

Finish milling dynamics simulation considering changing tool angles

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Abstract. The article presents the results of the dynamics simulation and analysis for five-axis milling, considering changing angles between the tool axis and the surface normal. The 3D structural dynamics model of the milling process is described based on the finite element tool and a workpiece dynamics model. Cutting forces in three directions Px, Py and Pz for different values of the tool angle are compared. Numerical simulation results enable identification of the optimal tool's position for increasing free-form surface milling performance (chip formation, tool reliability tool, etc.).

1. Introduction

Currently, CNC production centers are widely used in machine building for machining complex parts used in aerospace, automobile, and shipbuilding industries. To ensure maximum flexibility of the tool of the workpiece, five-axis milling tools are used. Modern CNC centers help to orient the tool and the workpiece to the surface normal at a contact point at any angle.

One of the key indices characterizing workpiece machining with CNC units is forming performance which is calculated as a workpiece surface area value formed per unit time. The value characterizes the intensity rate of a tool impact on the workpiece and assesses the intensity rate of the forming system of the CNC center [1].

Mean forming performance is calculated by formula [1]:

$$Pm = \frac{F}{t} \quad (1)$$

where F – area of the nominal workpiece surface;

t – forming time for the nominal workpiece surface.

Instant forming performance determines performance at a current moment of time and is calculated by formula [2]:

$$P = \frac{dF}{dt} \quad (2)$$

To achieve maximum performance of complex surface forming with regard to the requirements for the surface quality determined by the constant value of the residual ridge between adjacent lines of the



tool movement path, it is necessary to ensure its minimum length, setting a maximum line width formed with a spherical cylindrical tool.

In [3], it was proven that at each point of the surface, there is a tool movement direction vector by which a maximum path width can be achieved. An instant forming performance can be calculated by formula:

$$P = S \cdot w, \quad (3)$$

where S – longitudinal feed;

w – path line width measured in a direction transverse to the longitudinal feed.

The method allows selection of optimal forming strategies when machining workpieces using three-axis tools with a maximum path line width.

As distinct from the end three-axis milling, the five-axis one suggests orientation of the tool at any angle to axis OZ. Describing finish five-axis milling of complex surfaces, one can prove that at a constant cut depth, an increase in an angle between a tool axis and a surface normal increases a tool path line width. Forming performance also increases. However, at a large angle value, the cutting torque and the bending moment acting upon the tool increase.

Preliminary analysis allows us to make the following conclusions: five-axis finish milling performance for complex workpieces can be achieved by dividing the finished surface into local areas depending on curvature values and optimal machining strategies maximizing a path line width and ensuring a constant residual ridge value. Figure 1 shows the algorithm for choosing an optimal finishing strategy for each area of the complex surface.

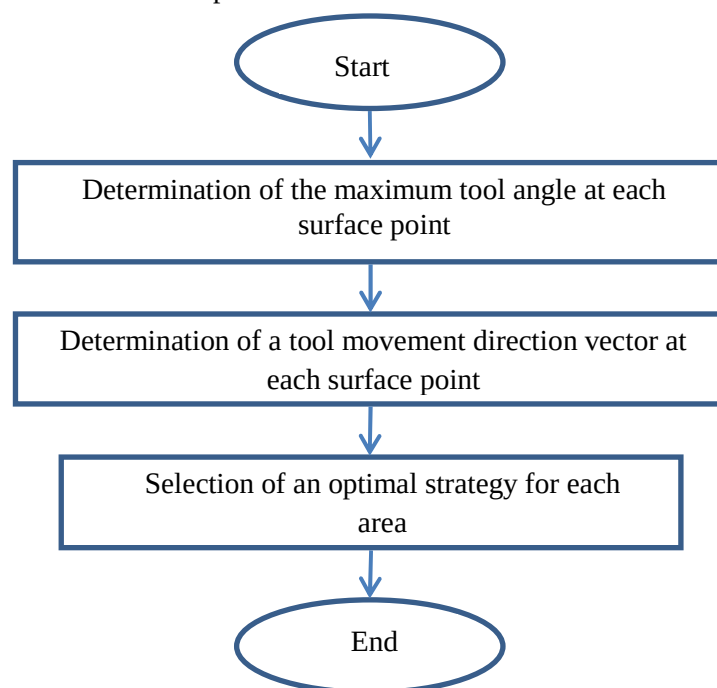


Figure 1. Algorithm for choosing an optimal strategy for five-axis milling

To determine a critical tool angle to the surface normal when it preserves all functional characteristics (tool life and strength), milling dynamics simulation can be used. Currently, there are different cutting simulation methods. But the method of finite elements is widely used. There are different specialized and universal software tools for finite element analysis such as DEFORM, ADVENTEDGE, ABAQUS, LSDYNA, ANSYS, AUTODYN and others. Abaqus/CAE was used as a key one. Abaqus/CAE solves tasks taking into account different non-linear effects and carries out static and dynamic analysis as a part of the unified approach combining advantages of explicit and

implicit finite element analysis. Flexibility and use of traditional numerical calculation methods are its advantage [4].

2. Abaqus/CAE simulation

2.1 Tool – workpiece models:

A 3D milling dynamics model includes 3D tool-workpiece models. An end spherical cylindrical mill of 5 mm in diameter made of rapid steel R9 was used. The workpiece is a plate of 200x100x20 mm in size made of aluminum alloy D16T (Figure 2).

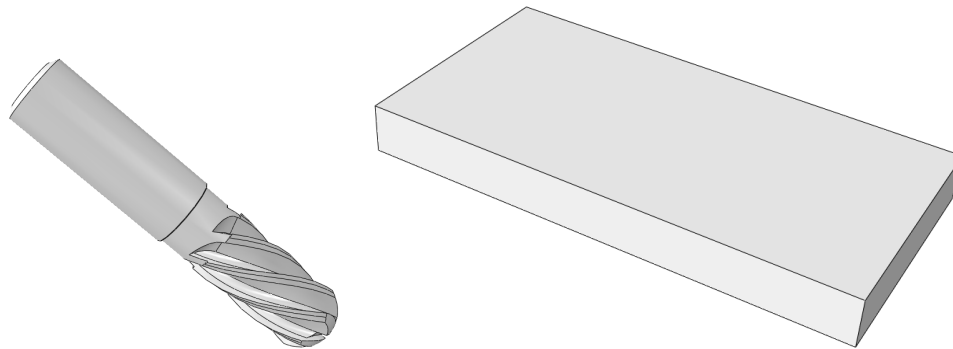


Figure 2. 3D tool-workpiece models

To set mechanical properties of the tool and workpiece material in **Abaqus/Explicit**, Johnson-Cook models are used for milling (chip-type machining). Tool and workpiece material parameters are shown in Table 1.

Table 1. Mechanical properties of tool and workpiece materials

	Steel R9	Aluminum alloy D16T
Density (kg/m^3)	8300	2770
Young's modulus (Pa)	2.1×10^{11}	7.2×10^{10}
Poisson's ratio	0.3	0.33
Malleability based on Johnson-Cook's parameters:		
A (Pa)	3750×10^5	3241×10^5
B (Pa)	5520×10^5	1138×10^5
n	0.457	0.42
Johnson-Cook Damage:		
D1	0.25	-0.77
D2	4.38	1.45
D3	2.68	-0.47
Reference deformation velocity	1	1

2.2 Setting of contacts:

When simulating material removal in Abaqus, a **surface-to-surface** contact can be used. The driving surface is a surface of all tools, and the driven surface is a workpiece surface (Figure 3). Friction coefficient equals 0.35.

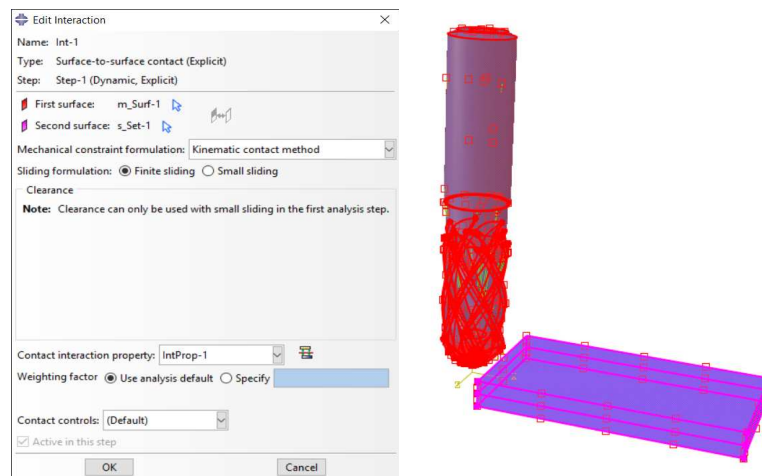


Figure 3. Setting of a contact between the tool and the workpiece

Abaqus cannot set velocities for movement around themselves for deformed bodies, so to set a tool rotating velocity in a **Contact constraints** module, **Coupling** as a link type was used. For this purpose, let us link all tool surfaces to a virtual point lying on a tool axis line. The virtual point is a control point (Figure 4).

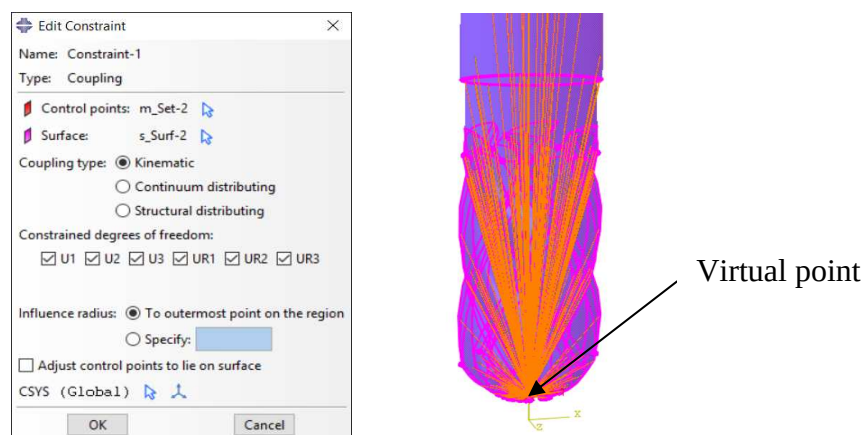


Figure 4. Creation of the module Coupling

Through that link, the tool can rotate around the axes going through the virtual point and parallel to the coordinate axes.

2.3 Mesh formation:

For more precise calculations, it is necessary to choose certain elements. For the chip removal, let us choose 8-noded hexa-hedral elements of the first order C3D8R; for the complex model such as a tool, let us choose 10-noded tetrahedra C3D10M.

3. Calculation analysis

Simulation results for end spherical cylindrical milling were obtained at a cut depth of 0,3 mm. The position of the tool axis to the workpiece is determined as angle α to the surface normal measured in a plane perpendicular to a cutting direction vector. The initial position and position during milling are shown in Figures 5 and 6 at angles $\alpha=0^\circ$ and $\alpha=30^\circ$. In Abaqus, the cutting force is determined by maximum values of a response acting on the tool in projection onto three axes OX, OY and OZ.

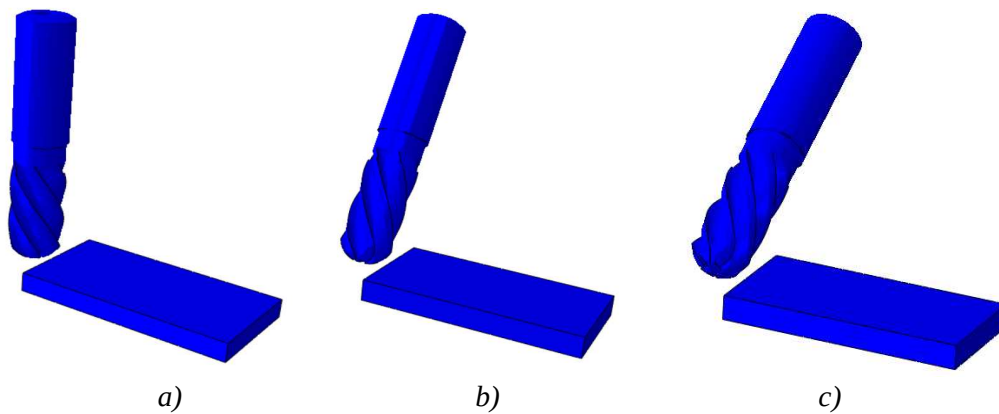


Figure 5. Initial positions of the tool and the workpiece at different angles α

a) $\alpha = 0^\circ$ b) $\alpha = 30^\circ$ c) $\alpha = 60^\circ$

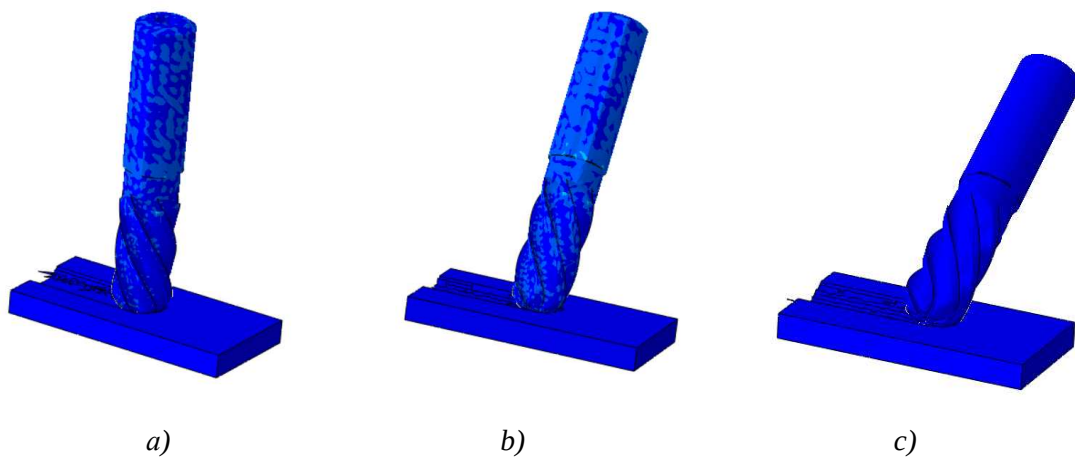


Figure 6. Positions of the tool and the workpiece during milling at different angles α

a) $\alpha = 0^\circ$ b) $\alpha = 30^\circ$ c) $\alpha = 60^\circ$

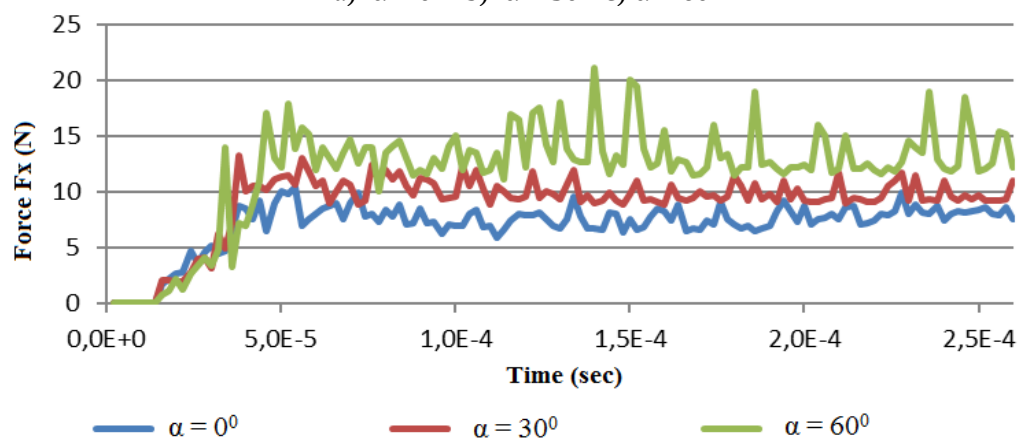


Figure 7. Time dependency of the cutting force F_x projection at different tool angles

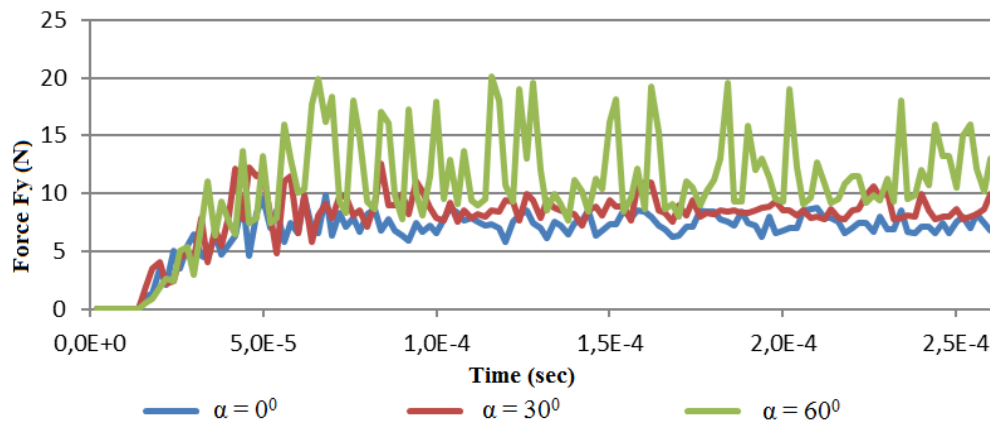


Figure 8. Time dependency of the cutting force F_y projection at different tool angles

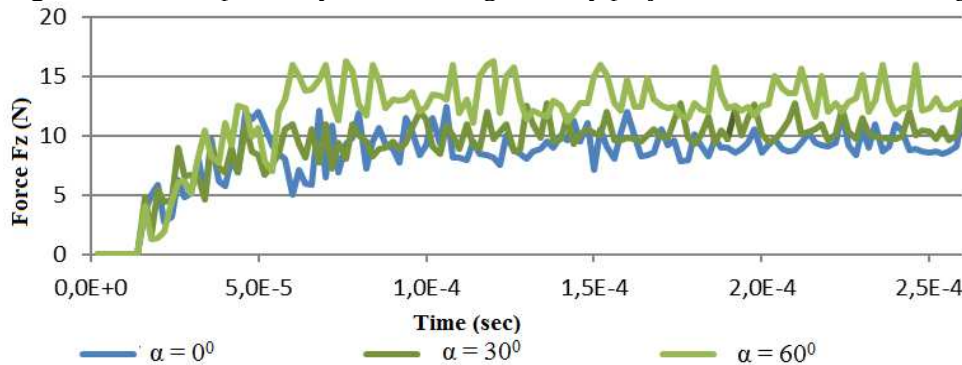


Figure 9. Time dependency of the cutting force F_z projection at different tool angles

Figures 7, 8, 9 show time dependencies of projections of cutting forces F_x , F_y , F_z at different tool angles. As can be seen, before the tool contacts the workpiece, cutting force projections equal 0. When the tool contacts the workpiece, the contact area of the mill tooth edge and the workpiece changes with regard to the tool rotating around itself. In steady-state, cyclic changes of cutting force projections occur.

When comparing F_x , F_y and F_z at different tool angles α , one can see that increase in angles causes increase in cutting force projections. At $\alpha=30^\circ$, maximum values in Ox and Oy directions increase 1.3-fold, and in Oz direction, they change slightly. At $\alpha=60^\circ$, F_x and F_y increase twofold, and F_z - 1.3-fold.

4. Chip removal performance analysis

Finish milling performance depends on a line width of the tool movement path and a chip volume removed per unit time. At the same residual ridge height, these parameters, determining the performance, depend on the angle of a spherical cylindrical cutting tool. To increase a line width formed on the workpiece as a tool movement mark, angle α has to achieve a value at which point C is above point B (Figure 10).

The following condition should be met:

$$t > h \quad (4)$$

where t - cutting depth

h - height determining the position of point B to the formed surface.

Formula 4 implies that:

$$\begin{aligned} t &> R - OD \\ t &> R(1 - \sin \alpha) \end{aligned} \quad (5)$$

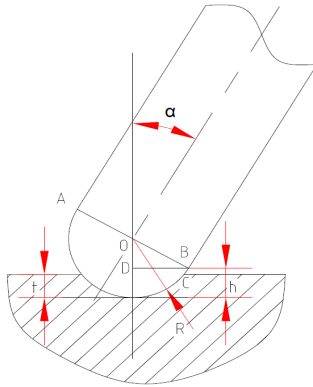


Figure 10. Determination of the increasing condition for a line width of the tool movement path

Mean removal performance can be used as chip removal performance:

$$P_c = \frac{V_c}{t}, \quad (6)$$

where V_c – chip volume removed in t .

In this case, the volume element is a product of the line cross-section area and its length in a cutting direction. Figure 11 shows a scheme of the mark when changing a tool angle.

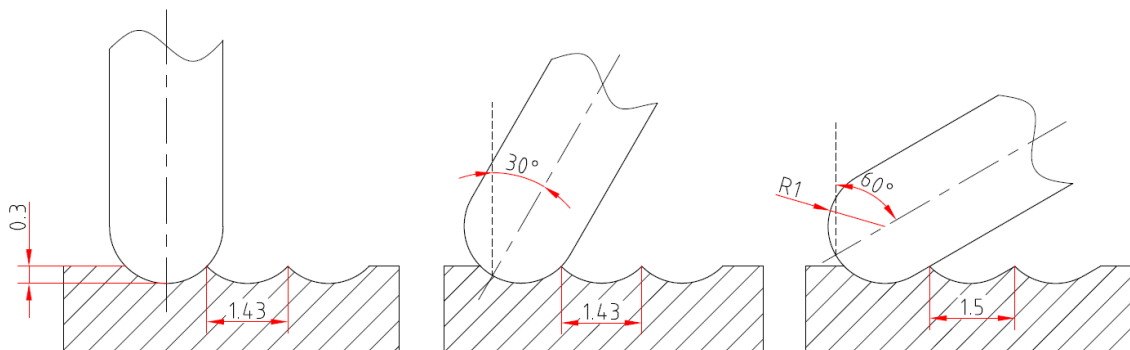


Figure 11. Formation of the mark of the spherical cylindrical mill of 2 mm in diameter at $t = 0.3$ mm

When (4) is met, the area of cross section of the line increases by an additional shaded area in Figure 12.

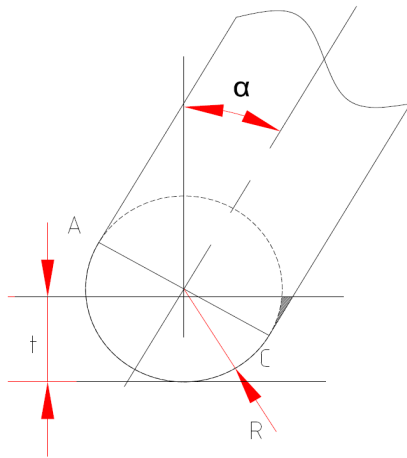


Figure 12. Determination of the cross section area of the tool path line

For further calculations, the authors used a spherical cylindrical mill of 2 mm in diameter. Operating finishing parameters were selected by standards and are shown in Table 2.

Table 2. Operating finish milling parameters

Mill	Spindle RPM n , min^{-1}	Tool approach rate V_s , mm/min	Work feed S_m , mm/min	Cutting depth, mm
Spherical cylindrical mill of 2 mm in diameter	1600	9	7	0.3

At 30° , $t = 0.3 \text{ mm}$, $h = (1 - \sin 30^\circ) = 0.5 \text{ mm}$. It means that (4) is not met so the line width does not change. At 60° , the width increases. Autodesk AutoCAD was used to determine the cross-section area for the tool mark line. Calculation results are shown in Table 2.

Table 3. Geometrics of the tool movement path line

Tool angle	Line width (mm)	Line cross-section area (mm^2)
0°	1.43	0.3
30°	1.43	0.3
60°	1.5	0.34

Thus, when increasing a tool angle, the tool movement path line width also increases and forming performance improves. An increase in cutting velocity causes increase in stock removal velocity.

5. Conclusion

Finish milling simulation allows us to conclude that:

- the value of an angle between the tool axis and surface normal in the contact area acts upon the cutting force;
- mathematical simulation of strengths in the tool when machining complex surfaces helps determine an optimal position of the tool to the workpiece for five-axis milling and avoid tool destruction;
- when the angle is 60° , forming performance can be increased 1.05-fold, and chip removal performance – 1.13-fold.

References

- [1] Radzevich S P 1991 *CNC-based forming of complex surfaces* (Kiev: Vyshha shkola,)
- [2] Radzevich S P 2001 *Parts surface forming. Theoretical background. Monography* (Kiev: Rastan)
- [3] Ponomarev B B, Repin V M 1998 Increase in CNC-based milling performance for complex parts *Bulletin of Irkutsk National Research Technical University* **3** 50-53
- [4] 2010 *Guidance manual in SIMULA/Abaqus "Abaqus for beginners"* (Abaqus Inc.)