

Progressive Strategy of Milling by means of Tool Axis Inclination Angle

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Abstract—This work deals with problems of tool axis inclination angles in ball-end milling. Tool axis inclination angle contributes to improvement of functional surface properties (surface integrity - surface roughness, residual stress, micro hardness, etc.), decreasing cutting forces and improving production. By milling with ball-end milling tool, using standard way of cutting, when work piece and cutting tool contain right angle, we have zero cutting speed on edge. At this point cutting tool only pushes material into the work piece. Here we can observe the following undesirable effects - chip contraction, increasing of cutting temperature, increasing vibrations or creation of built-up edge. These effects have negative results - low quality of surface and decreasing of tool life (in the worse case even it is pinching out). These effects can be eliminated with the tilt of cutting tool or tilt of work piece.

Keywords—CAD/CAM system, tool axis inclination angle, ball-end milling, surface roughness, cutting forces.

I. MILLING BY MEANS OF THE TOOL AXIS INCLINATION ANGLE

Thanks to tilt of cutting tool we can change effective diameter of cutting tool and with it also effective cutting speed.

Effective tool diameter (without tilt of cutting tool) can be calculated according to this mathematical expression:

$$d_{eff} = 2 \cdot \sqrt{a_p(d - a_p)} \quad [\text{mm}] \quad (1)$$

Where: a_p axial depth of cut [mm],
 d tool diameter [mm],
 d_{eff} effective tool diameter [mm].

Effective diameter of pulled cutting tool is calculated according to this mathematical expression [2]:

$$d_{eff} = d \cdot \sin \left[\arccos \left(\frac{d - 2 a_p}{d} \right) + \beta_f \right] \quad [\text{mm}] \quad (2)$$

Where: a_p depth of cut [mm],
 β_f inclination angle in feed direction [°],
 d tool diameter [mm],
 d_{eff} effective tool diameter [mm].

By milling with pushed tool the mathematical expression (2) changes positive sign (β_f) into negative one. From that expression it is obvious that it is preferable to use pulled tool.

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Very important is direction of feed. If the feed is designated as pulled, the tool runs silently, and also the surface of work piece improves, as opposed to pushed tool [5].

These two ways can be used with the tool axis inclination angle in feed direction and also in pick feed direction. Also using climb milling or conventional milling has big influence on surface quality and on tool life.

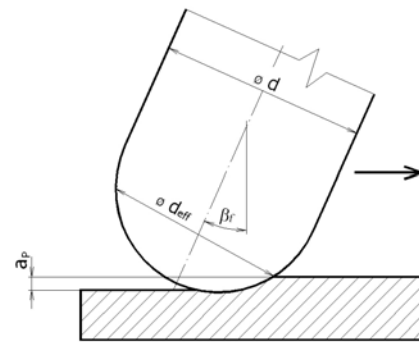


Fig. 1 Pulled tool

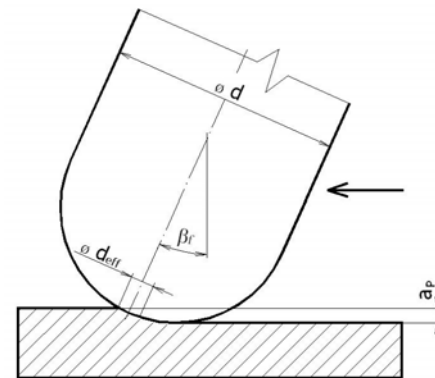


Fig. 2 Pushed tool

Next picture shows different milling strategy with tilt of milling cutter against normal line of surface.

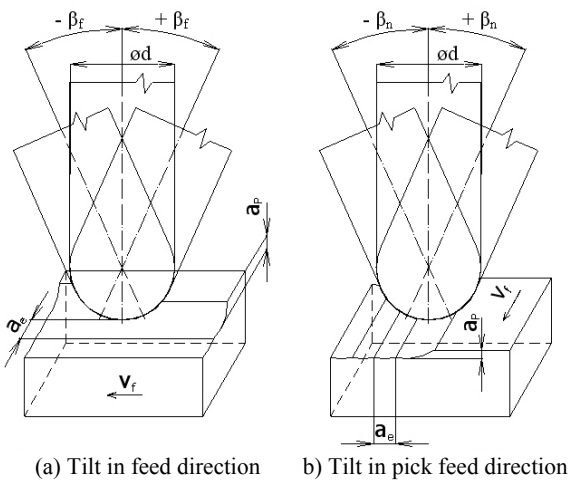


Fig. 1 Milling Strategy with tool axis inclination angle

Experiments are divided into groups of samples. Every group of samples contains 7 tilts of cutting tool in pick feed direction. Each sample size is 20 x 20 mm.

Experiment characterization:

- tool axis angle in pick feed direction,
- conventional milling and climb milling combination,
- strategy of feed designated as pulled tool,
- using cutting fluid,
- work piece 42 2906 (X3CrNiMo13-4),
- ball end milling cutter (cutting insert, 2 flutes, coating 8040 [2], [10]),
- cutting geometry of cutting insert: $\gamma_p=0^\circ$ a $\gamma_f=-7^\circ-14^\circ$.
- overhang $l_n=110$ mm.

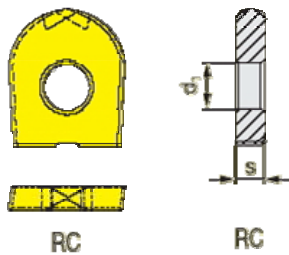


Fig. 2 Exchangeable cutting edge - Pramet Tools Company – type RC [2]

TABLE I
 CUTTING CONDITIONS

Examp.	Depth of Cut	Diam. of Endmill	Spindle Rev.	Cutting Speed	Theoretic Surface Roughness		Width of Cut	Feed per Tooth
					Pick Feed Direction	Feed Dir.		
-	a_p	d	n	v_c	R_a	R_a	a_c	f_z
-	[mm]	[mm]	[min^{-1}]	[$\text{m}\cdot\text{min}^{-1}$]	[μm]	[μm]	[mm]	[mm]
e	0.3	25	1 950	153	0.4	0.4	0.395	0.395
f					0.8	0.8	0.558	0.558

II. SURFACE ROUGHNESS

Only presentable demonstrations were chosen from all the figures and graphs.

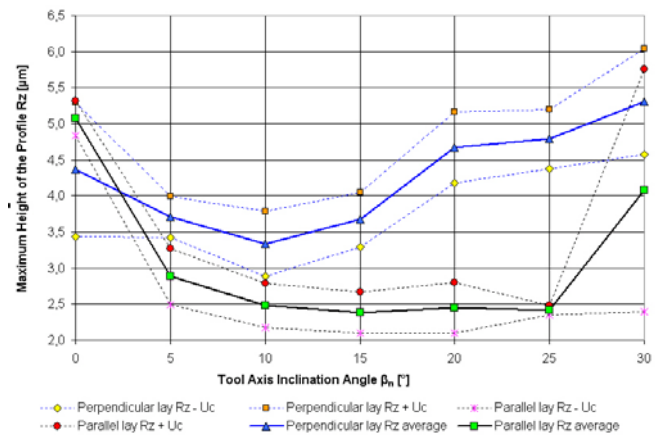


Fig. 3 Surface roughness (Rz) dependence on tool axis inclination angle, set of "e" samples

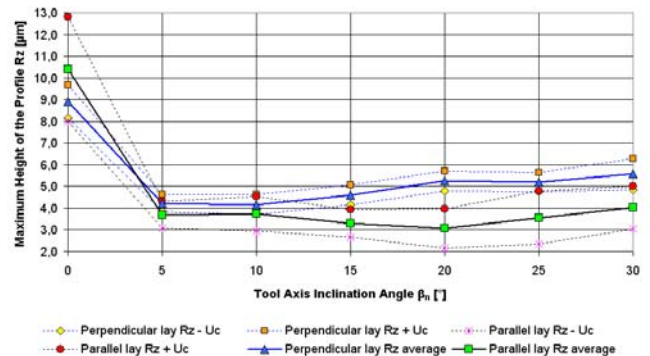


Fig. 6 Surface roughness (Rz) dependence on tool axis inclination angle, set of "f" samples

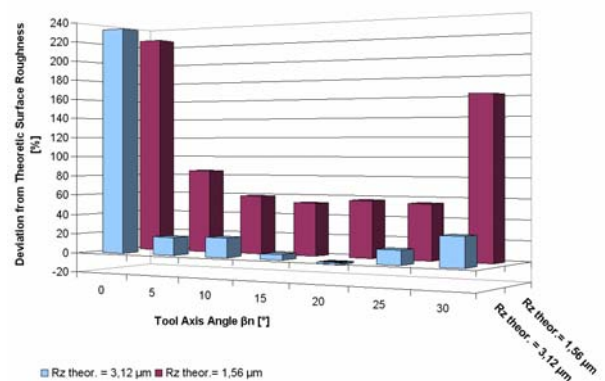


Fig. 4 Deviations of Theoretical Surface Roughness (Rz) at Different Tool Axis Angles, feed direction (25 mm, $a_c, f_z = 0,395$ mm a $a_c, f_z = 0,558$ mm, set of samples "e and f")

It is evident from the graphs that bigger width of cut and feed per tooth achieved smaller surface roughness. We can say that $\beta_n=10-15^\circ$ is an optimal value of tool axis inclination

angle. With the bigger tool axis inclination angle ($\beta_n > 15^\circ$) a greater surface roughness was shown thanks to changes of cutting tool geometry.

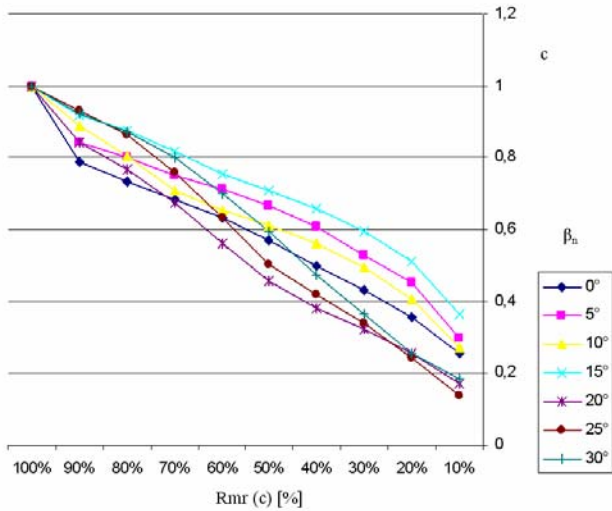


Fig. 5 Curves of the profile bearing length ratio (level 30%) at different tool axis angles - feed direction (parallel lay)

Profile bearing length ratio is changing in feed direction more, than in pick feed direction. Optimal values of profile bearing length ratio are in the range of tool axis inclination angle of $\beta_n = 5-30^\circ$ in the feed direction. Here we can see the greatest values of profile bearing length ratio. These results show favorable impact of the tool axis inclination angle on machined surface.

III. RESIDUAL STRESS

The question is, how the selected strategy of cutting, (changeable tool axis inclination angle) changes quality of the surface. The shape and size of cutting edge has the greatest influence on the integrity of surface. The cutting speed has the biggest influence, considering cutting conditions [7].

There are growing residual stresses thanks to selection of used technology of cutting in the area of surface layer. Residual stresses are effective all the time, even without external stress after expiration of cutting process [4].

Magnetolectric method (e.g. Barkhausen noise) is one of the possibilities to indicate structural and stress changes of ferromagnetic materials in surface layer.

The magnetic Barkhausen effect is a phenomenon that occurs during magnetization of ferromagnetic materials and is related to movements of magnetic domains under the influence of an alternating magnetic field. The Barkhausen noise is a collection of all information from material; therefore, voltage signal should be captured, processed and compared to the same signals from materials with specified properties [4].

The method is suitable for determination of size and variation of load tension of various microstructures, as well as residual stresses in a thin surface layer of material after

machining and heat treatment [4], [1].

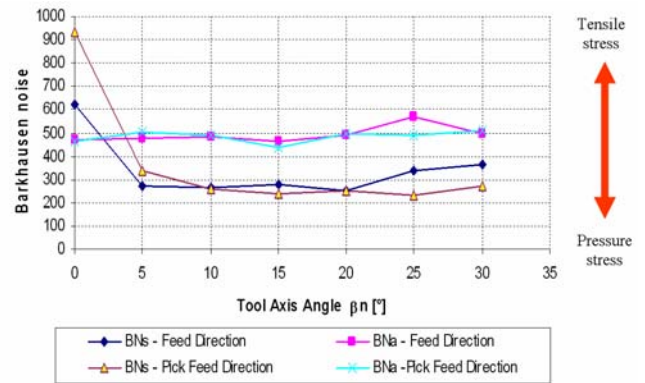


Fig. 9 Barkhausen noise dependence on tool axis angle - feed direction and pick feed direction (set of examples "f")

Experiment conclusion – the residual stress is reduced thanks to the tool axis inclination angle. The vertical orientation of cutting toll (tool axis inclination angle is 0°) with regard to machined surface causes increasing values of Barkhausen noise in machined surface (undesirable tensile stress, which we needed to eliminate).

We can watch minor influence of residual stress on work piece surface due to non vertical orientation of cutting tool (tool axis inclination angle is 5°) already. Most of sample groups show lowest residual stress with the tool axis inclination angles of $\beta_n = 5-30^\circ$. Values of residual stress measured in the feed and pick feed directions are similar.

IV. CUTTING FORCES

The cutting forces were measured by the Kistler 9255B dynamometer and DasyLab, Exel and Matlab software.

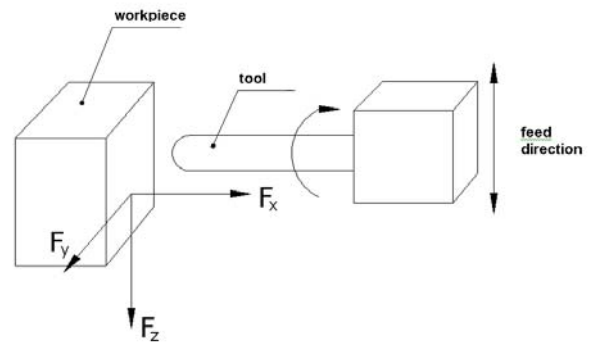


Fig. 10 Coordinate system of the selected experiment

Experiment conditions differed in horizontal 5-AXIS lathe H40 (TAJMAC - ZPS, a.s.), work piece 19552, Hardness 51 HRC) with the following cutting conditions.

TABLE II
 CUTTING CONDITIONS

Examp.	Depth of Cut	Diam. of Endmill	Spindle Rev.	Cutting Speed	Width of Cut	Feed per Tooth
-	a_p	d	n	v_c	a_e	f_z
-	[mm]	[mm]	[min^{-1}]	[$\text{m}\cdot\text{min}^{-1}$]	[mm]	[mm]
g	0.3	10	7 962	250	0.2	0.2
h	0.3	20	3 981	250	0.2	0.2

The graph no. 2 is shown as an example demonstrating the size of resultant force during climb milling. First graph shows general decrease of the cutting forces (F_v) in both tools. Decrease of the resulting cutting force to almost half has positive influence on all monitored aspects, e.g. surface roughness, planeness, cutting stability of the process, vibration reduction etc .

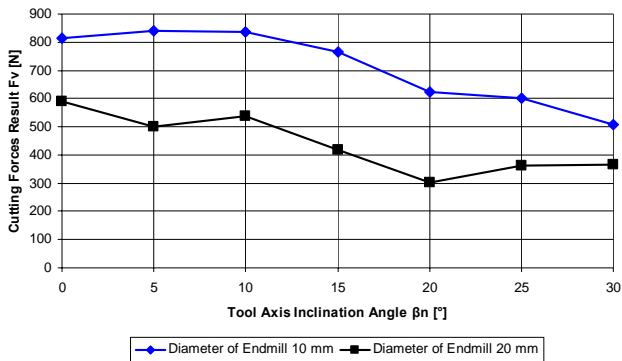


Fig. 11 Resulting cutting force depending on tool axis inclination angle during climb milling

The shape of the F_y function (in pick feed direction) shows decrease and then increase of values. The same shape of function (similar to bath curve) can be observed in surface roughness parameters that depend on tool axis inclination angle, and Barkhausen noise versus tool axis angle, see Fig. 5, 6 and 9. Particularly decrease of the F_y component with the tilt of cutting tool improves surface roughness. From that we can conclude that F_y is significantly affecting surface roughness and accuracy during consecutive milling. Further increase of tilt of the tool (above 15°) causes significant change of cutting geometry of exchangeable cutting edge. This increases F_y component and consequently surface roughness.

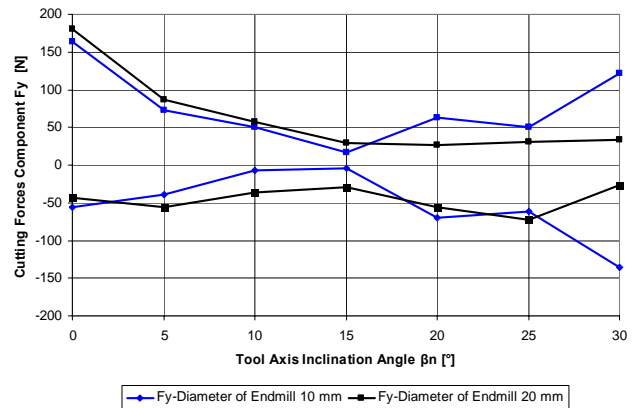


Fig. 12 Deviation of values of the cutting component F_y depending on tool axis inclination angles during conventional milling

Lower scattering of size of single components of the cutting forces was reached by inclination angle of tool axis. It brings more stability of cutting process and cause improvement of cutting parameters [8],[6], [9]. Conventional milling lowers scatter of single components cutting force values several times.

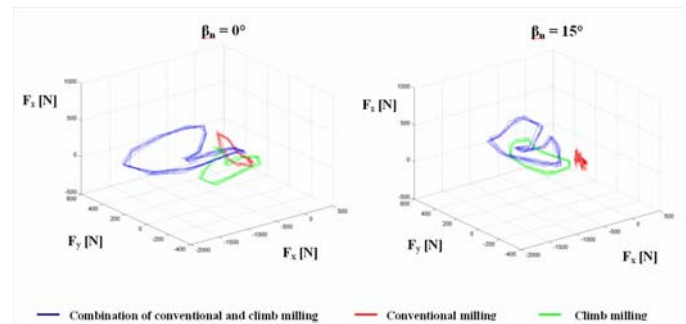


Fig. 13 Direction and size of cutting forces result (F_v) dependence on cutting time (tool axis angle $\beta_n=0^\circ$ end 15° , tool diameter 10 mm, $a_p=0.3$ mm, $f_z=0.2$ mm, $v_c=250$ $\text{m}\cdot\text{min}^{-1}$)

Benefits of using tool axis inclination angle:

- increasing cutting speed,
- increasing surface roughness in pick feed direction and feed direction,
- decreasing cutting time (using bigger a_e , f_z by the same surface roughness),
- increasing durability of cutting tool,
- increasing accuracy of cutting,
- constant cross sectional area of chip,
- constant cutting conditions,
- decreasing size of cutting forces components,
- favorable orientation of cutting forces direction,
- increasing functional surface properties of machined surface,
- inhibition of self-excited oscillations,
- decreasing of cutting temperature.

V. CONCLUSION

After the complete analysis we can say that tool axis inclination angle influences pick feed direction and feed direction surface roughness. Most of sample groups show dependence of tool axis inclination angle on residual stress.

Surface roughness and residual stress affect functional surface, life time and reliability of parts, their noise level, running-in period, losses due to friction, electrical resistance, heat transfer, fatigue strength, wear resistance, corrosion resistance etc.

Integrity of grinded surface is not adequate, e.g. from the point of view of heat and stress (residual stress) and interference in surface layer of material. Therefore research of suggested technology (optimized tool axis inclination angles in ball-end milling) contribute to elimination of grinding (i.e. final operation—hand finishing of parts), or at least reduce time and intensity of grinding.

Tool axis inclination angle and strategy of milling have strong influence on size and direction of cutting force components. This theory is useful for optimization of vectors angle of tilt of cutting tool with the view of effectivity and improvement of production quality.

Measured values of components of cutting forces will be used to set accuracy of cutting in research in the Technical University in Ostrava. Based on the measured cutting forces we can optimize the space tilt cutting angle of the tool. Then we can speak about adaptive optimization.

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