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Aspects of Using Tool Axis Inclination Angle

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This contribution deals with the research and proposal to change a position of tool axis against milled surface during multi-axial milling. Our target is achieving an increase in milling efficiency (improvement of functional surface properties, increase in milling accuracy, increase in tool durability, decrease in energy load on a machine, and shortening of milling time). This research attempts to make production of shape planes more efficient. This concerns production of molds, impression dies, and other complicated parts in various engineering industries, primarily automotive and aircraft ones.

Keywords: tool axis inclination angle, ball-end milling, surface roughness, cutting forces

0 INTRODUCTION

Pre-defined milling cycle possibilities are used during the programming of multi-axial milling centers in the CAM systems [1]. However, the question is whether programmers are able to utilize all the available setting options optimally. Do they put in all the significant information necessary for effective milling? Do these programmers know what values are the most effective?

These questions for programmers lead to an underestimated and neglected option to change tool axis position against the normal of milled surface. This work, among other things, attempts to find an answer to this question and confirm it scientifically. The result then should be determining an effective angle or rather an effective range of settings of the spatial angle of the tool axis position in relation to a milled surface.

All milling parameter settings have to lead to increased milling efficiency, i.e., to an increase in accuracy, improvement of functional properties of milled surface (roughness, waviness, residual stress, micro-hardness, etc.), a decrease in milling time, shortening of machine energy load, economical and ecological aspects, etc. [1] and [2].

Surface roughness and residual stress affect functional surfaces, durability and dependability of parts, their noisiness, break-in period, friction losses, electrical resistance, heat transfer, fatigue strength, wear and corrosion resistance, etc. [1], [3] and [4].

1 MILLING BY INCLINED TOOL

During standard milling with ball end milling cutters, when the material and the tool are in right angles, a spherical cutting edge has zero cutting speed at the tool axis. The tool merely pushes in the milled material at this place. Due to this, undesirable effects such as: chip contraction, increase in the cutting temperature, increase in vibrations, and increased creation of a build-up edge, can appear [4] to [6]. These phenomena result in a worsened quality of the milled surface and decreased tool durability. Fig. 1 shows the possibilities of tool inclination toward the surface normal.

The above mentioned phenomena can be eliminated by a change of the tool axis position in relation to the milled piece, i.e., by an inclination of the tool or the piece.

The effective diameter of the cutting tool during milling without tool inclination is calculated according to the following relationship [6]:

$$d_{eff} = 2 \cdot \sqrt{a_p \left(d - a_p \right)}, \qquad (1)$$

where d_{eff} is effective tool diameter [mm], a_p axial depth of cut [mm] and d tool diameter [mm].

Feed direction is highly significant. If the feed direction is (the so called) pulled one (Fig.

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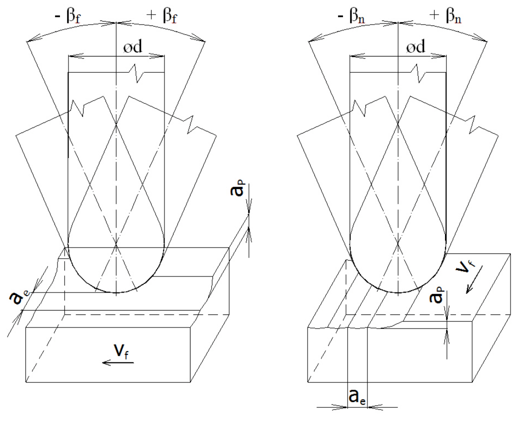
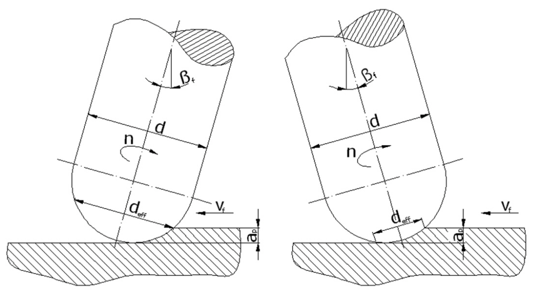
2a), the tool action is more silent and the surface of the milled material is better, as opposed to (the so called) pushed feed direction (Fig. 2b). These two ways can be used for an inclination in the feed direction and also for an inclination that is perpendicular to the feed direction.



a) *b)*

Fig. 1. *Milling strategy with tool axis inclination angle*, *a) tilt in feed direction, b) tilt in pick feed direction*



a) b)

Fig. 2. *Feed direction; a) pulled tool, b) pushed too*l

Owing to a change in position the effective tool diameter changes and so does the resulting (actual) effective cutting speed (Fig. 3).

The effective diameter of the cutting tool during milling with a pulled tool is calculated according to the following relationship [7]:

$$d_{eff} = d \cdot \sin\left[\arccos\left(\frac{d - 2\,a_p}{d}\right) + {}^{2}{}_{f}\right], \qquad (2)$$

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

Milling with pushed tool corresponds with negative values of β_f in the relationship (Eq. (2)). This signifies that, according to the mathematical expression, the use of a pushed tool is disadvantageous.

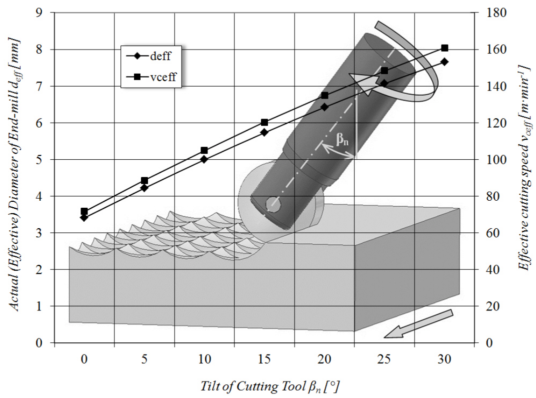


Fig. 3. *The relationship of the effective tool diameter d_{eff} and the effective cutting speed v_{ceff} on the angle of tool inclination βn, (d = 10 mm, a_p = 0.3 mm, v_c = 210 m·min-1)*

The problem of the scallop generation mechanism is quite complicated and falls into the field of applied mathematics. Many foreign publications describe this mechanism. However, these publications tend to only describe the situation when the tool and the workpiece are in a relative translation motion only (no rotation of ball-nosed cutter). The generating mechanism of the rotation ball-nosed end milling, however, is much comlicated because the orientation of the cutting edge is dynamically and periodically changed during the spindle rotation [8].

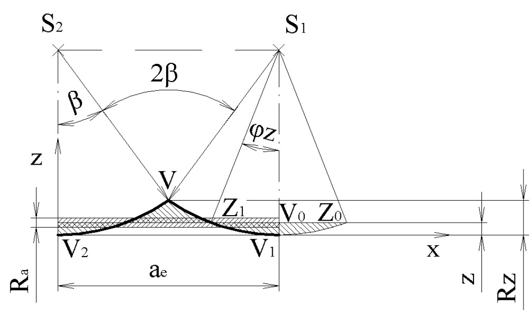


Fig. 4. *Occurrence of theoretical surface roughness in pick feed direction on the plane [6]*

Literature [9] presents a new geometrical model for the surface scallop estimation that considered the dynamic cutting edge rotation effect in the ball-nose end milling process. Literature [10] presented the model to include the effect of the tool axis inclination.

One of many published approaches used to determine theoretical surface roughness is described in [7].

According to this approach the resulting relationship for calculation of the average arithmetic deviation of surface roughness for milling with ball end milling cutter (Fig. 4) is [7]:

$$Ra = \frac{R^2}{a_e}\left\{arc2\left[\arccos\left(\frac{1}{2}\cos\arcsin\frac{a_e}{2\cdot R} + \frac{R}{a_e}arc\arcsin\frac{a_e}{2\cdot R}\right)\right] - \right.$$

$$\left. -\sin 2\left[\arccos\left(\frac{1}{2}\cos\arcsin\frac{a_e}{2\cdot R} + \frac{R}{a_e}arc\arcsin\frac{a_e}{2\cdot R}\right)\right]\right\}\cdot 1000, \quad (3)$$

where Ra is arithmetical mean deviation of the profile [µm], R cutter radius [mm] and a_e depth of cut [mm].

In the case of milling on inclined plane, a_e is substituted with a'_e modified by the angle of the inclined plane α:

$$a'_e = \frac{a_e}{\cos\alpha}, \quad (4)$$

where α *is*angle of the milled surface [°], a'_e angle of the inclined plane [°] and a_e -depth of cut [mm].

For practical application the calculation for the maximum height of the profile Rz, that can be found in the CSN EN ISO 4287 and CSN EN ISO 4288 standards, is sufficient:

$$Rz = R\cdot\left(1-\sqrt{1-\frac{a_e}{4\cdot R^2}}\right), \quad (5)$$

where: Rz maximum height of the profile [mm], R cutter radius [mm], a_e depth of cut [mm].

3 EXPERIMENTAL WORK

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,
- workpiece 1.7131,
- ball end milling cutter (cutting inserts, 2 flutes, coating 8040),
- cutting geometry of exchangeable cutting edge: γ_p = 0° and γ_f = -7° to 14°,
- cantilever length ln = 110 mm.

Representative examples of the surface roughness parameter Rz dependency on the angle of tool inclination (β_n) have been selected from many performed experiments (Figs. 5 and 6).

The biggest maximum height of the profile Rz was measured in the feed direction and in the direction perpendicular to it. The lines are shown with the expanded combined uncertainty *Uc*. Measurements of the surface roughness parameters were performed on Hommel – Tester T2000.

The graphs in Figs. 5 and 6 show that the most suitable cutter inclination is β_n around 15°. When the inclination angle is larger surface roughness increases, especially due to the change of cutting geometry, where there is cutting outside of the so called transitional edge. The best longitudinal (feed direction) roughness was achieved with the inclination β_n = 10°.

Deviations of theoretically calculated roughness from the actually measured value are presented on Fig. 7. The graph shows smaller measured roughness as opposed to the theoretical one for larger cut widths and feed per tooth. This result is related to the problem of the minimum chip thickness. For double cut widths and feed per

Table 1. *Cutting conditions*

collection of surfaces	depth of cut	diameter of endmill	spindle rev.	cutting speed	theoretic surface roughness				width of cut	feed per tooth
					pick feed direction		feed direction			
AMF	ap	d	n	vc	*Rz*	*Ra*	*Rz*	*Ra*	a_e	f_z
-	[mm]	[mm]	[min⁻¹]	[m·min⁻¹]	[µm]		[µm]		[mm]	[mm]
a	0.3	10	6685	210	0.78	0.2	0.78	0.2	0.1765	0.1765
b					1.56	0.4	1.56	0.4	0.2497	0.2497

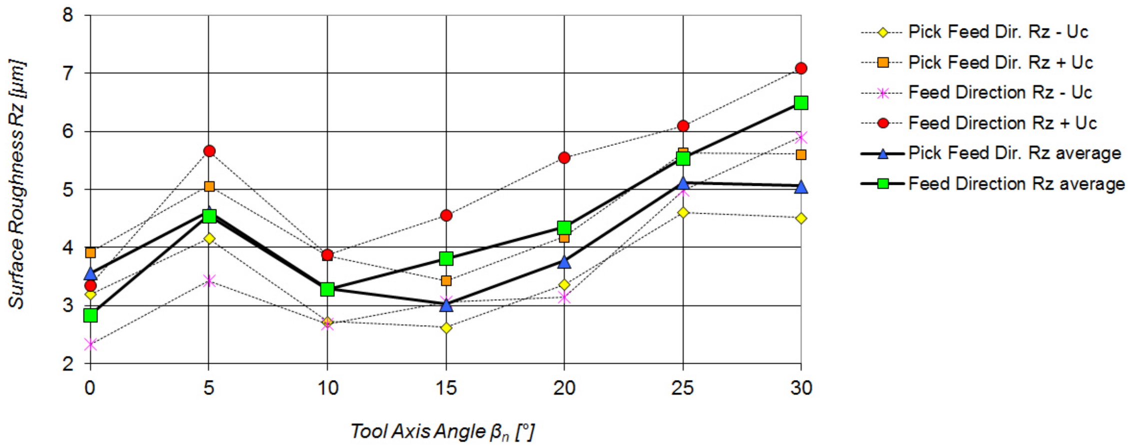


Fig. 5. *Surface roughness (Rz) dependence on tool axis inclination angle, collection of surfaces "a"*

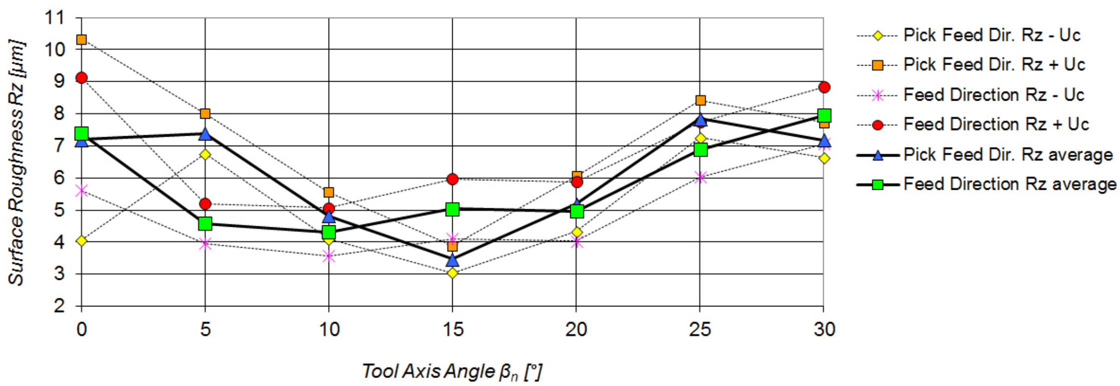


Fig. 6. *Surface roughness (Rz) dependence on tool axis inclination angle, collection of surfaces "b"*

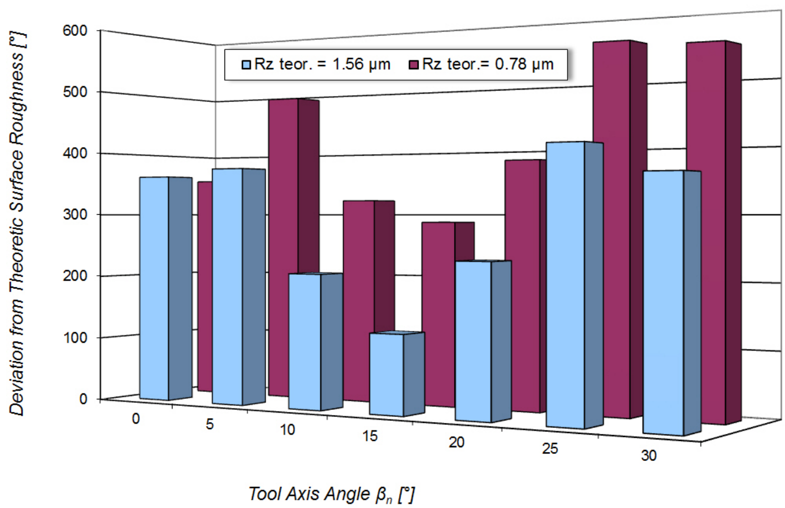


Fig. 7. *Deviations of theoretical surface roughness (Rz) at different tool axis angles, pick feed direction (d = 10 mm, a_e, f_z = 0.18 mm and a_e, f_z = 0.25 mm, collection of surfaces „a and b")*

tooth (a_e and f_z) relatively equal surface roughness can be achieved.

Bearing length ratio changes more in longitudinal direction then in transversal one (Fig. 8). The most advantageous values of bearing length ratio appear in the longitudinal direction with the tool inclinations of 5 and 15°. Here the bearing length ratio is the largest. These results indicate a beneficial impact of the tool inclination on functional aspects of milled surfaces.

The question is to what extent the variable tool inclination influences the change in surface properties. Shape and curvature of the tool edge have the biggest influence on surface integrity. Out of cutting parameters the fundamental influence is shown primarily by the cutting speed [1], [2] and [10].

Residual stress at the workpiece surface layer areas is a manifestation of the used machining technology. One of the possibilities how to indicate structural and tension states of ferromagnetic materials in the surface layer is using the magnetoelastic method.

From the experiments it follows that the cutter inclination results in a decrease in the residual stress, see Fig. 9. During perpendicular

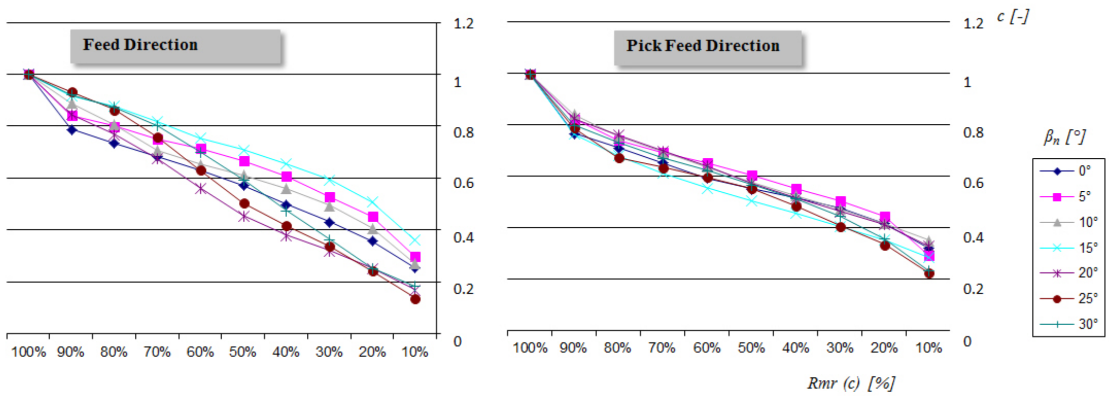


Fig. 8. *Curves of the profile bearing length ratio (level 30%) at different tool axis angles*

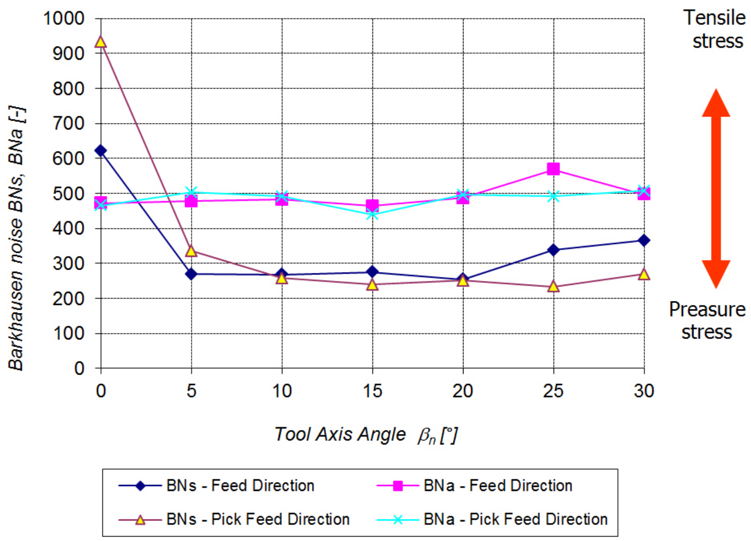


Fig. 9. *Barkhausen noise relation to tool axis angle - feed direction and pick feed direction (material X3CrNiMo13-4, d = 25 mm, v_c = 153 mm, a_p = 0.3 mm, a_e = 0.6 mm, f_z = 0.6 mm)*

position of the ball end milling cutter (inclination = 0°) in relation to a milled surface there is a relatively high value of Barkhausen noise (i.e., undesirable tensile stress that needs to be eliminated) due to pushing-in at the tool axis with zero cutting speed.

Already a tool inclination of five degrees results in a significant decrease of the residual stress influence on the surface (milled) layer. The Barkhausen noise values do not change with a further change of the tool position significantly. Curves of the values measured in feed and pick feed directions are similar.

Residual stress was measured in 0.01 to 0.04 mm depth.

In order to obtain stress values in [N] a calibration needs to be performed and the BS values should be recalculated using the calibration curves. This calibration, however, is economically demanding and time consuming, therefore it is not absolutely necessary for the confirmation of influence of inclination on residual stress.

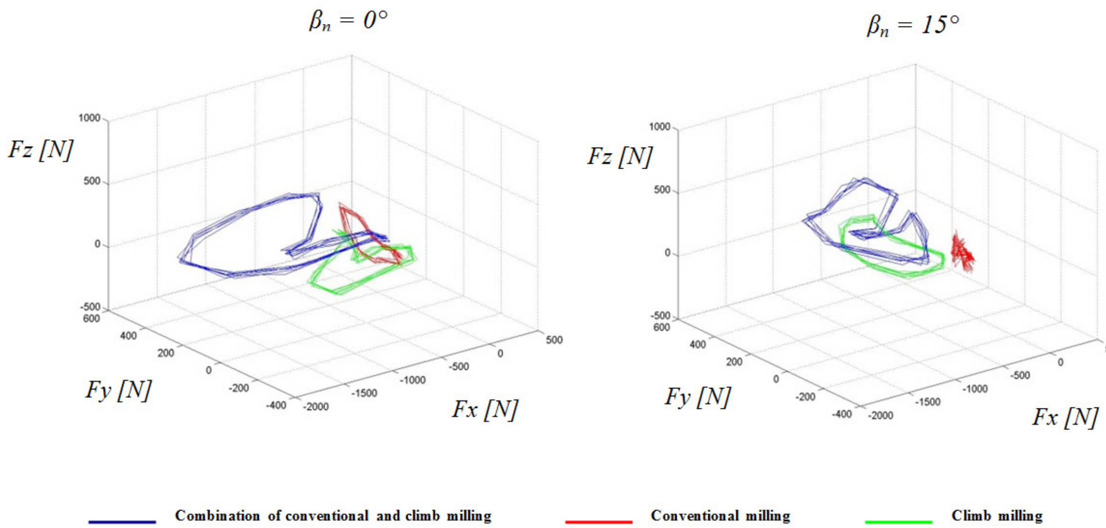


Fig. 10. *Direction and size of cutting forces result (Fv) dependence on cutting time (toll axis angle $\beta_n = 0°$ and 15°, $d = 10$ mm, $a_p = 0.3$ mm, $f_z = 0.2$ mm, $v_c = 250$ m·min^{-1})*

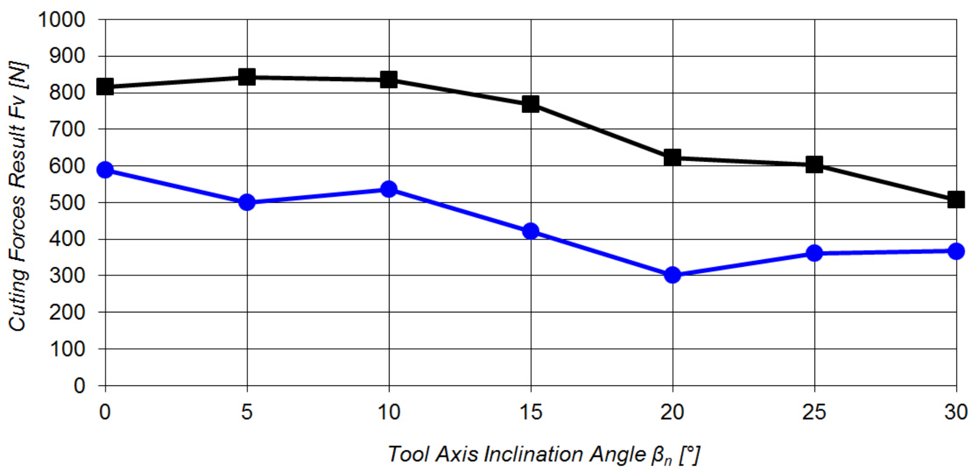


Fig. 11. *Resulting cutting force depending on tool axis inclination angle during climb milling (workpiece 1.2343, 47 – 51 HRC , $d = 10$ and 20 mm, $a_p = 0.3$ mm, $f_z = 0.2$ mm, $v_c = 250$ m·min^{-1})*

Dynamometer Kistler 9255B and DASYLab, Excel, and Matlab programs were used for measuring of cutting forces (Fig. 10).

As an example out of many measurements the curves of resultant forces during climb milling are shown in Fig. 11. Lower ranges of individual cutting force components were achieved by the cutting tool inclination angle changes. This leads to cutting process stability. For conventional milling several fold decreases of value range can be shown.

The course of the values component Fy (feed direction) decreases with tool inclination and then grows. Such a course (similar bathtub curve) is also noted for the results of measurements of roughness parameters, depending on the tool axis inclination angle. This confirms the fact that the decline in component Fy causes the improvement of surface roughness.

4 DISSCUSION AND CONCLUSIONS

After the final experiment evaluation it can be concluded that the tool inclination has a significant influence on the longitudinal and transversal surface roughness. With increasing cutter diameter smaller inclination can be selected.

Benefits of using tool axis inclination angle include:

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

During milling it is necessary not to exceed the maximum tool inclination in the relation to a workpiece; the inserts geometry needs to be maintained. When this inclination is exceeded the result is increased surface roughness. This eventuality can occur while milling steeper surfaces. With used inserts there was cutting outside the so called transition edge during higher inclinations (e.g., for d = 10 mm the critical β_n = 17°).

For most surface groups there was also considerable dependency of the tool inclination on residual stress.

The tool inclination against a workpiece has a significant influence on the size and direction of individual cutting force components. This can be used for the optimization of tool inclination spatial angle in order to achieve a better quality of milled surface, an increase of tool durability, and lower energy demands during milling. Based on the measured cutting forces the tool inclination spatial angle can be optimized online, which leads to adaptive optimization [10], [11] and [12] .

The application research area is the milling of shape surfaces with suppression of grinding operation. The integrity of ground surface is often unsatisfactory, for example from the point of view of heat and tension (residual stress) influence on surface layers [6]. Therefore, research of the proposed technology contributes to the effort to eliminate grinding (i.e., the final operation of manual finishing of shape surfaces), or to minimize it.

5 REFERENCES

[1] Županl, U., Čuš, F., Reibenschuh, M. (2011). Neural control strategy of constant cutting force system in end milling, *Robotics and Computer-Integrated Manufacturing*, vol. 27, no. 3, p. 485-493.

[2] Zetek, M., Řehoř, J., Strnad, T. (2006). *Increasing cutting tool efficiency*. PhD thesis, University of West Bohemia, Plzeň, p. 1-9.

[3] Adamczak, S., Miko, E., Čuš, F. (2009). A model of surface roughness constitution in the metal cutting process applaying tools with defined stereometry. *Strojniški vestnik - Journal of Mechanical Engineering*, vol. 55, no. 1, p. 45-54.

[4] Xu, Ch., Chen, H., Liu, Zh., Cheng, Zh. (2009). Condition monitoring of milling tool wear based on fractal dimension of

vibration signals. *Strojniški vestnik - Journal of Mechanical Engineering*, vol. 55, no. 1, p. 15-25.

[5] Wei, Z.C., Wang, M.J., Zhu, J.N., Gu, L.Y. (2011). Cutting force prediction in ball end milling of sculptured surface with Z-level contouring tool path. *International Journal of Machine Tools & Manufacture*, vol. 51, no. 5, p. 428-432.

[6] Čep, R., Neslušan, M., Barišić, B. (2008). Chip formation analysis during hard turning. *Strojarstvo*, vol. 50, no. 6, p. 337-345.

[7] Peterka, J. (2004). The new approach of calculating the arithmetic mean deviation of surface roughness of machined surfaces during ball end milling. *Engineering Technology*, vol. IX, no. 2, p. 28-32. (in Czech)

[8] Chen, J.S., Huang, Y.K., Chen, M.S. (2005). A study of the surface scallop generating mechanism in the ball-end milling process. *International Journal of Machine Tools & Manufacture*, vol. 45, p. 1077-1084.

[9] Mizugaki, Y., Hao, M., Kikkawa, K. (2001). Geometric generating mechanism of machined surface by ball-nosed end milling. *Annals of the CIRP,* vol. 50, no. 1, p. 69-72.

[10] Mizugaki, Y., Kikkawa, K., Teral, H., Hao, M. (2003). Theoretical estimation of machined surface profile based on cutting edge movement and tool orientation in ball-nosed end milling. *Annals of the CIRP*, vol. 52, no. 1, p. 49-52.

[11] Kopač, J., Kržič, P. (2008). CAM algorithm as important element by achieving of good machined surface quality. *Strojniški vestnik - Journal of Mechanical Engineering*, vol. 54, no. 4, p. 280-287.

[12] Čuš, F., Župerl, U. (2011). Real-time cutting tool condition monitoring in milling. *Strojniški vestnik - Journal of Mechanical Engineering*, vol. 57, no. 2, p. 142-150.