

Cutting Modes in Multi-Pass Turning on CNC Lathes

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Abstract— Rolled workpieces are widely used when turning on CNC lathes. The difference between the dimensions and shape of the workpiece and the machine part in these cases is significant and it is necessary to remove the excess of material with the least possible loss of time. This is achieved by means of sequential execution of the work steps (passes) with the corresponding program cycles. Determining the number of passes and the corresponding cutting mode is an optimization problem, which is the subject of the present work.

Keywords— machine building, CNC lathes, cutting modes

I. INTRODUCTION

In order to achieve high efficiency in labor (high productivity), rough machining is normally performed in one work step, provided that the machine power and the strength of the technological system do not limit this possibility. With CNC machine tools, when rolled workpieces are used, the possibility of single-pass machining is determined not only by the abovementioned limitations, but also by the significant difference between the shape of the target machine part and the blank, which in most cases makes the allowance variable in size. Different schemes for removing the allowance are applied for the differently shaped rotatory profile surfaces, with the machining being carried out in multi-pass. Examples of organizing typical cycles for these cases are given in the specialized literature [1, 2]. Recommended tools and cutting modes are given by the manufacturers of cutting tools for turning [3].

The analysis of the recommended rough turning modes shows that in almost all cases the feed f_n per revolution of the workpiece is less than the depth of cutting a_p . On the one hand, this is determined by the relatively large cutting depth in rough turning and, on the other hand, by the desire to achieve a small height of the micro-roughness on the machined surface. While the latter is essential and important for the process of clean

machining, either final or prior to finishing, in multi-pass rough machining the target function is productivity, not accuracy. In this sense, it is of interest to expand the range of research toward cases where the feed approaches or exceeds the depth of cut. Similar studies are reflected in publications [4, 5].

The aim of this study is to make more specific certain elements of the known analyses and complement them with solutions for productivity optimization of multi-pass roughing.

II. MATERIALS AND METHODS

Machining productivity, as a target function for optimizing the cutting mode, is usually represented by means of the basic (machine) time:

$$T_o = \frac{l_{px}}{v_f}, \text{ min}$$

or by the volume of the removed metal per unit of time:

$$w = a_p f_n v_c, \text{ cm}^3/\text{min},$$

where l_{px} is the length of the working pass in mm; v_f – the speed of the feed drive in mm/min; a_p – the depth of cut in mm; f_n – the feed per revolution of the part in mm; v_c – the cutting speed (of the main drive) in mm/min.

In the case of multi-pass machining on a CNC lathe, in addition to the time for the working passes T_{px} , the machine time should also include the time for the auxiliary strokes T_{cx} , without which it is impossible to accomplish the program cycle. An essential point in solving the optimization problem is determining the optimal number of working and auxiliary passes, which ensure the least machine time for the operation, and their corresponding operating mode. In this case the machine time formula will have the form:

$$T_o = T_m = T_{px} + T_{cx} \text{ min}, \quad (1)$$

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$$T_o = \frac{1}{v_f} \sum_{i=1}^{n_{px}} l_{px\ i} + \frac{1}{v_{cx}} \sum_{i=1}^{n_{cx}} l_{cx\ i} \text{ min,}$$

where l_{cx} is the length of the auxiliary pass in mm; v_{cx} – the speed of the auxiliary movement in mm/min; n_{px} – number of working passes; n_{cx} – number of auxiliary strokes.

In multi-pass cycles, when $n_{px} = n_{cx}$ and $l_{px} = l_{cx}$, formula (1) will have the form:

$$T_o = \sum_{i=1}^{n_{px}} l_{px\ i} \left(\frac{1}{v_f} + \frac{1}{v_{cx}} \right) \text{ min.} \quad (2)$$

The optimization problem is solved by satisfying the system of constraints [6]:

1. Regarding tool durability

$$v_c(T) \leq \frac{C_v K_v}{T^m a_p^{x_v} f_n^{y_v}} \text{ m/min,} \quad (3)$$

where the constant, correction factor and exponents are selected from specialized reference books [7].

The limit, concerning the cutting speed, can also be determined by using the recommendations of the leading companies in tool manufacturing. For example, for rough machining of medium-carbon steel 45 by a P25 hard-alloy plate, the recommended cutting speed in accordance with the feed at a tool durability of 15 is given in Table 1.

TABLE 1 RECOMMENDED CUTTING SPEEDS [3]

$f_n, \text{ mm}$	0,2	0,4	0,6	0,8
$v_{c,15}, \text{ m/min}$	375	290	240	205

In case the tool life is greater than 15 min, the speed is adjusted by a coefficient, presented in Table 2.

TABLE 2 DURABILITY CORRECTION FACTOR [3]

$T, \text{ min}$	15	20	25	30	60
k_{vc}	1	0,95	0,9	0,87	0,75

2. Regarding cutting power

$$P_c \leq P_e \eta, \quad (4)$$

where P_c is the cutting power; P_e – the electric motor power for the main drive in kW; η – efficiency coefficient of the main drive chain.

On the other hand [3]:

$$P_c = \frac{v_c a_p f_n k_{c;0,4}}{60.1000} \left(\frac{0,4}{f_n \sin \kappa_r} \right)^{0,29}, \quad (5)$$

where $k_{c;0,4}$ is the coefficient of relative cutting resistance for a chip with a thickness of 0,4 mm in N/mm²; κ_r – main angle of knife setting.

Solving (4) and (5) together, yields for v_c :

$$v_c(P) = \frac{60.1000 P_e \eta}{a_p f_n k_{c;0,4}} \left(\frac{0,4}{f_n \sin \kappa_r} \right)^{-0,29} \text{ m/min.} \quad (6)$$

3. Regarding the permissible height of the surface roughness

$$[R_z] \geq \varphi(f_n, r_\epsilon, \kappa_r, \kappa'_r) \text{ mm,} \quad (7)$$

where κ'_r is the auxiliary angle of knife setting; r_ϵ is the radius of rounding at the tip of the knife in mm.

4. Regarding the permissible cutting depth

It is selected according to the type of the plate and the material under machining, following the recommendations, given by the cutting tool manufacturer.

The following equalities also apply to the optimization model:

1. Of the number of working passes

$$n_{px} = \frac{z}{a_p} \text{ (integer number),} \quad (8)$$

where z is the roughing allowance in mm.

2. Of the chip cross-section

$$S_c = a_p f_n - S_{Rz}, \quad (9)$$

where S_{Rz} is the roughness cross-section in mm².

The roughness cross-section in formula (9) is likely to have a significant impact on the chip cross-section and cutting force only when $f_n > a_p$. Otherwise, it is ignored.

Examples of determining the function on the right-hand side of inequality (7), are shown in Fig. 1.

For a sharp-pointed knife (with a small radius of curvature at the tip), the cross-section of the roughness according to Figure 1a is obtained as:

$$S_{Rz} = \frac{0,5 f_n^2}{\frac{1}{\text{tg} \kappa_r} + \frac{1}{\text{tg} \kappa'_r}}. \quad (10)$$

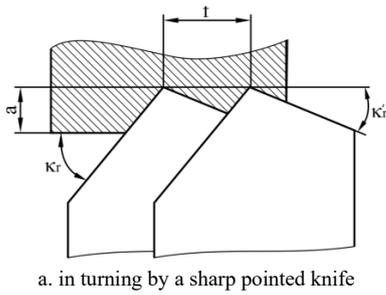
The roughness height is accordingly:

$$R_z = \frac{f_n}{\frac{1}{\text{tg} \kappa_r} + \frac{1}{\text{tg} \kappa'_r}}. \quad (11)$$

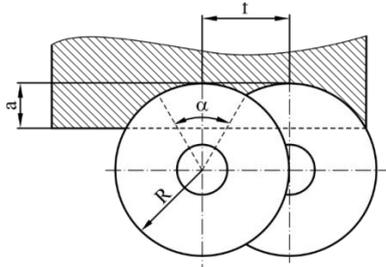
For a round plate, according to Fig. 1b, it is obtained:

$$S_{Rz} = R f_n \left(1 - 0,5 \cos \frac{\alpha}{2} \right) - \pi R^2 \frac{\alpha}{360}. \quad (12)$$

It is seen from Fig. 1 that it is necessary to impose a constraint on the feed magnitude. There is a limit, at which the height of the roughness reaches the depth of cut ($R_z = a_p$). In this case, the machining loses its meaning, because it does not create a new cylindrical surface, but forms a screw channel. This case is presented in Figure 2.

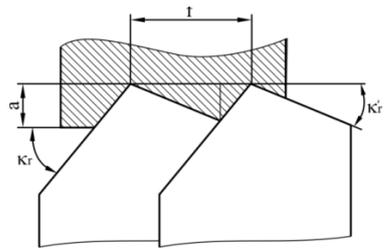


a. in turning by a sharp pointed knife

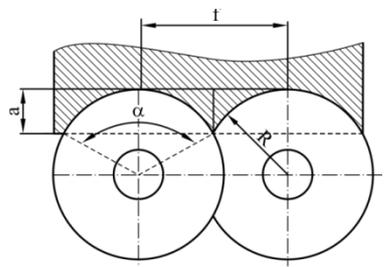


b. in turning by a knife with a round plate

Fig. 1. Roughness cross-section.



a. when turning with a sharp pointed knife



b. when turning by a knife with a round plate

Fig. 2. Limit feed.

The roughness height is accordingly:

$$R_z = R \left(1 - \cos \frac{\alpha}{2} \right), \quad (13)$$

where R is the radius of the round plate in mm.

$$\alpha = 2 \arcsin \left(\frac{f_n}{2R} \right). \quad (14)$$

Similar formulas for the height and cross-section of the roughness can be derived for other types of geometry of the knife's cutting part.

If a condition is set that the limit roughness height is $R_{z,lim} = 0,1a_p$, which in practice means that the cutting depth for clean turning must be greater than this height

($a_{p, clean} > 0,1 a_{p, rough}$), for the limit feed in the considered examples it will be obtained:

- with a sharp pointed knife:

$$f_{n,lim} = 0,1a_p \left(\frac{1}{\text{tg}\kappa_r} + \frac{1}{\text{tg}\kappa'_r} \right); \quad (15)$$

- with a round plate:

$$f_{n,lim} = 0,2\sqrt{20a_p R - a_p^2}. \quad (16)$$

For example, when a square hard-alloy plate is used, with $\kappa_r = 75^\circ$, $\kappa'_r = 15^\circ$, the following feed will be obtained: $f_{n,lim} = 0,4a_p$. That is, the limit feed is less than the depth of cut.

For working with round plates at $R = 8$ mm and $a_p = 2$ mm, from formula (16) it is obtained that $f_{n,lim} = 3,55$ mm, i.e., in this case the limit feed is greater than the cutting depth.

It is indicative for both examples that the cross-section of the roughness is relatively small and can be taken into account when determining the cutting force and power.

For rough turning with high feed, it is appropriate to work with purposefully designed hard-alloy plates [7]. Their geometry and recommended cutting modes are listed in the manufacturer's catalog.

III. RESULTS AND DISCUSSION

A. Optimization model

The conditions of the optimization problem, considered so far, show that the solution must be sought when working with a large volume of statistical data, obtained experimentally and presented tabularly. The possible approach for this case is numerical optimization. The variable parameter of the mode is the cutting depth (the number of working passes) with the machine time being the target function and the constraints and conditions of the optimization problem described by inequalities and equalities.

The numerical optimization algorithm will contain the following stages and procedures:

1. Selection of a metal cutting tool for roughing

The initial conditions are the type and quality of the material to be machined and the geometric shape of the machined surface. The selection is made based on information, provided by the selected cutting tool manufacturer.

2. Determining the domain of definition for the problem solution

In this case the limiting values of the cutting depth and feed must be defined, since they outline the domain for searching for the solution, leading to the least machine time.

The manufacturer's recommendations for $a_{p, max}$, $a_{p, min}$ and the corresponding $f_{n, min}$, $f_{n, max}$ are used as initial conditions.

3. Selection of a multi-pass cycle for roughing

The cycle is determined by the geometric shape of the machined surface and the selected tool.

4. Establishing the specific (partial) equation for the target function with the selected multi-pass machining cycle.

5. Scanning the optimization area and finding T_o , min.

Application example: Step turning of a semi-open cylindrical section

Example implementation is shown in Fig.3.

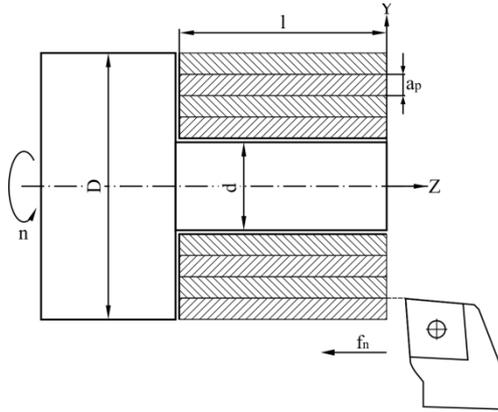


Fig. 3. Multi-pass cylindrical turning .

B. Description of the algorithm

1. The material under machining is medium carbon unhardened steel 45 with a hardness HB of 150 units. The target part is cylindrical in shape with step dimensions $D = 100$ mm; $d = 70$ mm; $l = 100$ mm.

According to [7], the appropriate rough turning tool is made of hard alloy GC4025 (P25), with a rhomboid metal-ceramic plate CNMG120412, having a tip radius $r_e = 1,2$ mm; $\kappa_r = 95^\circ$, $\kappa'_r = 5^\circ$. The length of the side of the plate is 12 mm.

2. Domain of definition for the problem solution:

a) The manufacturer's recommendation for the pair $a_{p \max}$, $f_{n \min}$: $a_{p \max} = 5$ mm, $f_{n \min} = 0,2$ mm will be used as an initial condition.

b) The recommended in Table 1 cutting speed is $v_{c,15} = 375$ m/min. For a tool durability of 25 min, the correction factor is 0,9 and for the speed it is obtained $v_{c,25} = 0,9v_{c,15} = 337,5$ m/min.

c) Checking for a power limit at $Pe = 6.5$ kW, $\eta = 0.8$ and $k_{c;0,4} = 2100$ N/mm² according to formula (6):

$$v_c \leq \frac{60 \cdot 1000 \cdot 6,5 \cdot 0,8}{5,0 \cdot 2,2100} \left(\frac{0,4}{0,2 \sin 95^\circ} \right)^{-0,29}, \text{ m/min.}$$

$$v_c = 182 \text{ m/min.}$$

Hence, the cutting speed must be 182 m/min.

d) Determining the limit $a_{p \min}$, $f_{n \max}$. The recommended minimum cutting depth for rough turning with the selected tool is $a_{p \min} = 0,5$ mm.

The recommended maximum feed value at $r_e = 1,2$ mm is from 0,5 to 1 mm. It is assumed that $f_{n \max} = 1$ mm.

The recommended cutting speed for this feed value is $v_{c,25} = 167$ m/min.

From formula (6) for the cutting speed it is obtained:

$$v_c \leq \frac{60 \cdot 1000 \cdot 6,5 \cdot 0,8}{0,5 \cdot 1 \cdot 2100} \left(\frac{0,4}{0,2 \sin 95^\circ} \right)^{-0,29}, \text{ m/min.}$$

$$v_c = 363,7 \text{ m/min.}$$

Consequently, the cutting speed must be 167 m/min.

Finally, for the definition of the domain it is obtained:

$$a_{p \max} = 5 \text{ mm}, f_{n \min} = 0,2 \text{ mm}, v_c = 182 \text{ m/min};$$

$$a_{p \min} = 0,5 \text{ mm}, f_{n \max} = 1 \text{ mm}, v_c = 167 \text{ m/min.}$$

3. Selecting a multi-pass cycle for roughing

The cycle is presented in Figure 3.

4. Establishing the specific (partial) equation for the target function with the selected multi-pass cycle of machining

Formula (2) is used to determine the machine time, and the number of working passes is determined by formula (8).

For each of the listed feeds per workpiece revolution f_n , the minute feed f_o will be different for the sequential working passes, since the diameter of the machined surface changes. At $v_c = \text{const}$ the frequency of rotation will increase from the diameter of the workpiece to the diameter of the machine part and so will f_o accordingly. To simplify the solution in this case, the average feed \bar{f}_o can be used:

$$\bar{f}_o = n_{cp} f_n, \text{ where } n_{cp} = \frac{2000 v_c}{\pi(D+d)}. \quad (17)$$

Thus, the machine time for the working passes is obtained:

$$T_{px} = \frac{l_{px}}{\bar{f}_o}. \quad (18)$$

5. Scanning of the workspace will be performed at variable values of the cutting depth $a_p = 0,5; 1,0; 1,5; 2,0; 2,5; 3,0$ mm and for the feed per revolution of the part, respectively $f = 0,25; 0,50; 0,75; 1,00$ mm.

The cutting speed will be determined by the manufacturer's recommendation, presented in Table 1 and will be corrected for a tool durability of 25 min, according to Table 2, with a limit on the machine's power according to formula (6).

Multi-pass machining is performed at the specified speed $v_c = \text{const}$.

The obtained results for the cutting speed are presented in Table 3.

TABLE 3 CUTTING SPEED ACCORDING TO TOOL LIFE (IN NUMERATOR) AND ALLOWABLE BY MACHINE POWER (IN DENOMINATOR)

a _{ps} , mm	f _{ps} , mm			
	0,25	0,50	0,75	1,0
0,5	<u>315</u>	<u>235</u>	<u>190</u>	<u>167</u>
	1036	634	475	387
1,0	<u>315</u>	<u>235</u>	<u>190</u>	<u>167</u>
	518	317	239	194
1,5	<u>315</u>	<u>235</u>	<u>190</u>	<u>167</u>
	348	211	158	129
2,0	<u>315</u>	<u>235</u>	<u>190</u>	<u>167</u>
	259	159	119	97
2,5	<u>315</u>	<u>235</u>	<u>190</u>	<u>167</u>
	207	127	95	77
3,0	<u>315</u>	<u>235</u>	<u>190</u>	<u>167</u>
	173	106	79	65

Of the two speeds, the lower one is selected for operation.

The results for the machine time are presented in Table 4. The speed of the auxiliary movement is assumed to be v_{cx} = 6000 mm/min.

TABLE 4 CUTTING SPEED v_c (IN NUMERATOR) AND MACHINE TIME T_M (IN DENOMINATOR)

a _{ps} , mm	i, number of passes	f _{ps} , mm			
		0,25	0,50	0,75	1,0
0,5	30	<u>315</u>	<u>235</u>	<u>190</u>	<u>167</u>
		10,67	7,31	6,12	5,29
1,0	15	<u>315</u>	<u>235</u>	<u>190</u>	<u>167</u>
		5,33	3,66	3,06	2,65
1,5	10	<u>315</u>	<u>211</u>	<u>158</u>	<u>129</u>
		3,56	2,70	2,42	2,42
2,0	8	<u>259</u>	<u>159</u>	<u>119</u>	<u>97</u>
		3,43	2,82	2,53	2,33
2,5	6	<u>207</u>	<u>127</u>	<u>95</u>	<u>77</u>
		3,19	2,62	2,35	2,18
3,0	5	<u>173</u>	<u>106</u>	<u>79</u>	<u>65</u>
		3,17	2,60	2,34	2,14

To illustrate the analysis, some typical results are presented in Figure 4.

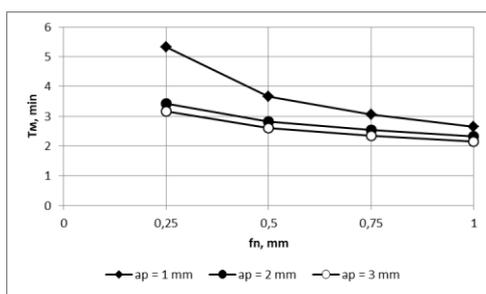


Fig. 4. Machine time.

With the proposed algorithm and methodology for numerical analysis, possibilities for optimizing the cutting mode in multi-pass machining of other types of rotary profile surfaces can be considered.

IV. CONCLUSIONS

The presented analysis for optimizing the cutting modes in multi-pass turning on CNC machine tools allows to draw the following conclusions:

1. The developed algorithm and methodology for numerical analysis make it possible to find cutting modes, ensuring maximum productivity in multi-pass roughing of rotary profile surfaces by turning.

2. For rough turning, it is advisable to use tools, purposefully designed by the tool manufacturers, and providing the possibility to work with large feeds at relatively slight roughness of the machined surface.

3. The cutting speed for small cross-sections of the cut layer is limited by the durability of the tool, and for larger cross-sections - by the permissible cutting power.

4. After reaching a limit in the cross-section of the cut layer, at which the cutting power reaches the permissible value, maximum productivity is achieved for the specific conditions of machining. Further increase in the cross-section by means of the feed does not lead to an increase in productivity. This is confirmed by the considered example and the results, presented in Table 4 and Figure 4.

5. The previous conclusion gives reason to recommend the introduction of adaptive power control in multi-pass rough turning, which will ensure self-programming of the number of working passes while achieving maximum productivity for the set cutting power.

6. Among all cutting modes, providing approximately the same productivity, it is advisable to prefer those, in which the tool durability will be greater.

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