ARCH. MECH. TECH. MATER.VOL. 38 (2018) 40-44

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The effect of changes in depth of cut and cutting speed of CNC toolpaths on turning process performance

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ARTICLE INFO

Received 08 May 2018
Received in revised form 14 June 2018
Accepted 25 July 2018

KEY WORDS

Cutting speed
Depth of cut
CNC
Cutting force
Optimization

ABSTRACT

In this article, a novel approach to computer optimization of CNC toolpaths by adjustment of cutting speed v_c and depth of cut a_p is presented. Available software works by the principle of adjusting feed rate on the basis of calculations and numerical simulation of the machining process. The authors wish to expand upon this approach by proposing toolpath optimization by altering two other basic process parameters. Intricacies and problems related to the adjustment of $\mathbf{a_p}$ and v_c were explained in the introductory part. Simulation of different variant of the same turning process with different parameter values were conducted to evaluate the effect of changes in depth of cut and cutting speed on process performance. Obtained results were investigated on the account of cutting force and tool life. The authors have found that depth of cut substantially affects cutting force, while the effect of cutting speed on it is minimal. An increase in both depth of cut and cutting speed affects tool life negatively, although the impact of cutting speed is much more severe. An increase in depth of cut allows for a more significant reduction of machining time, while affecting tool life less negatively. On the other hand, the adjustment of cutting speed helps to reduce machining time without increasing cutting force component values and spindle load.

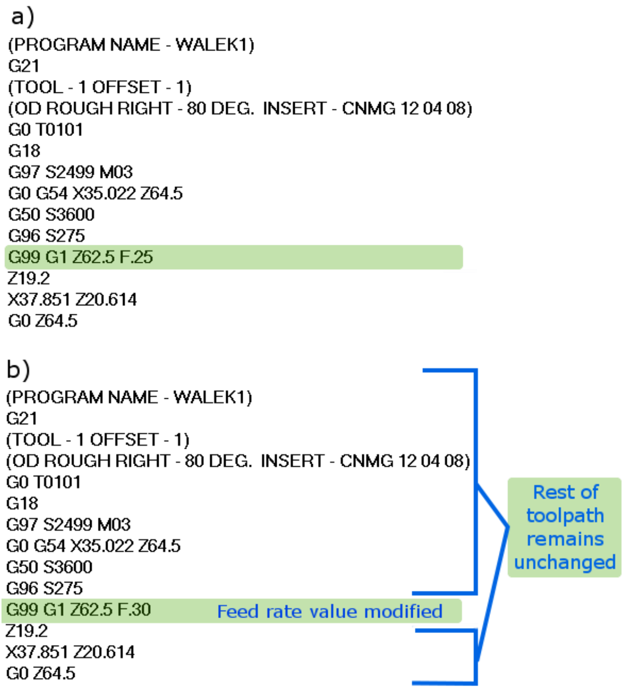
1. INTRODUCTION

CNC machine tools play a dominant role in today's machining industry. Computer Aided Manufacturing (CAM) software is widely used for design of CNC toolpaths, allowing for automated toolpath generation. The end user has to provide input data, such as 3D model of the finished workpiece or basic process parameters, including tool geometry, cutting speed, feed rate and depth of cut. The choice of process parameters affects the outcome of the machining process in the form of machining time, cutting forces, spindle power, surface quality or dimensional accuracy. Normally, the end user has to choose the correct parameters on the basis of personal experience, which does not always produce a satisfied outcome. The other possibility is conducting a series of experimental tests to determine correct parameter values. Obviously, this is time-consuming and generates additional costs. An alternative solution is the use of dedicated software designed with process simulation and CNC toolpath optimization in mind. Optimization in the case of CNC toolpaths can be understood as searching for the best available solution (basing on user-assumed criteria), without exceeding previously assumed boundary conditions [1]. The simulation results can provide users with a plethora of information regarding cutting conditions. Examples include cutting force component values, spindle load, cutting zone temperature, machining time or material removal rates.

Despite the availability of different CAE software solutions meant for CNC toolpath optimization, all of them work by changing tool feed rates of the base CNC toolpath. This can be attributed to the fact that feed rate is easy to modify, as its value is given explicitly in CNC toolpaths. Adjustment of feed rate value has a significant impact on such factors as machining time and cutting force. Therefore,

DOI: 10.2478/amtm-2018-0007

process outcome can be changed with accordance to end user requirements without interfering with CNC toolpath structure. An example of feed rate modification performed by commercial Production Module 2D (PM2D) software is presented in Fig. 1.



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G21
(TOOL - 1 OFFSET - 1)
(OD ROUGH RIGHT - 80 DEG.  INSERT - CNMG 12 04 08)
G0 T0101
G18
G97 S2499 M03
G0 G54 X35.022 Z64.5
G50 S3600
G96 S275
G99 G1 Z62.5 F.25
Z19.2
X37.851 Z20.614
G0 Z64.5
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Z19.2
X37.851 Z20.614
G0 Z64.5
```

Fig. 1. Fragment of CNC toolpath before (a) and after (b) feed rate optimization in commercial PM2D software

Working principles of commercially available CAE software designed for CNC toolpath optimization, along with potential areas of application and optimization results, have been the subject of previous research by the authors [2, 3, 4].

Recent works by other authors concern prediction of cutting times via virtual machining [5], physics model-based optimization [6], integration of virtual machining into process control and monitoring [7] or multi-objective optimization with emphasis on environmental concerns [8]. Different optimization strategies were investigated by Dodok et al. [9]. The aim of this work is to present a novel approach to toolpath optimization and to investigate the possibility of modification of two basic process parameters other than widely optimized tool feed rates – namely surface speed v_c and depth of cut a_p and their effect on machining time, cutting force components, spindle power and tool life relative to base process.

2. TOOLPATH OPTIMIZATION BY ADJUSTMENT OF CUTTING SPEED AND DEPTH OF CUT

In G-code CNC toolpath, a G96 command is used to set the constant surface speed (CSS) value. A desired cutting speed value in m/min is specified next to the G96 command. Therefore, optimization by means of adjustment of cutting speed does not require extensive modification of CNC toolpath. Experimental research has shown that cutting force decreases [10] or slightly increases [11] with an increase in cutting speed. It is also worth noting that an improvement in surface roughness was observed after increasing cutting speed [11, 12, 13]. However, a negative impact of increasing cutting speed on tool life has been found by other researchers [14, 15]. Therefore, considering tool life is mandatory in case of eventual toolpath optimization by cutting speed adjustment.

Eventual adjustment of depth of cut is more problematic than in the case of aforementioned parameters. This is because here are no specific G-codes used to define the value of depth of cut (DOC), as is the case of feed rate f and cutting speed v_c. The depth of cut adjustment necessitates interference with toolpath coordinates. For example, X and Z coordinate values have to be altered to change depth of cut for turning processes. This task would prove to be especially challenging in the case of complex workpiece geometries. Total depth of cut, or total machining allowance is the sum of machining passes in the CNC toolpath. Adjustment of depth of cut without taking into the account the value of total machining allowance would result in workpiece shape error. This is explained in Fig.2.

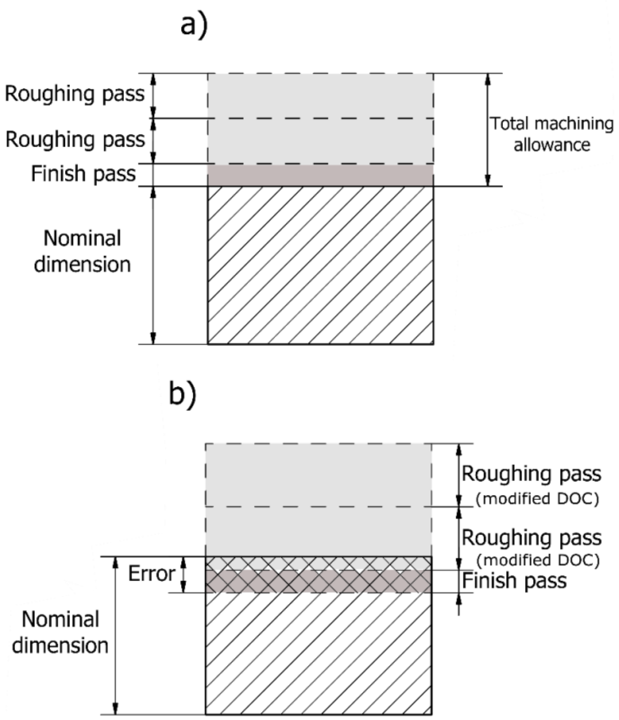

Fig. 2. Workpiece geometry error resulting from depth of cut adjustment: a) original workpiece geometry, b) geometry error resulting from depth of cut optimization of roughing passes without taking total depth of cut (DOC) into account [2]

On the other hand, the depth of cut has the least effect on tool life of three basic process parameters. Moreover, an increase in the depth of cut value would result in the reduction in the number of machining required to machine the workpiece, thus reducing total machining time. Reducing depth of cut also reduces spindle load and cutting forces, providing a potential solution in case of problems with available spindle power or machine-tool-workpiece system stability.

3. TURNING SIMULATIONS

Simulations were carried out with the intent of analyzing the effect of cutting speed and depth of cut adjustment on process indicators such as machining time, cutting force and tool life, therefore showcasing potential advantages or shortcomings of toolpath optimization by altering v_c and a_p. Toolpaths were prepared in Mastercam X9 software.

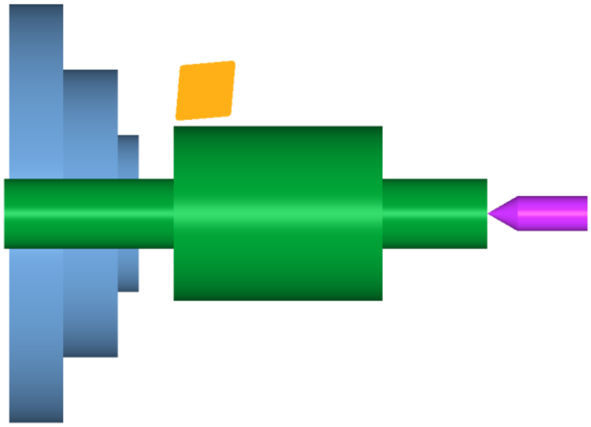

Fig. 3. Simulation setup

Process parameters were selected on the basis of values recommended by the tool manufacturer. Four different variants of the turning process were simulated in Production Module 2D software. Simulation parameters are presented in Table 1, whereas a graphical representation of the simulation setup is given in Fig.3.

Table 1. Simulation setup

Workpiece	1.0503 medium-carbon steel, *D*=50 mm			
Tool	CNMG120408, uncoated carbide			
Tool parameters	Lead angle κ, °		Rake angle α, °	
	-5		-5	
Variant No.	1	2	3	4
Cutting speed v_c, m/min	150	220	150	220
Number of roughing passes	2		1	
Depth of cut a_p, mm	1.5		3	

Production Module 2D software allows the end user to obtain information about a variety of process parameters. Cutting forces and machining times for all process variant, which were of particular concern, are presented in the next chapter of this work.

4. SIMULATION RESULTS

Simulation results for each process variant were exported from PM2D and processed for purposes of their graphical presentation, comparison and analysis. Plots of cutting force in machining time for all simulation variants are presented in Fig. 4.

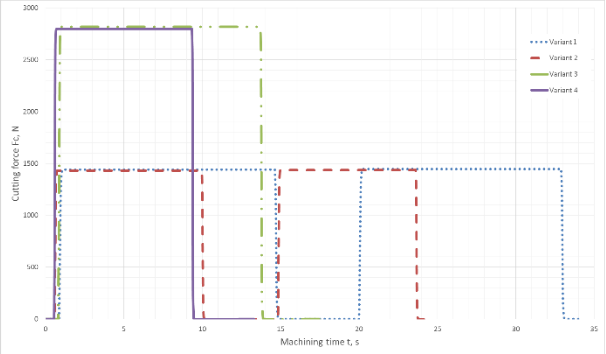

Fig. 4. The effect of cutting parameters on cutting force and machining time

As can be seen on Fig. 4, a change of depth of cut and cutting speed results in significant differences in both machining time and cutting force. The lowest cutting force of 1446 N and the longest total machining time of *t*=32 s were observed for the base process given as Variant 1.

Increasing the cutting speed in Variant 2 to 220 m/s results in a minor drop in cutting force value to 1435 N, whereas total machining time is reduced by 27% to *t*=24 s in relation to the base process. The drop in cutting force value when increasing cutting speed is in agreement with data available in literature [16].

Most evident time savings can be observed for Variant 3 and Variant 4 (see Table 1). It can be inferred that this is due to the reduction in the number of cutting passes. The workpiece is machined in a single pass instead of two. In respect to base process, total machining time was reduced respectively by 56% and 71% in the case of Variants 3 and 4. However, a major increase in cutting force was also observed. F_c=2818N and F_c=2797 N were noted respectively Variants 3 and 4. Therefore, cutting force value has increased by as much as more than 93% in comparison to the base process. This leads to a conclusion that an increase in demand for spindle power can be expected.

5. THE EFFECT OF CUTTING PARAMETERS ON TOOL LIFE

According to the basic form of Taylor's formula (1)[16], cutting speed v_c is the main factor affecting tool life. Other process parameters (a_p and *f*) are not included in the equation, as their effect is deemed to be negligibly small.

$$T = C_T v_c^k \tag{1}$$

Where:

T- Tool life, min;
C_T- constant;
v_c – cutting speed, m/min;
k- characteristic exponent dependent on work material.

However, the extended form of Taylor's formula (2) [16] accounts for the effect of cutting parameters other than cutting speed on tool life.

$$T = \sqrt[n]{\frac{C}{f^{n1} \cdot a_p^{n2} \cdot v_c}} \quad (2)$$

Where:

T- Tool life, min;

C- Constant dependent on tool and workpiece material, cutting conditions and tool geometry;

v_c, f, a_p – basic process parameters;

n, n_1, n_2 – exponents dependent on tool and workpiece material.

Values of exponents for assumed tool and workpiece material interface are presented in Table 2.

Table 2. Exponent values for tool and workpiece materials assumed in the simulation [16]

Tool material	Workpiece material	n	n_1	n_2
Uncoated carbide	Structural steel	0.30	0.31	0.13

The value of constant C does not affect percentile differences in tool life that occur with the change of cutting parameters. Therefore, relative tool life calculated with the use of a fixed C value was used by the authors to showcase the effects of cutting parameter changes on tool life. Results of those calculations are shown in Table 3.

Table 3. The effect of process parameters on tool life

Variant 1	Variant 2	Variant 3	Variant 4
t_m = 14+13 = 27 s	t_m = 9+9 = 18 s	t_m = 14 s	t_m = 9 s
T = 113.3 min = 6798 s	T = 31.6 min = 1896 s	T = 84 min = 5040 s	T = 23.4 min = 1404 s
T_w = 0.397%	T_w = 0.949%	T_w = 0.278%	T_w = 0.641%
N_w=251	N_w=105	N_w=360	N_w=156

The t_m is understood as the in-cut machining time, as in the time when the tool is engaged with the workpiece. This excludes rapid tool motions between machining passes. T_w is the percentage of total tool life T that is needed to machine a single workpiece. N_w is the total number of workpieces that can be machined completely with the use of a single cutting insert.

A graphical representation of the effect of assumed process parameters on tool life is presented in Fig. 5. By the observation of changes in tool life, two characteristic "groups" of tool life can be identified. The first group (Variants 1 and 3) can be characterized by a longer tool life period of T>80 min. For the second group (Variants 2 and 4), significantly shorter tool life of approximately 30 minutes can be observed. Variants for which the cutting speed was not increased (1 and 3) show the longest tool life in the range of assumed parameters. An increase of cutting speed by 47% (from v_c=150m/min to v_c=220m/min) results in tool life dropping by over 70%, regardless of used depth of cut. This shows that the adverse effect of cutting speed on tool life is much more evident than in the case of depth of cut.

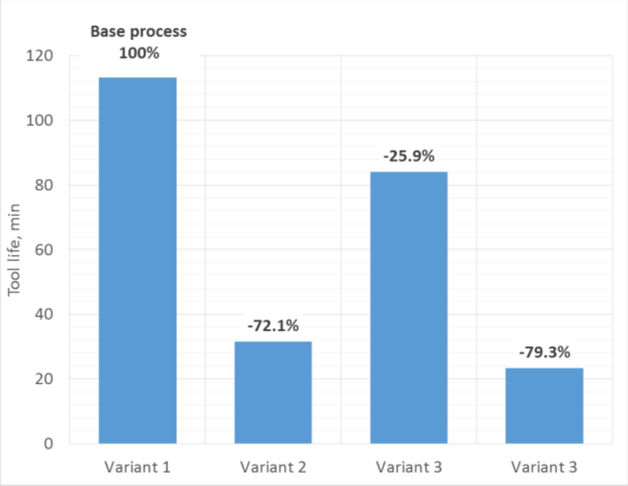

Fig. 5. The effect of used cutting parameters on relative tool life

6. CONCLUSIONS

The analysis of the obtained simulation results and performed calculations leads to the following conclusions:

- In the assumed range of parameters, increasing cutting speed causes a significant decrease of tool life, regardless of used depth of cut;
- It needs to be taken into consideration whether cutting speed optimization is economically justifiable for a particular cutting process, as the costs associated with the drop in tool life can outweigh the savings resulting from shorter machining time;
- Biggest time savings (as much as 71%) were obtained by increasing both cutting speed and depth of cut. However, a 100% percent increase in depth of cut (a_p=3 mm vs. a_p=1,5 mm) while retaining the same cutting speed (v_c=150 m/min) allowed to shorten the machining time by 56% in relation to the base process.

Process optimization by the adjustment of a_p seems to be a reasonable alternative, as it allows to substantially shorten overall machining time without severely affecting tool life. However, an increase in cutting force can be a source of problems with chatter and machine tool rigidity. Adjustment of cutting speed helps to reduce machining time without increasing cutting force component values and spindle load. This is a promising alternative to increasing depth of cut and feed rate, as they both impact process dynamics and machine load negatively. Moreover, a slight decrease in cutting speed can help increase tool life at the expense of a negotiable increase in machining time. Further research by the authors will focus on experimental testing to investigate the effect of depth of cut adjustment of surface roughness and identification of eventual problems stemming from increases in cutting forces, such as machine-tool-workpiece system rigidity or increased demand for spindle power. Currently, the authors are also working on a software solution which would allow for optimization of depth of cut and cutting speed in an automated way, while retaining correct workpiece geometry and surface finish.

REFERENCES

[1] **Morek R.,** Optymalizacja procesu technologicznego, STAL Metale & Nowe Technologie 1- 2 (2012) 34 – 38.

[2] **Jarosz K., Löschner P., Niesłony P., Krolczyk G.,** Optimization of CNC face milling process of Al-6061-T6 aluminum alloy, Journal of Machine Engineering 17 (2017). 69 - 77.

[3] **Niesłony P., Jarosz K.,Löschner P.,** Nowe podejście do optymalizacji programów dla obrabiarek CNC na przykładzie toczenia, Stal, Metale & Nowe Technologie 10-11 (2016) 92 - 96.

[4] **Niesłony P., Jarosz K., Löschner P.,** Porównanie strategii frezowania czołowego w celu wyboru optymalnego sposobu obróbki., Stal, Metale & Nowe Technologie 11-12 (2016) 45 - 48.

[5] **Altintas, Y., Tulsyan, S.,** Prediction of part machining cycle times via virtual CNC. CIRP Annals 64.1, (2015) 361-364.

[6] **Xu, Q., Wadell, J., Keele, R.,** Physics-based optimization of OMC machining. Proceedings of International SAMPE Technical Conference, (2017).

[7] **Altintas, Y., Aslan, D.,** Integration of virtual and on-line machining process control and monitoring. CIRP Annals 66.1 (2017) 349-352.

[8] **Li, L., Deng, X., Zhao, J., Zhao, F., Sutherland, J. W.,** Multi-objective optimization of tool path considering efficiency, energy-saving and carbon-emission for free-form surface milling. Journal of Cleaner Production 172 (2018) 3311-3322.

[9] **Dodok, T., Čuboňová, N., Císar, M., Kuric, I., Zajačko, I.,** Utilization of strategies to generate and optimize machining sequences in CAD/CAM. Procedia engineering 192(2017) 113-118.

[10] **Sivaraman V., Sankaran S., Vijayaraghavan L.,** The effect of cutting parameters on cutting force during turning multiphase microalloyed steel, Procedia CIRP 4 (2012) 157 - 160.

[11] **Korkut, I., Donertas M. A.,** The influence of feed rate and cutting speed on the cutting forces, surface roughness and tool–chip contact length during face milling, Materials & design 28.1 (2007) 308 - 312.

[12] **Korkut I., Kasap M., Ciftci I., Seker U.,** Determination of optimum cutting parameters during machining of AISI 304 austenitic stainless steel, Materials & Design 25 (2004) 303 - 305.

[13] **Bouacha K., Yallese M. A., Mabrouki T., Rigal J. F.,** Statistical analysis of surface roughness and cutting forces using response surface methodology in hard turning of AISI 52100 bearing steel with CBN tool, International Journal of Refractory Metals and Hard Materials 28 (2010) 349-361.

[14] **SreeramaReddy T. V., Sornakumar T., VenkataramaReddy M., Venkatram R.,** Machinability of C45 steel with deep cryogenic treated tungsten carbide cutting tool inserts, International Journal of Refractory Metals and Hard Materials t. 27.1 (2009) 181-185.

[15] **Królczyk G., Gajek M., Legutko S.,** Effect of the cutting parameters impact on tool life in duplex stainless steel turning process, TehničkiVjesnik-Technical Gazette 20.4 (2013) 587-592.

[16] **Grzesik W.,** Advanced machining processes of metallic materials: theory, modelling and applications. Amsterdam: Elsevier, 2008.