OPTIMIZATION OF TURNING PARAMETERS USING AN ALGORTIM BASED ON COMBINED LINEAR AND BINARY SEARCH METHODS

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Abstract: Optimization of cutting parameters in machining operations is a complex task requiring extensive knowledge and experience to reach the maximum potential for cost reductions in manufacturing. Through the work presented in this paper a cutting parameters optimization algorithm for roughing and finishing turning has been realized. The proposed optimization algorithm is based on a combination of linear search and binary search methods, heaving as objective criterion the minimization of the machining time. Examples for roughing and finishing turning have been presented to illustrate the application of the proposed algorithm and analyse the results.

Keywords: turning parameters optimization, cutting parameters, linear search and binary search algorithms

1. INTRODUCTION

Realizing a product with the required shape, size and properties depends not only on design but also on the choice of an appropriate machining process. Even though the selection of cutting tools and the calculation of cutting parameters is only a sub-function of the manufacturing process planning, it is a complex task requiring extensive knowledge and considerable experience affecting many other production parameters [1-4].

The use of computer technology for process planning was initiated more than fifty years ago being known as Computer Aided Process Planning (CAPP). Due to CAPP importance in manufacturing a large amount of research in this area have been conducted for actual implementations in industry. Optimization of cutting parameters in machining operations has been an area of high interest for many researchers in the frame of CAPP development which presented several approaches based on traditional and non-traditional optimization algorithms [5-10].

2. CUTTING PARAMETERS OPTIMIZATION ALGORITHM

2.1. Process parameters

Cutting parameters or cutting conditions include depth of cut (a_p), feed rate (f_n) and cutting speed (V_c). Selecting the optimal tools and cutting parameters is an essential task for each machining process planning, requiring extensive knowledge and experience to reach the maximum potential for cost reductions in manufacturing.

Cutting speed (V_c) is calculated according to equation [11]:

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$$V_c = \frac{\pi \cdot D_m \cdot n}{1000} \ [m/min] \quad (1)$$

Where D_m is the piece diameter and n is the turning speed.

Simultaneous turning with two machine heads on different features requires a synchronization of the turning speed. In practice, one head is leading, and the other head is following. For the leading head the turning speed (n) is calculated depending of maxim cutting speed according to equation [11]:

$$n = \frac{V_c \cdot 1000}{\pi \cdot D_m} \ [rpm] \quad (2)$$

For the second head the maxim cutting speed will be recalculated according to the turning speed of the leading head with formula (1).

The maximum feed is dependent on the allowable machine power and surface finish requirements. In general, the maximum feed in a roughing operation is limited by the machine power, cutting tool force and fixture. The maximum feed in a finish operation is limited by the surface quality requirements and can be calculated based on the surface roughness and tool nose radius.

The depth of cut is selected at maximum possible value depending on cutting speed, feed rate and constrains.

2.2. Constrains

Maximum and minimum permissible cutting speed:

$$V_{c\,min\,prod.} \leq V_c \leq V_{c\,max\,prod.} \quad (3)$$

Where V_c is the cutting speed and $V_{c\,min\,prod.}$ respective $V_{c\,max\,prod.}$ are the minimum and maximum cutting speed recommended by the tool manufacturer.

Maximum and minimum permissible feed rates:

$$f_{n\,min\,prod.} \leq f_n \leq f_{n\,max\,prod.} \quad (4)$$

Where f_n is the feed rates and $f_{n\,min\,prod.}$ respective $f_{n\,max\,prod.}$ are the minimum and maximum feed rates recommended by the tool manufacturer.

Maximum and minimum permissible depth of cut:

$$a_{p\,min\,prod.} \leq a_p \leq a_{p\,max\,prod.} \quad (5)$$

Where a_p is the depth of cut and $a_{p\,min\,prod.}$ respective $a_{p\,max\,prod.}$ are the minimum and maximum depth of cut recommended by the tool manufacturer.

Surface roughness limitations:

$$R_a \leq R_{a\,max} \quad (6)$$

Where R_a is the surface roughness $R_{a\,max}$ is the maximum surface roughness required.

Power limitation:

$$P_c \leq P_{c\,max} \quad (7)$$

Where P_c is the power required for machining and $P_{c\,max}$ is the maximum available power on the machine.

The power required for machining (P_C) is an essential condition for cutting parameters optimisation and is calculated according to equation [11]:

$$P_c = \frac{V_c \cdot a_p \cdot f_n \cdot k_c}{60 \cdot 10^3} \ [kW] \quad (8)$$

Where a_p is the depth of cut, f_n is the feed rate, V_c is the cutting speed and k_c is the specific cutting force calculated according to equation [11]:

$$k_c = k_{c1} \cdot h_m{}^{-m_c} \cdot \left(1 - \frac{\gamma_0}{100}\right) \quad (9)$$

Where γ_o is the rake angle, m_c is the raise of specific cutting force and h_m is the chip thickness calculated according to equation [11]:

$$h_m = f_n \cdot \sin KAPR \quad (10)$$

Where KAPR is cutting edge angle.

2.3. Objective function

An optimization problem consists of optimizing one or multiple objective functions while satisfying several constraints. For the work presented in this paper the objective is to minimize the machining time of each phase of the turning process according to the specific constrains.

The turning operation usually includes several passes of rough machining and a final pass of finishing. The machining time for one pass is calculated according to equation [11]:

$$T_c = \frac{l_m}{f_n \cdot n} \ [min] \quad (11)$$

Where T_c is the machining time, l_m is the total cutting length, f_n is feed rate and n is the turning speed.

2.4. Optimization algorithm

The algorithm is started with the calculation of the initial values for maxim cutting speed, maxim feed rate and maxim depth of cut depending on the type of operation and specific conditions.

The calculation of the maxim cutting speed is independent of the operation type and is taking into the consideration the raw material hardness and the specified durability of the insert according to equation:

$$V_{c\,max.} = V_{c\,max\,prod.} \cdot FC_i \cdot FC_m \ \left[\frac{m}{min}\right] \quad (12)$$

Where $V_{c\,max.}$ is the maximum cutting speed, $V_{c\,max.\,prod.}$ is the maximum cutting speed recommended value by tool manufacturer, FC_i is the correction factor for insert durability from Table 1 and FC_m is the correction factor for the hardness of the material from Table 2. In this paper, data from the tool manufacturer Sandvik is considered as an example.

Cutting speed has a high effect on tool life, having the greatest influence compared to depth of cut or feed rate. It is often possible to obtain much higher metal removal rates without reducing tool life by increasing the feed and decreasing the speed. Chip breaking is also depending on cutting speed, tool type and workpiece material.

Tools manufacturers, in general, are providing tables with correction factors for cutting speed, depending on the intended tool life or on the workpiece material. An example from tool manufacturer Sandvik of correction factor depending on tool life is presented in Table 1.

Table 1. Correction factor for insert durability from Sandvik [11].

Tool life (min)	10	15	20	25	30	45	60
Correction factor	1.11	1.0	0.93	0.88	0.84	0.75	0.70

Another example from tool manufacturer Sandvik of correction factor depending on workpiece material is presented in Table 2.

Table 2. Correction factor for the hardness of the material from Sandvik [11].

			Reduced hardness ←				Increased hardness →				
ISO/ ANSI	**MC(1)**	**HB(2)**	**-60**	**-40**	**-20**	**0**	**+20**	**+40**	**+60**	**+80**	**+100**
P	P2	HB 180	1.44	1.25	1.11	1.0	0.91	0.84	0.77	0.72	0.67
M	M1	HB 180	1.42	1.24	1.11	1.0	0.91	0.84	0.78	0.73	0.68
K	K2	HB 220	1.21	1.13	1.06	1.0	0.95	0.90	0.86	0.82	0.79
	K3	HB 250	1.33	1.21	1.09	1.0	0.91	0.84	0.75	0.70	0.65
N	N1	HB 75			1.05	1.0	0.95				
S	S2	HB 350			1.12	1.0	0.89				
H	H1	HRC(3) 60			1.07	1.0	0.97				

The maxim feed rate, in case of finish operation, is limited by the surface quality requirements and can be calculated based on the surface roughness and tool nose radius according to equation [12]:

$$f_n(Rz) = \sqrt{\frac{8 \cdot R_\varepsilon \cdot Rz}{1000}}\ [mm/rev] \tag{13}$$

Where R_ε is insert nose radius and Rz is the required surface roughness

Depending on the insert type and on the process stability a correction factor should be applied to feed rate calculation, the correction factor (FC_{pp}) is calculated according to equation:

$$FC_{pp} = FC_{process} \cdot FC_{insert} \tag{14}$$

where $FC_{process}$ is the correction factor depending on process stability and FC_{insert} is the correction factor depending on insert type, for conventional inserts is equal to 1 and for wiper inserts is equal to 1,8. Generally, the correction factor for process stability $FC_{process}$ is equal to 0,8 and should be adjusted according to the processing conditions in practice.

The maxim depth of cut in case of roughing is calculated depending on the maximum depth of cut recommended by the tool manufacturer and the total material removal.

After the initialization of variables and calculation of maxim cutting parameters for the start of optimisation, depending on the operation type, the algorithm will use a combination of linear and binary search methods to find the optimum combination of cutting parameters according to the objective function and the given constrains.

In case of finishing operation, if the given constrains are not satisfied with the current values of feed rate and cutting speed in combination with minim depth of cut, the algorithm will determine with respect to the objective function, which cutting parameter is better to reduce, feed rate or cutting speed. The selected parameter will be reduced according to a linear variation, the constrains will be checked again and the algorithm will continue until the constrains are satisfied. When this point is reached the algorithm will apply a binary search to find the optimum depth of cut.

In case of roughing operation, if the given constrains are not satisfied with the current values of feed rate and cutting speed in combination with the calculated depth of cut according to the number of passes, the algorithm will determine with respect to the objective function, which cutting parameter is better to reduce, feed rate or cutting speed. The selected parameter will be reduced according to a linear variation, the constrains will be checked again and the algorithm will continue until the constrains are satisfied or until, with respect to the objective function, is better to increase the number of passes.

3. RESULTS AND DISCUSSION

Several tests were conducted to validate the results of the optimisation algorithm. Below are presented two examples, one for finishing and one roughing turning, to illustrate the data generated on each iteration of the algorithm. The input data for each example are presented in Table 3.

Table 3. Input data for tests examples.

Operation	Ø Row [mm]	Ø Finish [mm]	Length [mm]	Material	Rz	Pc [kW]	Insert
Finishing	-	500	100	100Cr6	16	20	CNMG 19 06 12-QM 4025
Roughing	550	500	100	100Cr6	-	20	DNMG 15 06 08-PR 4315

The results generated on each iteration of the algorithm for finishing turning, corresponding to first example, are presented in Figure 1 and in Figure 2.

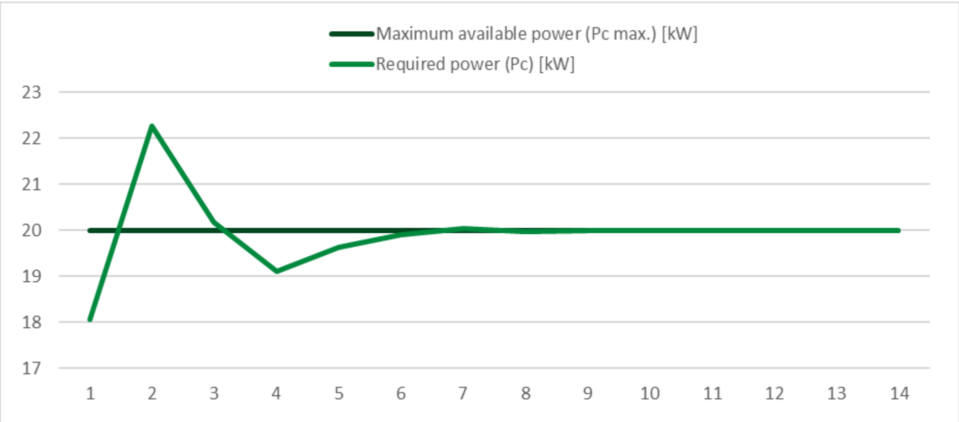

Fig. 1. Required power at each iteration for finishing turning.

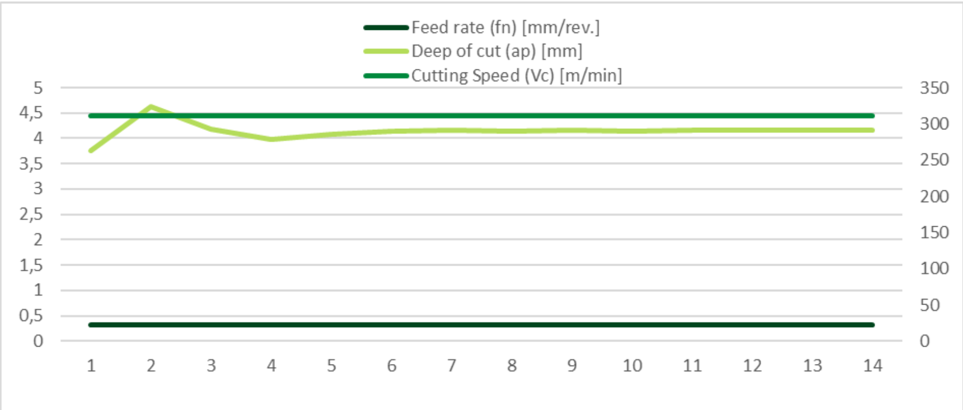

Fig. 2. Turning parameters at each iteration for finishing turning.

The results generated on each iteration of the algorithm for roughing turning, corresponding to second example, are presented in Figure 3, Figure 4. and Figure 5.

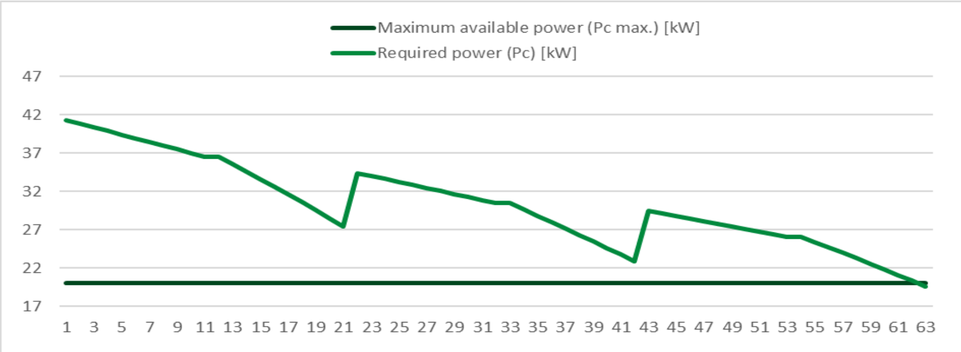

Fig. 3. Required power at each iteration for roughing turning.

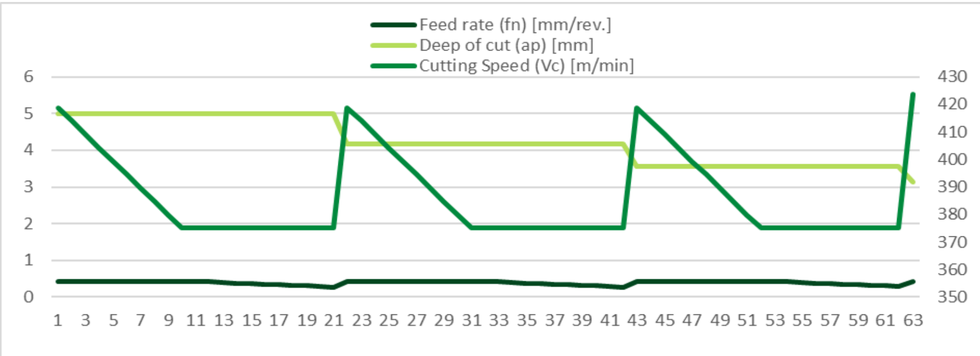

Fig. 4. Turning parameters at each iteration for roughing turning.

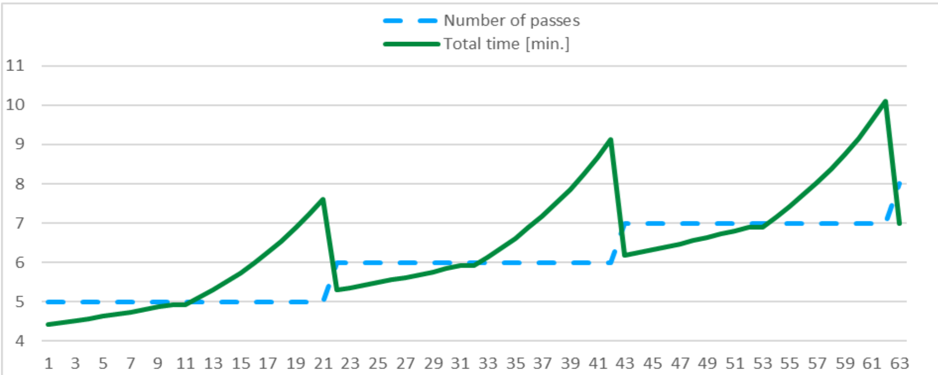

Fig. 5. Number of passes and total time for roughing turning.

In the first example, for finishing operation, the cutting speed and feed rate are set to maxim assuring a minimum cutting time according to the set objective. For depth of cut determination, it is used the binary search method until it is satisfied the available power constrain. The total number of iterations for finishing until the optimum solution is found is 14.

In the second example, for roughing operation, the first calculated depth of cut according to the number of passes is five and the cutting speed and feed rate are determined using the binary search assuring a minimum cutting time according to the set objective and checking the available power constrain which will be satisfied when the number of passes reaches eight passes. The total number of iterations for roughing until the optimum solution is found is 63.

4. CONCLUSIONS

The current paper presents a cutting parameters optimization algorithm for roughing and finishing turning which can be implemented in different Computer Aided Process Planning systems (CAPP) or it can be used as a standalone calculation algorithm. The proposed optimization algorithm is based on a combination of linear search and binary search methods, having as objective criterion the minimization of the machining time. Examples for roughing and finishing turning have been presented to illustrate the application of the proposed algorithm and to validate the results. This method can be applied for all tools from different manufacturers, in this paper, data from the tool manufacturer Sandvik is considered as an example.

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