{-9} \cdot v_f^{\ 2} \quad (1)$$

By using the previously mentioned formula in the software, the response of the model of the consumed electrical energy during the milling process, obtained on the basis of various parameters, was formed. Observing the diagram from Figure 6, it can be concluded that with increasing of the feed rate and decreasing the cutting depth, the total consumption of electrical energy decreases, and while with a decreasing of the feed rate and increasing of the cutting depth, the opposite situation occurs, i.e. the total consumption electrical energy during milling process increase. This is a consequence of the shorter processing time, which was obtained during use a high value of the feed rate and relatively higher power of the machine tool.

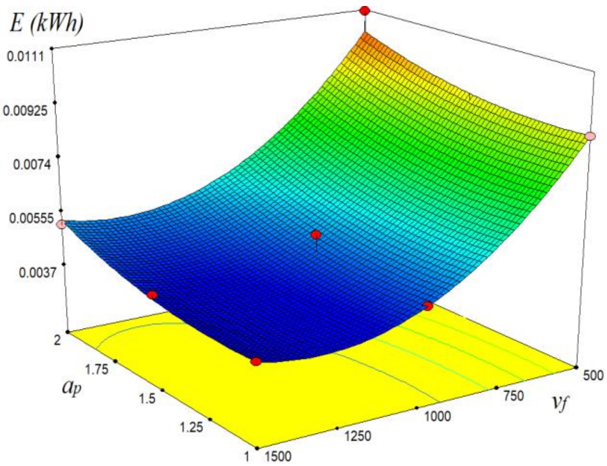

Figure 6. Response surface plot – effect of the feed rate and cutting depth on the total energy consumption

4.1 Process parameter optimisation

In the case of rough milling, the main goal is to remove as much material as possible from the workpiece in the shortest possible time, and all this with the less amount of total consumed electrical energy. The final goal, which refers to the greatest possible material removal in the shortest possible time, can be represented by maximizing productivity, i.e. the degree of material removal rate per time unit. The goal of consuming as less energy as possible can be represented by minimizing the electrical energy consumption. For all parameters, the same importance and degree of priority in terms of impact on the optimization process and procedure was defined (Table 4).

Based on the set mathematical formulation of the optimization, several suitable solutions were obtained, ordered according to the desirability of the solution, which represents the percentage of satisfaction of the optimization goals. As an optimal solution, the following process parameters were obtained: cutting depth a_p = 2 mm and feed rate v_f = 1500 mm/min. The amount of material removed rate per time unit, for optimal parameters, is *MRR* = 90000 mm³/min, and the amount of total consumed energy is *E* = 0.005274 kWh.

Table 4. Mathematical framework for optimisation

Parameter	Goal	Lower Limit	Upper Limit
a_p (mm)	Stay in a domen	1	2
v_f (mm/min)	Stay in a domen	500	1500
MRR (mm³/min)	Maximise	15000	90000
E (kWh)	Minimise	0.00402	0.01105

The diagram of the optimization results which is in function of cutting depth and the feed rate is shown in the Figure 7. According to the diagram and the previously set of optimization goals, it can be concluded that it is preferable to use higher values of the process parameters, which is in accordance with the theoretical settings. The percentage of the optimization goals satisfaction, with the optimal solution, is 91%.

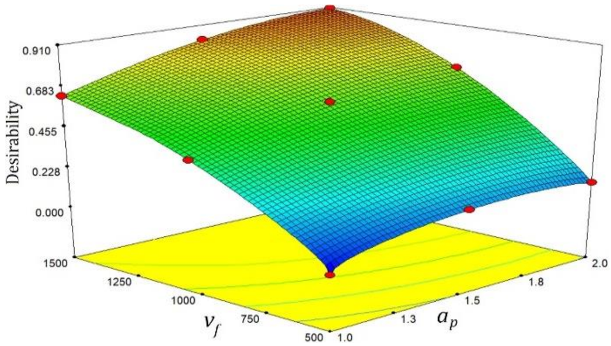

Figure 6. Diagram of the optimization desirability results

4. CONCLUSION

The analysis of the results showed that using lower values of the cutting depth and higher values of the feed rate results in less total consumption of electrical energy during milling, while in the opposite case, during using higher values of the cutting depth and lower feed rate, relatively higher consumption of electricity was obtained. By using the developed model, the optimization of the high-feed milling process on the machining centre was carried out. As a criterion, it was chosen that the cutting depth and the feed rate were in the domain between the smallest and the largest value, and their optimal values were obtained. By summarizing the research and defining the mathematical bases for static analysis, model development and the mathematical framework for the optimization process, resulted in a successfully developed methodology for planning of the high-feed milling operations. Future research should be based on the analysis of high-feed milling of other materials, i.e. hard-to-machine materials, such as: titanium, hardened steel, grey cast iron and similar.

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References:

Araujo, A. C., Fromentin, G., & Blandent, P. (2020). Investigation on PCD cutting edge geometry for Ti6Al4V high-feed milling. *The International Journal of Advanced Manufacturing Technology*, *111*, 1785–1796. doi: 10.1007/s00170-020-06086-z

Davim, J. P. (2017). *Sustainable Machining*, Springer - Verlag, Berlin.

Gresik, W. (2008). *Advanced Machining Processes of Metallic Materials: Theory, Modelling and Application*. Elsevier, Amsterdam.

Jiang, B., Nie, Q., Zhao, P., Ma, Q., & Sun, S. (2023). Identification method for Instantaneous Friction and Wear Energy Density Variation of High-Feed Milling Tool Flank. *Applied Sciences*, *13*(8), 4807. doi: 10.3390/app13084807

Saikumar, S., Shunmugam, M.S. (2012). The International Journal of Advanced Manufacturing Technology, vol. 59, p. 869 – 884, DOI: 10.1007/s00170-011-3561-6

Zhang, T., Liu, Z., Sun, X., Xu, J., Dong, L., & Zhu, G. (2020). Investigation on specific milling energy and energy efficiency in high-speed milling based on energy flow theory. *The International Journal of Advanced Manufacturing Technology*, *59*, 869 - 884. doi: 10.1016/j.energy.2019.116596

Zhao, P., Zhang, L., Jiang, B., & Wang, Y. (2022). Instantaneous friction energy consumption and its evolution of high energy efficiency milling cutter. *Advances in Mechanical Engineering*, *14*(5), 16878132221095917. doi: 10.1177/16878132221095917

Zhao, P., Cheng, K., Jiang, K., Jiang, B., & Zuo, L. (2021). Development of the innovative differential tool wear modelling for high-feed milling and its experimental verification. *Proceedings of the Institution of Mechanical Engineers Part B Journal of Engineering Manufacture*, *235*(4), 095440542094922. doi: 10.1177/0954405420949226

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