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Cutting forces during turning with variable depth of cut☆,☆☆

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Summary The purpose of this paper is to investigate the problems with increasing the efficiency of turning cycles. This paper also describes and suggests the possibility of using effective strategies and their application in programming CNC turning centers. It proposes new roughing turning cycles where variable depth of cut is applied. Suggested roughing cycles with the use of variable depth of cut will ensure increasing the durability of the cutting tool and the efficiency during turning.

The proposed research for the paper is an experimental work — measuring cutting forces and monitoring of the tool wear on the cutting edge. It compares the turning where standard roughing cycle is used and the turning where the proposed roughing cycle with variable depth of cut is applied.

Roughing tool path in turning

CAD/CAM systems produce the technological basis for computer-controlled production. For standard programming of rough turning tool paths online programing SFP — Shop Floor Programing is commonly used. For specific programming of tool paths (non-linear tool path and cycles that are not in cycles at the workshop) it is appropriate to use CAM systems (Hatala, 2007; Svetlik and Dobransky, 2005; Sadílek et al., 2011).

The conventional roughing cycles in turning, where a cutting tool performs constant depth of cut, can be adapted and extended with the cycles when the tool cuts with variable depth of cut. The proposed roughing cycles are as follows:

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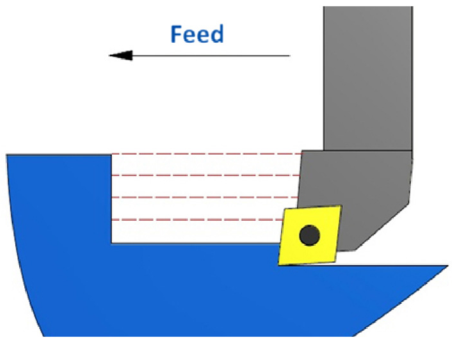

Figure 1 Roughing cycle with constant depth of cut. Figure adapted from Sadílek et al. (2013).

- Tool paths ''decreasing of engagement'', see Fig. 2.
- Tool paths with creating conic surface, see Fig. 3.
- Tool paths with the use of nonlinear methods, see Fig. 4.

Fig. 1 shows commonly used roughing cycle. In Fig. 1 it is possible to see a constant depth of cut, which is used in this roughing cycle. The machining process results in wear that prevails in one point of the cutting edge only.

During the roughing strategy — cut decrement, each chip removal is performed with a different depth of cut so a different cutting part of the tool is under stress during each cutting operation. This method of machining can be time consuming due to more passes. This is compensated for by increased tool life, lower loading of the machine spindle and reduced machine noise. The depth of cut is reduced when the final diameter is being approached. The maximum wear point is therefore moved outwards from the cut, prolonging by doing so a longer cutting tool durability. This type of roughing cycle is already contained in some CAM systems (for example Mastercam and Edge CAM). Application of this feature when longer parts are turned is advantageous for the elimination of ever-decreasing workpiece stiffness.

The cutting where a conical surface is formed starts with the greatest depth of cut which decreases in the feeding direction, see Fig. 3. The second cut is programmed to be parallel with the workpiece axis. This provides for efficient removal of the conical surface formed in the previous cut. Thanks to this strategy, the tool wear moves along the cutting edge from the maximum to minimum depth of cut (a_{pmax} to a_{pmin}).

The non-linear roughing cycle method also ensures the variable depth of cut. For example, the tool path's wavy profile (Fig. 4) will achieve the same effect as the previous methods. In the first cut and the second cut, the machined material is on gradual increase and decrease and a variable depth of cut is thereby achieved. It is also possible to shift the machined surface and, in doing so, change the depth of cut. However, this requires an advanced CAD/CAM system joined with the CNC cutting machines.

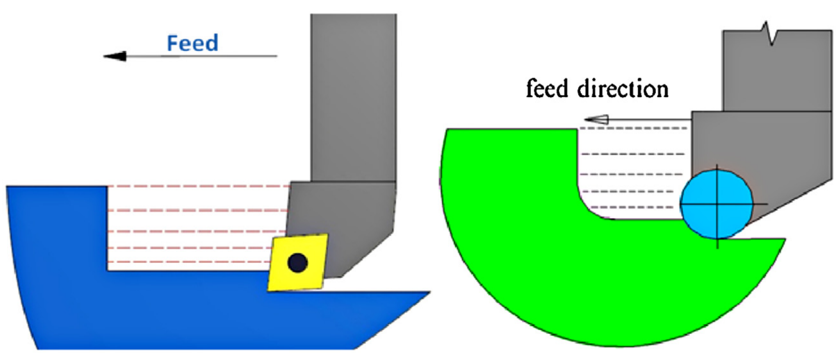

Figure 2 Tool paths — decreased cut with two types of insert (ramping). Figure adapted from Sadílek et al. (2013).

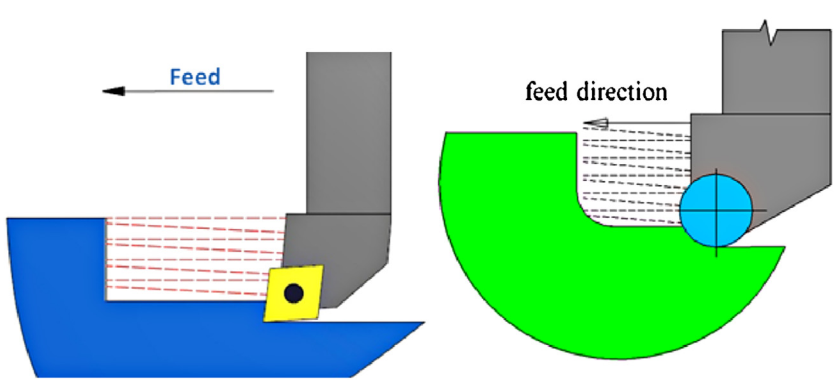

Figure 3 Tool paths creating a conic surface with two types of insert. Figure adapted from Sadílek et al. (2013).

Table 1 Cutting conditions: constant depth of cut strategy and creating a conic surface strategy.

Cutting conditions			Rough turning		
			Constant depth of cut	Variable depth of cut	
Cutting speed	v_c	[m min^{-1}]	230	230	
Feed	f	[mm ot^{-1}]	0.4	0.4	
Depth of cut	a_p	[mm]	2	a_{pmin} = 1.5	a_{pmax} = 2.5

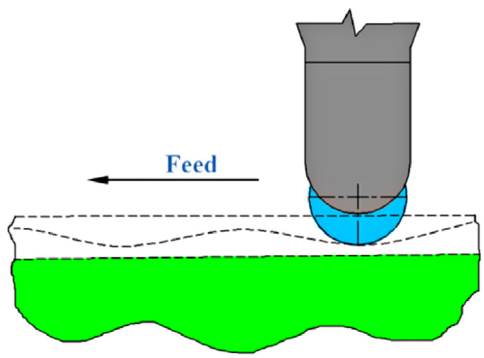

Figure 4 Roughing cycle — nonlinear method.
Figure adapted from Sadílek et al. (2013).

Experimental work

Two strategies were used during longitudinal turning: conventional method with constant depth of cut and turning with the creating the conical surface.

Within this experiment cutting machine was used: DMG MORI NLX 2500MC/700 with control system Mitsubishi M730BM and with the spindle power 18.5 kW. The work piece material was used cold-work tool steel 1.2379 which corresponds to the DIN X155CrVMo12 1 (ČSN 19 573) with hardness 23 HRC. Typical applications include punching and blanking dies. Size of workpiece (flange) was external diameter Ø D = 150 mm, length L = 450 mm. Cutting tool was external radial turning tool DWLNR 2525 M08 (company Sandvik) with cutting inserts: WNMG 080408 E-FM (company Pramet tools). This tool is suitable for longitudinal medium roughing and roughing. During cutting, cutting fluid was not used. The cutting conditions differed only in the cut size and depth shape, see Table 1. Amount of material to be machined (per unit time) is the same.

The different depths of cut (stock removals) in the internal roughing cycle are shown in Fig. 5. Here a gradual removal of material from first tool path to the last (nth) is shown. Total number of tool paths (n) depends on the size of the workpiece and technological possibilities of insert as well.

During machining components of cutting forces and tool wear were measured. Conclusions of tool wear results are shown below. Tool live of strategy variable depth of cut was increased from 6.2 min to 8.3 min (ΔT = 2.3 min, this is about 20%) (Fig. 6).

Dynoware software (company Kistler) was used for the measurement of cutting forces and subsequent analysis of the data obtained. For further processing Excel was used. Three-component piezoelectric dynamometer and connection with PC are shown in Figs. 7 and 8.

The direction of each axis of the dynamometer has been set as shown in Fig. 8.

F_x component of cutting force acts perpendicular to the axis of the workpiece — expressing radial (passive) component of cutting force F_p. F_p greatly affects dimensional accuracy of machined surfaces, the geometric deviations of shape and position and surface roughness of the machined surface.

F_y component of cutting force acts tangentially — expressing cutting component of cutting force F_c. F_c is the basis for determining the limiting conditions in the choice

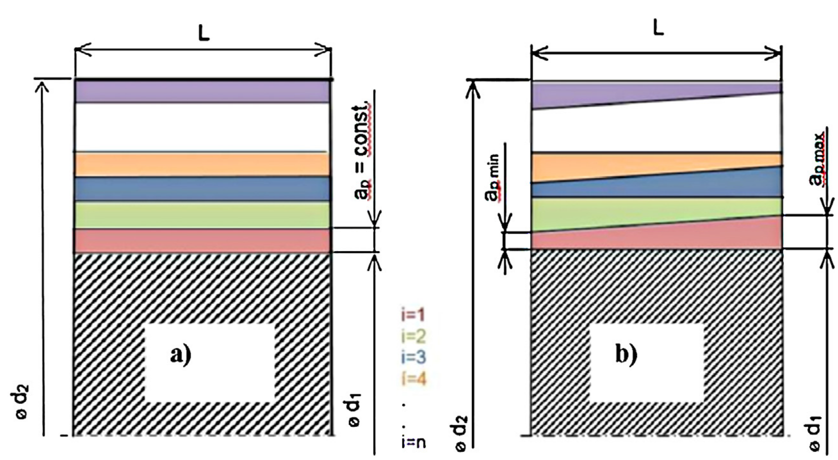

Figure 5 Tool paths: (a) constant depth of cut, (b) variable depth of cut (i < 1, $n \geq$ number of tool paths, n = total number of tool paths, L, Ø$d2$ = dimension of workpiece, L, Ød1 = dimension of semi product before finishing).

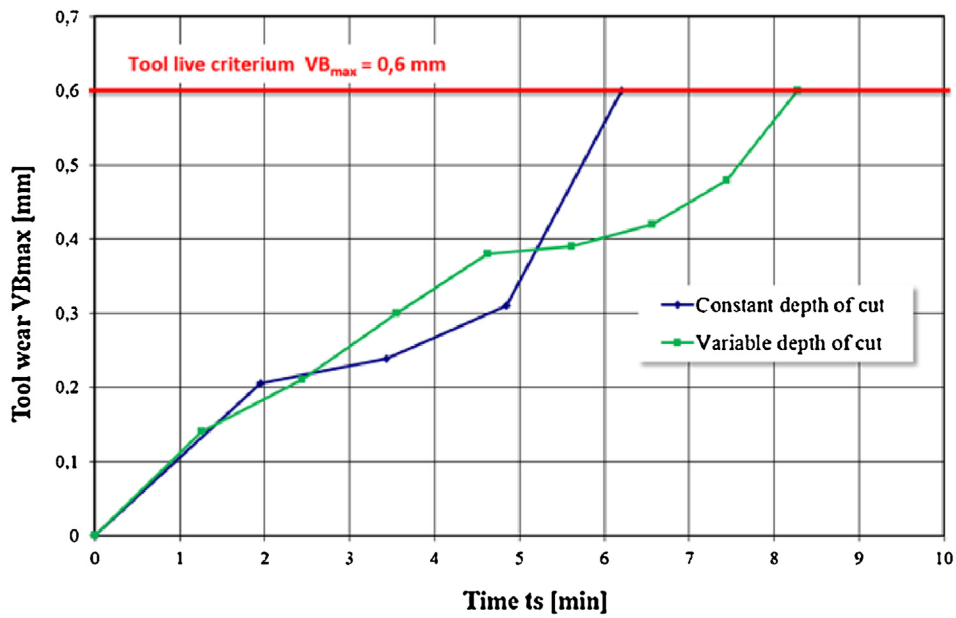

Figure 6 Compare dependences of tool wear VB_{max} on the machining time at strategy constant depth of cut and variable depth of cut.

Figure 7 Complete measuring system (Tool Holder for Turning Tool, Dynamometer KISTLER 9129AA, Multichannel charge amplifier, DAQ system, PC).

of cutting parameters. Specifies the required power and the total amount of heat in the cutting zone.

F_z component cutting force acts in the direction of feed — expressing feed component of cutting force F_f. F_f is used in the dimensioning traverse mechanisms.

A. Cutting forces during turning

Fig. 9 shows the one tool pass during the strategy with variable depth of cut when the depth of cut starts at a minimum depth a_{pmin} = 1.5 mm and ends a_{pmax} = 2.5 mm. This tool pass

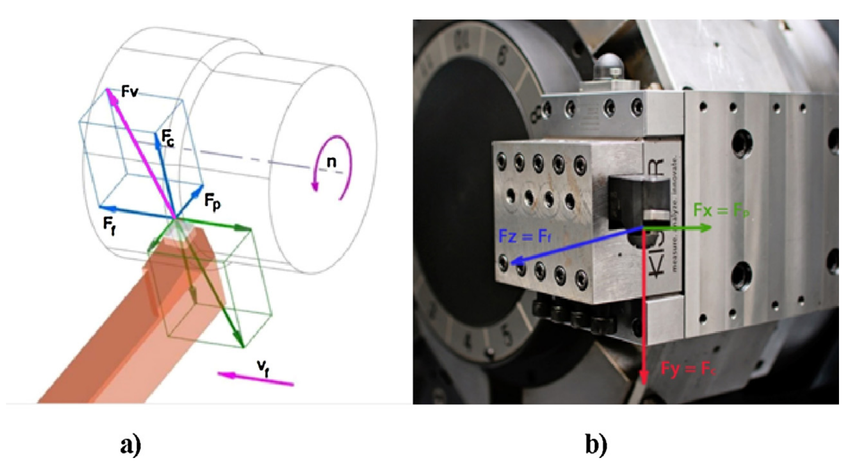

Figure 8 (a) Cutting forces components during turning. (b) Three-component piezoelectric dynamometer in a plant lathe DMG MORI NLX 2500 MC/700 and component force measurement system.

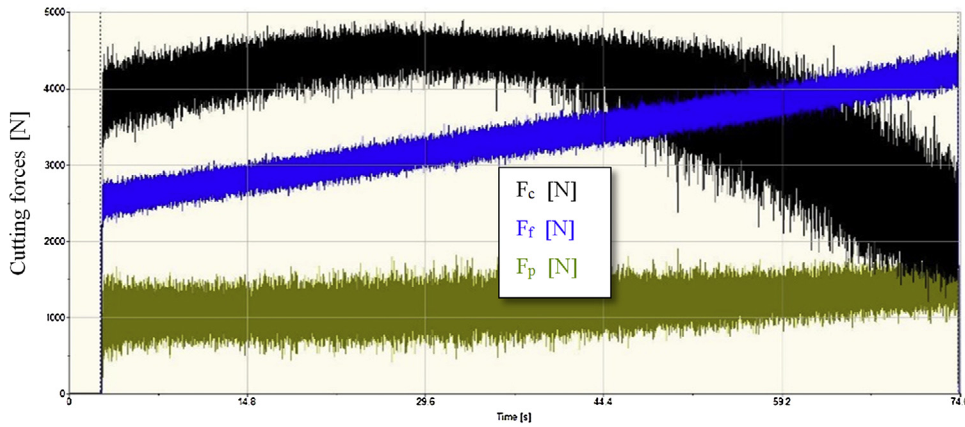

Figure 9 The course of the cutting components of forces during the 2nd cut at strategy variable a_p (a_p = 1.5—2.5 mm, f = 0.4 mm, v_c = 230 m min^{-1}).

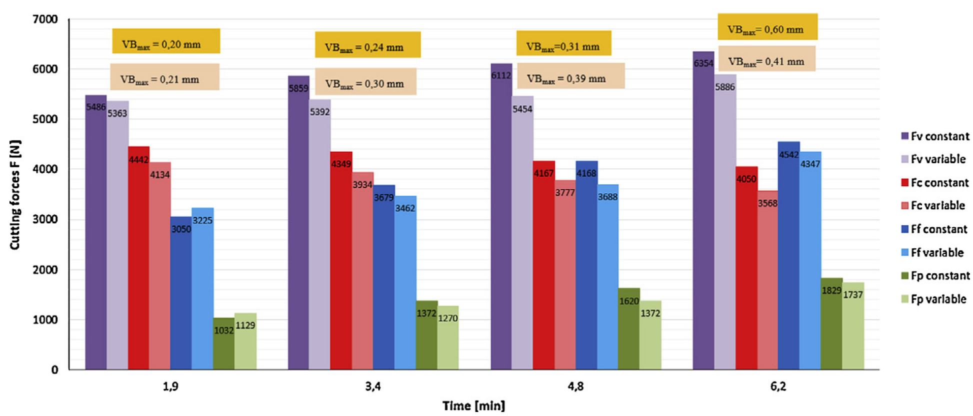

Figure 10 Comparison cutting force components and resultant of cutting force during strategy constant a_p = 2 mm and variable a_p = 1.5—2.5 mm (f = 0.4 mm, v_c = 230 m min^{-1}).

represents the total file measured data and is intentionally selected for the size of the wear inserts (VB_{max} = 0.205 mm after ts = 2.4 min), which is in the region of steady-state wear (2nd region of wear).

Strategy with variable a_p has lower resultant of the cutting forces and also has lower cutting forces of all components, see Fig. 10. Fig. 10 also marked tool wear VB_{max} corresponding to the machine time.

The percentage comparison (cutting forces) of both strategies is shown in Fig. 11. Besides the first two minutes the new strategy with a variable depth of cut is better.

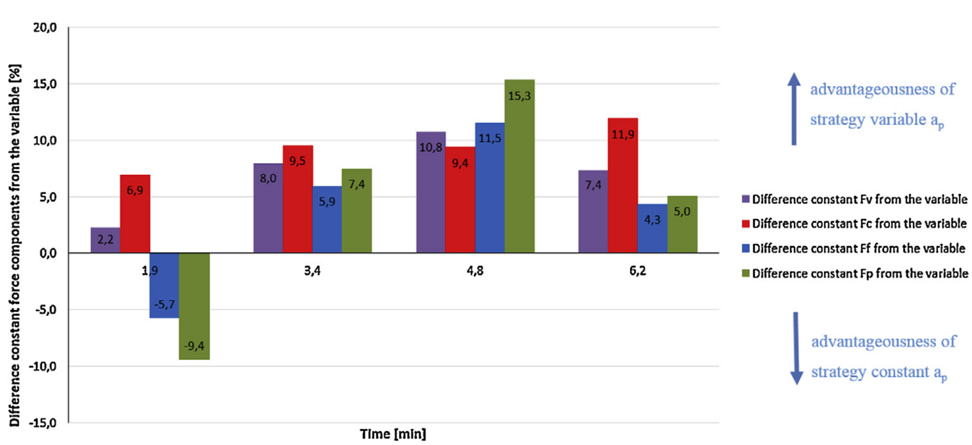

Figure 11 Difference cutting forces components — strategy constant and variable depth of cut (constant a_p = 2 mm and variable a_p = 1.5—2.5 mm, f = 0.4 mm, v_c = 230 m min^{-1}).

Table 2 Component ratio of cutting forces depending on the machining time.

Time	Strategy constant *ap*			Strategy variable *ap*		
	Fc	*Ff*	*Fp*	*Fc*	*Ff*	*Fp*
[min]	[−]	[−]	[−]	[−]	[−]	[−]
1.9	1	0.69	0.38	1	0.53	0.27
3.4	1	0.85	0.48	1	0.61	0.32
4.8	1	1	0.60	1	0.65	0.36
6.2	0.89	1	0.66	0.92	1	0.39
6.6	—	—	—	0.82	1	0.40
7.4	—	—	—	0.70	1	0.41
8.3	—	—	—	0.74	1	0.52

From Table 2 machine time is evident, when there is a change cutting force component ratio. Changing ratio of strategy constant a_p is earlier than the ratio of strategy variable a_p. After a time ts = 4.8 min will change the ratio. Dominant cutting component changes into a dominant feed component. This can be explained by tool wear, which is in 3rd region (accelerated wear region).

The ratio of the individual components of the cutting force is determined primarily by technology of machining, cutting conditions, geometry and material of the cutting tool (Antic et al., 2012; Čep et al., 2011, 2013; Neslušan et al., 2011).

With respect to cutting forces strategy constant depth of cut and strategy variable depth of cut (conic surface strategy) were compared:

- For both compared strategies projected increase is seen in components of cutting forces F_f and F_p at increasing the tool wear, but the downward course of F_c.
- The comparison shows the positive impact of the proposed strategy to cutting force action and thus the energy performance of the machining process.
- Variable depth of cut strategy has lower values of cutting force resultant during durability of cutting tool ($\Delta F_v = 658$ N, i.e. $\Delta F_v = 10.8\%$).
- Variable depth of cut strategy has lower values of cutting component of cutting force F_c during durability of cutting tool ($\Delta F_c = 482$ N, i.e. $\Delta F_c = 11.9\%$).
- Variable depth of cut strategy has lower values of feed component of cutting force F_f during durability of cutting tool ($\Delta F_f = 480$ N, i.e. $\Delta F_f = 11.5\%$).
- Variable depth of cut strategy has lower values of radial component of cutting force F_p during durability of cutting tool ($\Delta F_p = 248$ N, i.e. $\Delta F_p = 15.3\%$).

Experimental results and discussion

Cutting forces while turning with constant and variable depth of cut increases knowledge of the practical implementation of the proposed strategies with variable depth of cut to streamline production. Strategy with variable depth of cut has a beneficial effect on the size the cutting forces and cutting forces and their amplitude.

Main advantages of using a variable depth of cut are:

- Increased tool life by $\Delta T = 2$ min (this is about 20%).
- Reducing the energy load of the machine.
- Reducing the cutting forces during tool life by up to $\Delta F_v = 658$ N, $\Delta F_v = 10.8\%$.
- Changing the relations of cutting forces components, which can signalize the end of tool life.

The proposed manufacturing technology of the flange and shaft components ensures reduced tool wear, i.e. increased turning tool durability and tool life. This is a more favorable distribution of wear to the replaceable tool insert while employing the proposed technology of turning. Increased durability of the tool significantly reduces the total costs for cutting tools. These costs are also reduced by the less frequent downtimes of insert when a wear insert is replaced. The disadvantage is more complicated tool path programming for the roughing cycle with variable depth of cut.

The suggested roughing cycles do not have only positive effect on the machining process. It is necessary to carefully consider all the aspects associated with the proposed cycles. These can include requirements imposed on the software (CAM system) and the CNC programmer/operator.

Conflict of interest

The authors declare that there is no conflict of interest.

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