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COMPARATIVE STUDY OF THE BALL NOSE END MILL MACHINED SURFACE QUALITY

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Abstract: *Ball nose end mills are highly used for 3–5 axes milling operations. The current paper presents a package of experiments for ball nose end milling, considering two cases: machining with the tool in a vertical position and machining with the tool in a tilted position compared to the machined surface. In comparison to the experiments presented so far in the known literature, the tool is tilted on two directions thus providing specific data. The results cover surface profile, texture and surface roughness measured on two perpendicular directions. References with similar data obtained by other researchers are also made.*

Key words: *ball nose end mill, 5 axes milling, surface profile, surface roughness.*

1. INTRODUCTION

When it comes to ball nose end milling, there are a lot of aspects to cover. The cutting conditions can vary in a wide interval and a complete approach to 5 axes milling by using such tools has not been identified. The International Organization for Standardization has not released any material related to how these tools should be used or how one can assess the tool wear. The most complex standard regarding milling is ISO 8688 which refers to the assessment of tool's wear for face and end mills but not ball nose end mills. This could be explained by the fact that the geometry of the ball nose end mill can vary a lot depending on the usage conditions and having a major effect accordingly.

It is the geometry of these tools that enables their usage in a vertical position or in a tilted position with respect to the surface to be machined (Fig. 1).

The tilting of the tool or of the workpiece must be allowed by the technological capabilities of the machine-tool. The tool can be tilted on feed direction θ_f, on pick feed direction θ_n or on an angle resulting from a combination of the previously mentioned two inclinations.

It is highly recommended to use the ball nose end mill in such a way as to avoid entering the workpiece material with the tip of the tool. The cutting speed at the tip of the tool is 0 m/min and for this reason no cutting takes place in that area.

Theoretically these tools can be tilted according to the technological possibilities of the machine-tool and the constraints imposed by the piece configuration.

In the known literature, only the study of one direction tilting has been noticed (either tilting on the feed direction or on the pick feed direction).

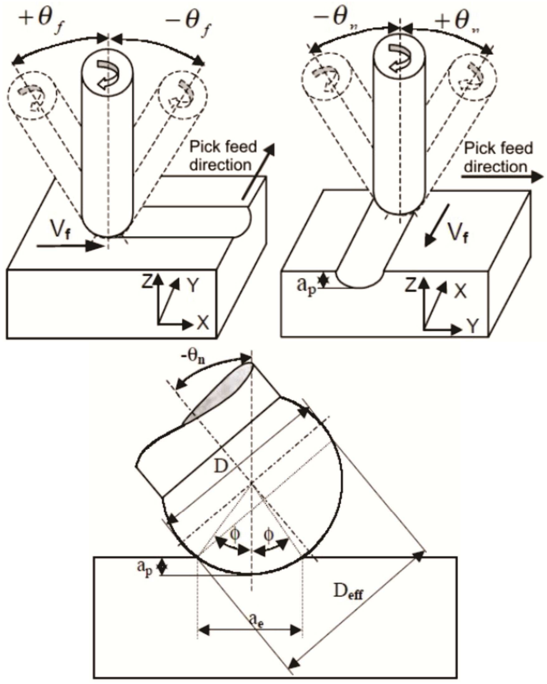

Fig. 1. Tool tilting in one of the two directions (feed or pick feed direction) – adapted after [5].

Regardless of the modeling method used within these studies [1–4; 6–10; 12, 15, 16], it was noticed that most of them present tool's inclination values like 10°, 15°, 30°, 45°, 60° and/or 75°. In one paper [5] the inclination of 17° (θ_n) has been considered, without a clear specification as to why it has been chosen.

In most of the 5 axes milling cases, there are no technological capabilities for tool inclination with more than 20°–30° with respect to the surface to be machined. Most of the time, these limitations are dictated by the piece shape/configuration. For this reason, it can be assumed that an optimization for this tilting interval would be of great interest.

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The model used to obtain the undeformed chip (Fig. 4 and Fig. 8) according to the cutting regime and tilting angles of the tool is a CAD parametric model devised for 5 axes milling.

The current paper contains a study of the milling process with this type of the tool in two different cases:

- in a vertical position;
- in a tilted position.

The tests will be carried out on a plain surface as it aims at obtaining reference data which will be used further as a comparison base. Another reason for using a flat surface for the tests can be found in the fact that when it comes to machining complex surfaces on 3 axes machines, where there is no possibility of maintaining a constant inclination angle to the machined surface, there are moments when the tool is in a vertical position to the machined surface so the tilting angle is 0°. This hypothesis was also met in another paper [3].

For the second case, the tool will be tilted on two directions with different angles (−20° θ_f and 5° θ_n), so as to avoid using the tip of the tool for machining and to be able to compare the two situations.

The results will also be compared with other studies for which it was used the same modeling technique [11, 13, 14] and which presented practical/experimental data for machined surface quality.

2. EXPERIMENTAL SETUP

The machining operation has been carried out on an annealed ISO C45 workpiece material with the chemical composition according to the manufacturer (Mital Steel Galati S.A.). The chemical composition of the material is presented in Table 1 and its dimensions were 95×95×245 mm according to ISO 8688-2/1989, chapter 3.

It is specified that the workpiece should be a bar or billet of rectangular cross-section with a minimum width of 2 times the cutter diameter and a minimum length of 10 times the cutter diameter but preferably with a recommended length of 20 times the cutter diameter. Such dimensions were chosen to use the workpiece also for tool wear studies, later on.

The hardness of the workpiece material has been measured after annealing and roughing the part, on two different testing areas (Fig. 2).

Each area was tested in 5 equally distanced points, reaching an average value of 170 HB which was within the deviation interval of the measurements (±5%) specified in the ISO standard.

Table 1

Chemical composition of the workpiece material

ELEMENT	VALUE	ELEMENT	VALUE
C	0.420	As	0.004
Si	0.240	Ti	0.003
Mn	0.640	Cu	0.010
P	0.019	Ni	0.015
S	0.009	Cr	0.020
Al	0.002	Mo	0.009

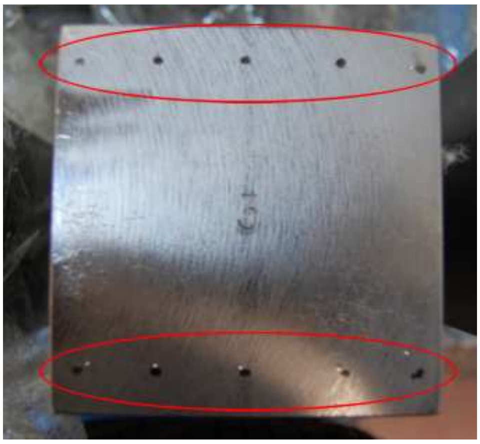


Fig. 2. Hardness testing areas and points.

The machine tool on which the experiments were carried out was MU-400VA 5 axes milling machine from Okuma with the following characteristics, listed as requested by the ISO 8688-2/1989:

- maximum machining length X/Y/Z: 762/460/460 mm;
- maximum rotation on A/C axis: +20° to −110°/360°;
- maximum loading capacity: 300 kg;
- maximum spindle speed: 15 000 rev/min.;
- rapid feed movement XY: 40m/min, Z: 32m/min, A: 14 400°/min, C: 18 000°/min;
- engine power: 30 kW.

The cutting tool used for the experiments was a ball nose end mill from Seco Tools-Minimaster with 2 mechanically fixed carbide inserts:

Shank code: MM12-20095.3-3027;

Insert code: MM12-14014-B120PF-M03, F15M with z = 2 teeth and D = 14 mm;

Coating: multilayer TiC, TiN and Al2O3.

MM12 shank was chosen because it offers stability and accessibility in difficult to machine areas, according to Seco specifications. The insert was chosen considering the type of the material to be machined and the type of milling operation i.e. finishing.

The cutting data were chosen according to the type of milling process and of insert, to its diameter, to the material to be machined, etc.

The surface roughness level and the surface profile were monitored by means of a portable TR200 roughness tester made by Micro Photonics Inc., having ±10% measuring precision. The cutoff was set to 0.8 mm and the number of cutoffs to 2, the pick-up sensor having thus a moving speed of 0.5 mm/s. The measuring range was for R_a between 0.01–40 μm and for R_t between 0.02 and 160 μm.

The quality of the surface/surface texture was recorded by means of a digital camera as part of a CV-HB 100-type Brinell hardness testing device supplied by CV Instruments Europe BV, having a magnifying power of 30×.

The roughness and surface profile have been measured on two perpendicular directions: on pick-feed direction noted with OX and also on feed direction noted with OY.

The geometrical precision of the machined surface was probed by using a dial indicator.

Table 2

The cutting regime used for the experiments

ELEMENT	VALUE 1	VALUE 2
Tool tilting [°]	0°	−20° θ_f and 5° θ_n
Cutting speed [m/min]	132	250
D_{eff} [mm]	Ø4.054	Ø 6.82
n [rev/min]	10368	11675
a_p [mm]	0.3	0.3
a_e [mm]	0.3	0.3
f_z [mm/tooth]	0.07	0.1

The chosen cutting regime for these experiments is presented in Table 2 and it was selected so as to satisfy a finishing operation.

In the first set of experiments a smaller cutting speed and a smaller feed/tooth were used. The reason for this was the difficulty of chip removal from the cutting area and the more harsh cutting conditions due to peripheral cutting speed equal to 0 m/min on the tip of the tool.

When machining different materials (X40CrMoV5 1, St37-3 and C45), it was concluded that the best roughness value of the machined surface is obtained when applying the one way raster strategy and climb milling. For this reason, within the tests described in this paper, the same raster climb milling strategy was used.

For each of these toolpaths the CNC code was devised using PowerMill 9 CAM software from Delcam.

Both experiments have been conducted in the following temperature and humidity conditions (average values): 21.4°C and 42% HR and have been repeated for results confirmation. The values presented stand for the average of the measured values.

3. EXPERIMENTAL RESULTS

For the first set of experiments, the tool was set in a vertical position to the workpiece material (Fig. 3). The resulting undeformed chip can be seen in Fig. 4 and the machined surface texture in Fig. 5.

The surface roughness recorded in both sets of experiments after 15 minutes of machining is presented in Table 3.

Different new tools were used in each set of experiments.

The measured surface profile, on which the roughness values have been calculated are presented in Fig. 6.

These experiments have been conducted in an industrial environment so as to get a closer grasp towards such machining processes and to better assess the possible issues coming from this environment.

For the second set of experiments, the tool was set in a tilted position to the workpiece material (Fig. 7).

The resulting undeformed chip can be seen in Fig. 8 and the surface texture in Fig. 9.

Table 3

The surface roughness values

Roughness parameter	OX VALUE 0° θ_f and 0° θ_n	OY VALUE 0° θ_f and 0° θ_n	OX VALUE -20° θ_f and 5° θ_n	OY VALUE -20° θ_f and 5° θ_n
R_a	3.299	2.308	0.544	0.500
R_q	4.072	2.708	0.694	0.649
R_z	17.450	11.430	3.710	3.490
R_t	19.050	12.570	4.579	4.079
R_p	6.940	6.119	1.830	1.640
R_v	10.520	5.309	1.880	1.850
RS	0.100	0.073	0.084	0.038
RS_m	0.178	0.178	0.145	0.059
RS_k	−0.671	0.353	0.171	−0.330

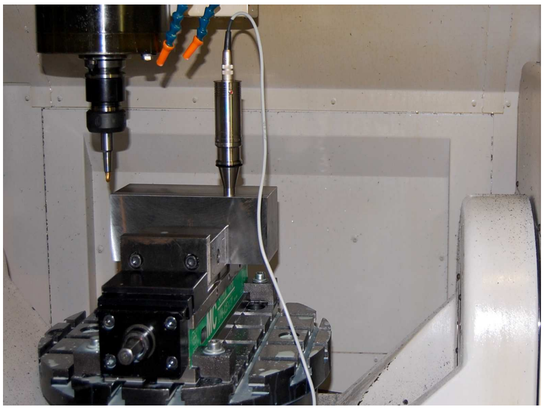


Fig. 3. Experimental setup for the first set of experiments.

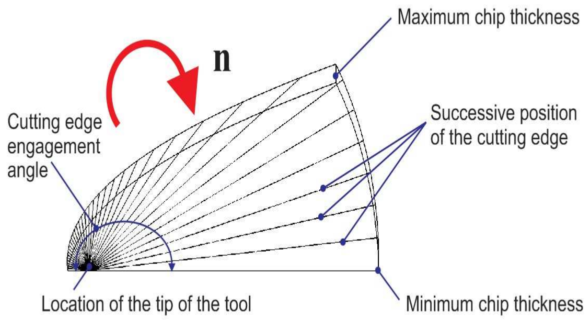


Fig. 4. Undeformed chip for the first set of experiments.

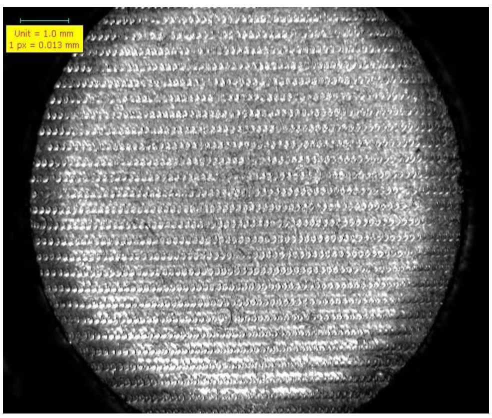
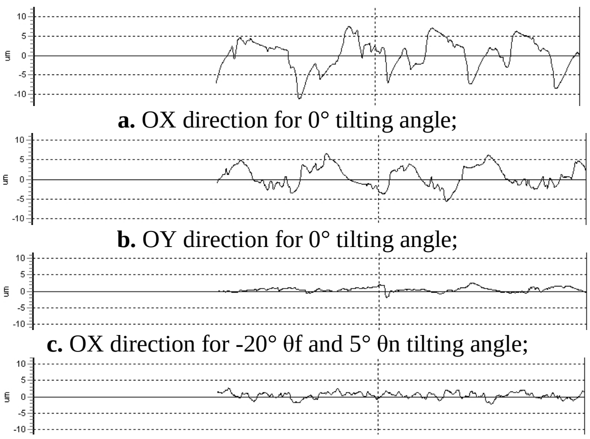


Fig. 5. Surface texture for the first set of experiments.



a. OX direction for 0° tilting angle;

b. OY direction for 0° tilting angle;

c. OX direction for -20° θf and 5° θn tilting angle;

d. OY direction for -20° θf and 5° θn tilting angle

Fig. 6. Machined surface profile.

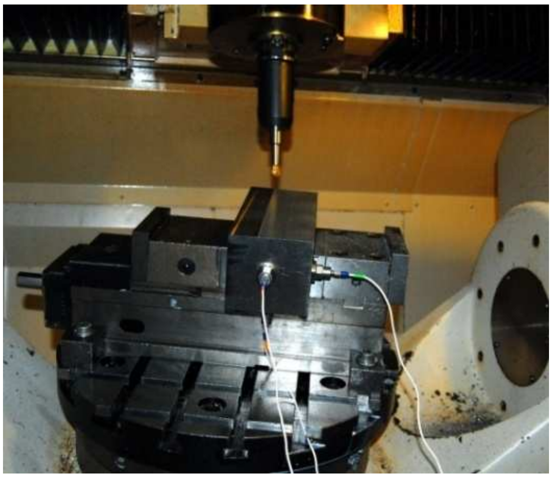


Fig. 7. Experimental setup for the second set of tests.

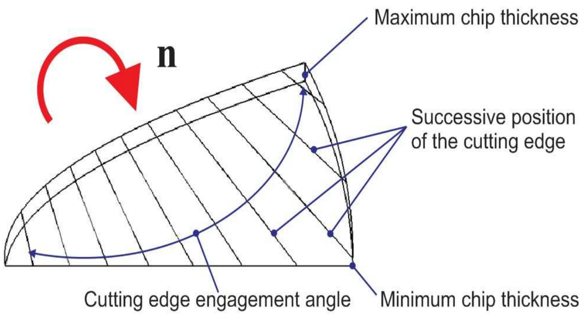


Fig. 8. Undeformed chip for the second set of tests.

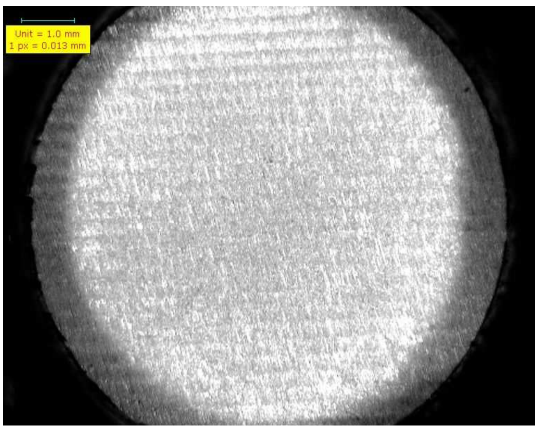


Fig. 9. Surface texture for the second set of tests.

4. COMPARATIVE STUDY. DISCUSSIONS

a) The first comparison is made between the case when the cutting tool is in a vertical position with respect to the surface to be machined and the case when it's tilted with the angle composed of −20° θ_f and 5° θ_n. One may notice based on the undeformed chip that in the first case. The tip of the tool is present in the cutting area. i.e. it meets the chip during its rotation. This aspect is influencing the quality of the machined surface in a negative way. These details have been discussed in the previous chapters.

By further analyzing the undeformed chip it can be seen that the cutting edge of the tool enters and exits the chip in the area of minimum thickness. This happened even though the milling strategy used was climb milling. Moreover, the entry of the cutting edge into the chip is being done on a small contact length. The cutting edge engagement angle is 180°, which equals to a lot of time spent by the cutting edge in the worpiece material during one revolution of the tool. Due to a longer time spent in the workpiece material, the cutting edge could heat up and when exiting the chip it would meet the cutting fluid, resulting in thermal shock and thermal fatigue which could seriously alter the tool life span.

The machined surface texture shows small traces in the shape of a comma, which most probably have resulted due to the presence of the tip of the tool in the cutting area or to the process of chip formation. These marks have led to a surface roughness R_a = 3.299 μm on pick-feed direction and R_a = 2.308 μm on feed direction.

The resulting surface profile is not a uniform one and no rule or repeatability/pattern can be noticed on either direction. This aspect points to an unstable cutting process which must be avoided by all means.

By evaluating the undeformed chip for the second case, when the tool is tilted with respect to the material to be machined, it can be seen that the tip of the tool is no longer present in the cutting area. Also, the cutting edge of the tool enters the chip at almost maximum chip thickness. This comes as a big help in the chip forming process for finishing operations. Moreover, the contact length on which the tool enters and exits the chip is a medium one and of almost equal size. This supposedly contributes to the reduction of vibrations during the cutting process.

The cutting edge engagement angle is approximately 55° (the traces left by the cutting edge in the undeformed chip have been generated with a 5° increment). It can be seen that the cutting edge engagement angle is smaller compared to the first case, resulting in much less time spent by the cutting edge in the workpiece material at one revolution of the tool.

All these details contribute to a surface roughness R_a equal to 0.544 μm on pick-feed direction and 0.500 μm on feed direction. Similar values have been obtained when machining Inconel 718 [2], with a tilting angle of 45°. It can be concluded that the cutting process is a stable and uniform one. This is also confirmed by the texture of the machined surface which is much better than in the first case.

By analyzing the machined surface profile, it can be noticed that it presents certain repeatability on the feed direction, indicating, one more time, the good cutting conditions of the process with this setup.

One may notice that although the spindle speed has been increased with only 12.6%, at the same axial and radial depths of cut, the cutting speed was almost doubled which underlines the major impact the tool tilting has over the machining parameters of the process. By having different parameters of the cutting process, one may get different outcomes of the process, i.e. different surface roughness, different surface profile, and different surface texture. All of these contribute to the tribological behavior of that part during its life cycle.

Tilting the cutting tool with respect to the machined surface increases the effective cutting diameter which in turn allows for the usage of the same effective cutting speed at lower tool speed or for higher effective cutting speed at the same speed as when the tool is in a vertical position. It is possible this way to overcome some technological limitations imposed by the machine tool.

b) When comparing the experimental results with the results from other similar studies, the following aspects emerge:

- roughness R_a equal to 0.78 μm and 0.86 μm were obtained [17] when machining a complex surface with such tools (the workpiece material, the tilting angle (tilting interval) of the machined surface or cutting regime are not specified);
- a roughness R_a equal to 3.7 μm on pick-feed direction and 2.8 μm on feed direction has been obtained [18] when machining workpiece material 1.7131 with vertical tool position, using the following cutting regime: f_z = 0.1765 mm/tooth, a_e = 0.1765 mm, a_p = 0.3 mm, d = 10 mm, v_c = 210 m/min. In the same study [18], the roughness R_a values equal to 3.6 μm on pick-feed direction and 4.4 μm on feed direction were obtained when machining the same workpiece material with a tool inclination of 20° on pick-feed direction (θ_n);
- also, when machining special alloys like Inconel 718, it was noticed that the resulting surface roughness was better when the tool was used in a tilted position that in the case when the tool had no tilting angle.

The roughness values obtained in this study for the situation when the tool was tilted on two directions were compared with roughness values obtained by other researchers who inclined the tool only in one direction. It can be seen that the cutting process can be improved by adding a second direction inclination and the same or better surface quality can be obtained at lower tilting angles if combined on two directions. This is also confirmed [18] by the fact that when increasing the tilting angle on one direction, the surface quality has not been improved.

5. CONCLUSIONS AND FURTHER WORK

By using the ball nose end mill in a tilted position, an improvement of the cutting conditions is noticed. The machined surface texture, profile and roughness can be enhanced this way, the tip of the tool not being present in the cutting area.

When using the tool in a tilted position, for the same cutting regime (axial and radial depths of cut, feed per tooth and spindle speed), a bigger effective cutting speed is reached than in the case of no tool tilting. This aspect presents two major advantages: it can be used to increase productivity or to decrease the spindle speed necessary to obtain a certain cutting speed (the effective cutting diameter increases).

By tilting the tool, the way the cutting edge enters and exits the chip is modified in a controlled manner. This fundamentally influences the cutting conditions (the cutting force. contact length on the cutting edge and surface quality). The presented solution modifies in a controlled manner the cutting edge engagement angle.

The presented research model implies that the tool tilting angle along with the cutting regime to be considered as input parameters for the cutting process. Having this new input, together with the data resulting from the parametric 3D CAD model of the undeformed chip, a multi-criteria optimization of the cutting process is imposed.

The objective function of this multi-criteria optimization can be summarized as follows:

$$F(X) = F(x_1, x_2, x_3, x_4, x_5), \tag{1}$$

where:

- x_1 – parameter that considers the area where the cutting edge enters the undeformed chip;
- x_2 – parameter that considers the presence of the cutting tool's tip in the cutting area;
- x_3 – parameter that considers the modulus of the maximum cross sectional area of the chip (A_{max});
- x_4 – parameter that considers the modulus of the maximum contact length between the cutting edge and the undeformed chip (L_{max});
- x_5 – parameter that considers the cutting edge engagement angle φ.

The results of the above optimization are the tilting angle on both feed and pick-feed directions. This inclination angle assures the conditions that have been simulated.

Thus the results will become technological instructions for CAM operators aiming at global process efficiency.

In order to maintain the inclination angle along the cutting path, especially when machining complex components, powerful CAM software is required to manage the NC data. Such a CAM software is NX V9 from SIEMENS. Due to its ability to control the tool axis position on the surface, it is recommended to be used in such complex situations. Multiple options are available through the control points (Fig. 10) that NX CAM generates all over the surfaces that will be machined.

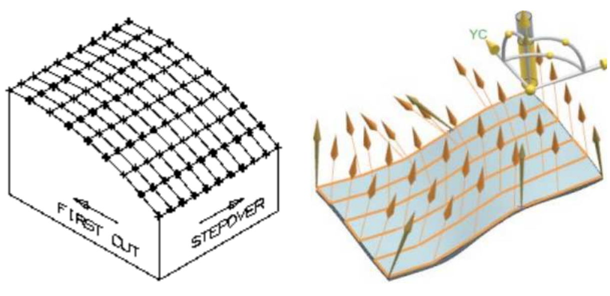


Fig. 10. Tool axis control points over the surface to be machined (NX CAM) [19].

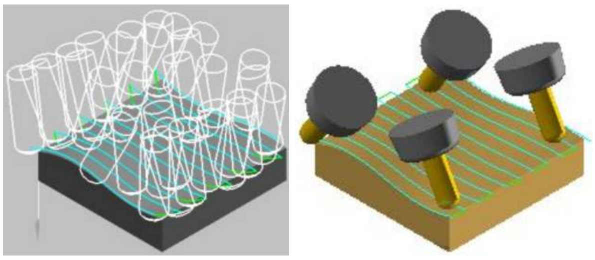


Fig. 11. Tool axis variation along the tool path (NX CAM) [19].

One may choose to maintain the same inclination angle towards the surface being machined or it may choose the variation of the inclination based on a very well defined variation law. For example, along the feed direction, the tool can start in a tilted position of −20° θ_f and 5° θ_n. By the time it reaches the middle of the cutting length, the inclination can change to about −10° θ_f and 8° θ_n and in the end could be for example +10° θ_f and −5° θ_n. This variation can be done regardless of the surface profile, as long as the workpiece and machine tool geometrical limitations allow it (Fig. 11).

Having such powerful tools at CAM engineer's disposal, the tool path can be generated however it best suits the cutting preferences/requirements.

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