

blade feed has been adopted according to the manufacturer's recommendations (table I).

TABLE I. List of tools and applied technological parameters

No. of tool	Tool diameter d , mm	Feed rate per cutting edge f_z , mm/cutting edge	Cutting speed v_c , m/min	Radial depth of cut a_e , mm	Axial depth of cut a_p , mm	No. of cutting edges
t_1	20	0.070	120	10	10	3
t_2	14	0.055	120	7	7	3
t_3	8	0.035	120	4	4	3
t_4	7	0.030	120	3,5	3,5	3
t_5	5	0.025	120	2,5	2,5	3

Note: Eliminated and selected tools for analyzing the effectiveness of programmed machining strategies.

TABLE II. Summary of the analyzed sequences of tools for processing the set of machining features analyzed (TOE)

Sequence S_k	Time * T_{Mo} , min	Subsequent tools in k -th sequence				
S_1	36.36	t_1	t_2	–	–	t_5
S_2	35.42	t_1	–	t_3	–	t_5
S_3	41.2	t_1	–	–	t_4	t_5
S_4	50.35	t_1	–	–	–	t_5
S_5	40.23	–	t_2	–	–	t_5
S_6	41.23	–	–	t_3	–	t_5
S_7	45.18	–	–	–	t_4	t_5
S_8	58.48	–	–	–	–	t_5

* For: $a_e = 0.5d$ and $a_p = 0.5d$.

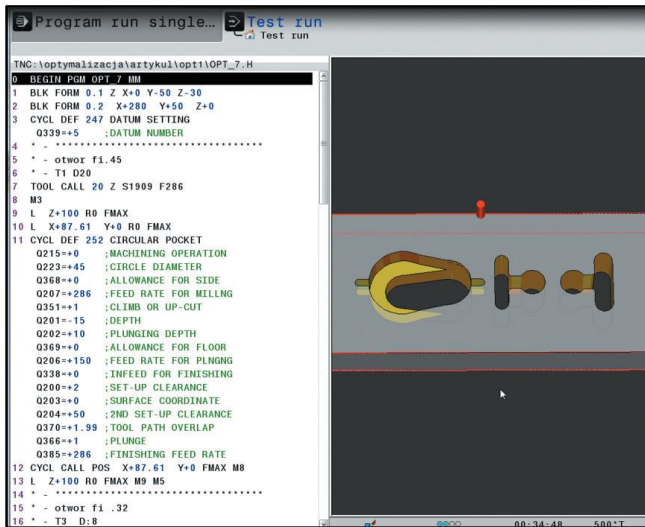


Fig. 2. Machining simulation with round pocket milling cycle declaration in Heidenhain TNC-640 controller simulator

Research results and their evaluation

The machine tool power is one of the basic limiting factors in planning a machining process for specific machines. The net cutting power (kW) in the analyzed case of C45 steel hardness of 32 HRC was determined according to the known formula:

$$P_c = \frac{a_e a_p v_f k_c}{60 \cdot 10^6} \quad [\text{kW}] \quad (1)$$

where: a_p – axial cutting depth in mm, a_e – radial cutting depth in mm, v_f – feed rate in mm/min, k_c – material factor determining cutting resistance in N/mm^2 .

According to equation (1), increasing the cutting depth and feed rate is associated with an increase in power demand (fig. 3) with high material removal rate (fig. 4), as defined by the equation:

$$Q_v = \frac{a_p a_e v_f}{1000} \quad [\text{cm}^3/\text{min}] \quad (2)$$

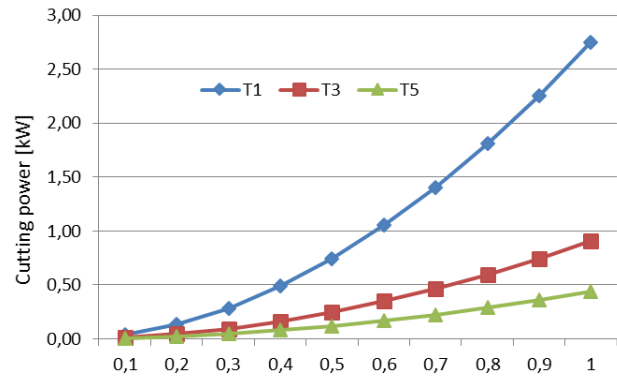


Fig. 3. Effective cutting power for subsequent tools of selected sequence S_2 , for different values of radial depth of cut: $a_e = w_g \cdot d$ and axial $a_p = w_g \cdot (d/2)$

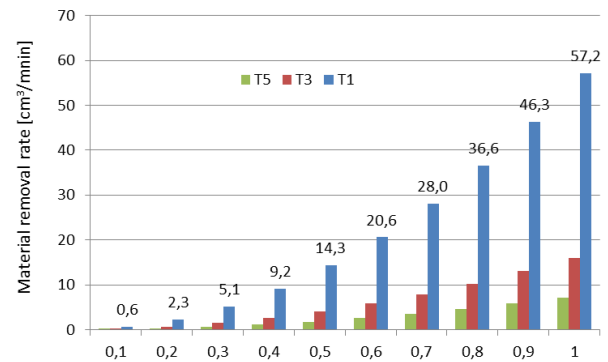


Fig. 4. Comparison of the material removal rate for individual tools from the analyzed sequence S_2 for different radial cutting depths $a_e = w_g \cdot d$ and axial depth of cut $a_p = w_g \cdot (d/2)$

Increasing the cutting efficiency, however, is limited by the recommendations of the tool manufacturers, the geometry of the workpieces and the programming strategy of the workpiece, e.g. using programmable cycles. The machine-elicited machine operation times allowed the sequence to be selected with minimal processing time for all TOEs. Sequence No. 2 was selected from all sequences (table II) as follows:

$$\min T_{Mo}(F), \text{ where: } F = \bigcup_{i=1}^4 f_i \quad (3)$$

Analysis of subsequent process steps performed with the tools from Sequence No. 2 shows that there is a limit value of the radial depth of cut, after which the machine time cannot be shortened (table III). This is directly related to the geometric dimensions of the machining features and the diameters of the applied tools. With feature dimensions equal to tool diameters, machining time cannot be shortened, as shown in table III for t_{M3} time and t_5 tool.

TABLE III. Machine time values of subsequent machining operations from the selected sequence for variable radial depth of cut a_e , at a fixed value of $a_p = 0.5d$

a_e	t_{M1} for t_1 , min	t_{M2} for t_3 , min	t_{M3} for t_5 , min
$0.1d$	3.21	38.15	1.51
$0.2d$	2.86	33.85	1.51
$0.3d$	2.86	32.24	1.51
$0.4d$	2.46	31.84	1.51
$0.5d$	2.46	31.45	1.51
$0.6d$	2.46	31.05	1.51
$0.7d$	2.46	30.65	1.51
$0.8d$	2.46	30.65	1.51
$0.9d$	2.46	30.65	1.51
d	2.46	30.65	1.51

Among technological cutting parameters, the cutting speed is most influenced by the cutting speed and the depth of cut is the lowest [7]. With respect to the cost criterion, it is necessary to determine the value of the working life of the replacement tool, which can be carried out using computer programs provided by utility companies.

The machining time at a fixed depth of cut $a_p = 0.5d$ decreases markedly at the initial radial depth of cut (fig. 5) and then reaches the limit value for $a_e = 0.7d$. This value was adopted to the analysis of machining time variation for variable axial depth of cut a_p , tested in the range of $0.1 \cdot (d/2)$ to $d/2$. As for a_e , the feature geometry determines the time of the operation (fig. 6). The increase in depth to $a_p = 0.5R$ leads to a significant reduction in machining time, with slight changes in the operation time above this depth.

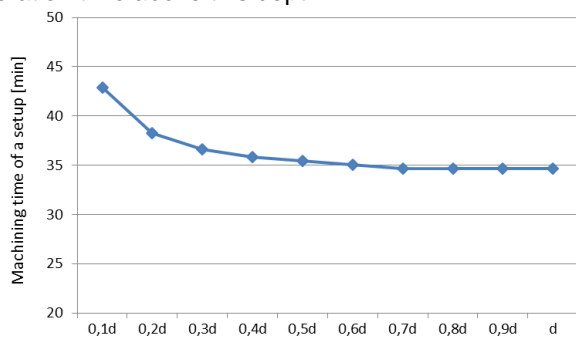


Fig. 5. Machining time at various settings of the depth a_e for fixed value of $a_p = 0.5d$

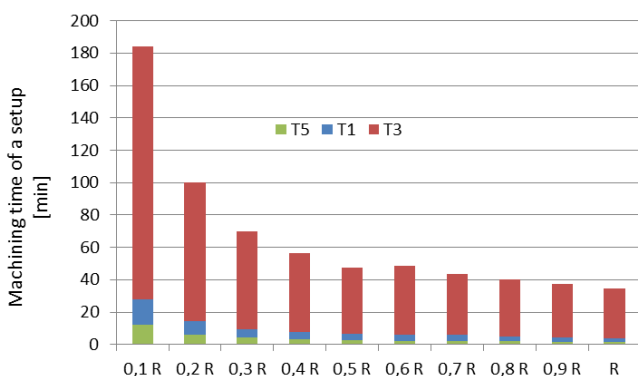


Fig. 6. Machine operating time at various depth settings a_e for fixed value $a_p = 0.7d$

Conclusions

Presented planning method of multistage machining a compound surface area of complex pockets allows for a rational selection of settings for such process parameters as: axial and radial depth of cut, within a fixed sequence of tools derived from a definite, and in an industrial practice usually limited tool resource.

An analysis of subsequent steps of a selected tool sequence shows that there is a limit value for cutting depth beyond which machining time cannot be shortened, which is directly related to the geometric dimensions of the features and the diameters of the tools used. Further analyzes may be conducted in the direction of determining these values for parameterized models with different feature dimensions without machining simulations, but requiring artificial intelligence and algorithmic inference techniques [4].

Determining the machining costs requires determining the tool life under cut and taking into account the tool change times, tool depreciation costs and machine tool utilization costs.

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