CROSS SECTION OF THE CUTTING LAYER IN SIMULTANEOUS FIVE-AXIS MACHINING OF SCULPTURED SURFACES

In the process of simultaneous five-axis milling of sculptured surfaces it is important to acknowledge the formation mechanism of area of the cut. It affects the cutting force components, and thus the accuracy of the multi-axis machining of sculptured surfaces. For the area of the cut, influencing parameters are the lead angle $\alpha$ and/or tilt angle $\beta$ and varying curvature profile in the feed’s direction. The paper presents the results of simulation study of the cut’s area shaping. The study focused on the process of five-axis milling of sculptured surfaces using toroidal cutter. Advanced NX Siemens CAD/CAM system was used, together with direct mapping of the workpiece and the tool. The objects under study were concave and convex sculptured surfaces with varying radius of curvature. These surfaces were milled in an environment of simulation with different tool’s axis orientation settings. The research has shown that both the variable radius of curvature, and the lead angle, generate the formation of variable values of the area of the cut.

Key words: simultaneous five-axis milling, sculptured surface, area of cut

1. FIVE-AXIS MILLING TOROIDAL CUTTER

1.1. The geometric fundamentals

In the process of five-axis milling, a motion can be performed which changes the tool’s displacement and the direction of its axis in space [1]. The example of such trajectory is shown in Figure 1a. In Figure 2, presented is a draft of kinematics of a five-axis machining center which enables movements with such trajectory.

Five-axis milling machine moves in the directions of three mutually perpendicular linear axes and two rotary axes. The movement of axially symmetric action surface of toroidal cutter can be described by five functions: three Cartesian coordinates $x(t)$, $y(t)$, $z(t)$, center coordinate $C(t)$ and two spherical coordinates $\alpha(t)$, $\varphi(t)$ of versor of tool axis (Figure 1b). Programming of simultaneous five-axis machining in the CAM system includes determining the contact point path, as well the direction of the axis of the tool in the following checkpoints of trajectory [2, 5, 7].

* Faculty of Mechanical Engineering and Aeronautics, Rzeszow University of Technology.
The possibility of toroidal cutter axis orientation in space can significantly increase the width of cut. This results from the matching of the position of the tool to the shape of the machined sculptured surface.

1.2. Machining with constant angle $\alpha$ between the tool axis and the direction of feed

In machining of concave and convex sculptured surfaces, such as turbine blades, into consideration taken are the kinematics of simultaneous five-axis machining with constant lead angle $\alpha$ between the tool axis direction and the direction of the movement of the contact point [1, 6]. The set of tools is shown in Figure 3.
Movement progresses in a way that the versor of the tool axis \( \mathbf{v} \) forms a constant angle \( \alpha \) between the versor \( \mathbf{n}(P) \) normal to the surface at the contact point \( P \). Such description of the trajectory allows to define the movement of the tool by the projection of movement of the contact point [7].

1.3. Contact area and its approximation

From the above mentioned follows that the cutter is tangent to the surface \( S \) at point \( P \) therefore the versor of its axis forms angle \( \alpha \) with the normal \( \mathbf{n}(P) \), which in the case of tool’s tilt in the feed direction becomes the lead angle. Area of action toroidal cutter inclined by an lead angle \( \alpha \) determines of the spherical bowl \( C(\alpha) \) shown in Figure 4. Making approximations of the contact area introduced is the circle \( K \) passing through point \( P \) and lying on the torus in a plane perpendicular to the \( \mathbf{v} \), whose radius is determined by the equation (1). Projection circle \( K \) in a plane \( T \) is an ellipse \( E \) of a halfaxis \( a \) and \( b \), which is described by the equation (2) [3, 4, 7].

\[
\begin{align*}
r_k &= 1 + r_p \sin \alpha \\
a &= r_p \cos \alpha \\
b &= r_p
\end{align*}
\]

Arc \( L \) is a part of a circle \( K \) and positioned in the removable material layer. Because the circle \( K \) is positioned on a spherical cap \( C(\alpha) \), thus projection arc on a plane \( T \) is the intersection arc \( M \) of the ellipse \( E \) and the contact area. Arc \( L \) is
positioned in the removable layer of material and cutter torus, so its projection arc \( M \) also belongs to the contact area [7].

Using arc \( M \), the impact of five-axis positioning parameters of the tool’s axis on the point and contact area can be graphically presented, as well as the formation of cross-sectional area of cut (Figure 5).

Figure 6 shows shapes of the contact area typical for machining of small curves of surfaces with different values of lead angle \( \alpha \).

Figure 4. The approximation of the contact area of toroidal cutter and machining sculptured surface

Figure 5. The effect of tool axis orientation on the change of point and contact area
2. METHOD OF DIRECT MAPPING OF CUTTING TOOL IN CAD SYSTEM

2.1. Introduction

The method of direct mapping cutting tool in CAD system is based on mathematical solid models used in CAD/CAM systems. The workpiece and the tool are modeled as a 3D solid. The characteristic feature of solid modeling in CAD systems is the ability to perform Boolean operations on solids. Before performing direct mapping tools, the model of the workpiece is the blank [6, 9].

Simulation of tool’s mapping is based on changing relative positions of the discrete models of the workpiece and tool’s movements resulting from the kinematics of machining. In each a discrete position, shared part of solid tools and the blank is subtracted from the workpiece. The simulation results in forming of the body, which, depending on the tool’s modeling process, is either precise or approximate, representing the real workpiece [1, 8].

Because the logical operations are carried out in a purely geometric form, the simulation does not take into account phenomena such as the minimum thickness of cut, deformation, vibration, temperature, etc. [1].

One option for the simulation is to simulate the interference of the workpiece and the tool in their successive discrete positions. This option would require the implementation of two logical operations: intersection and subtraction. The
method is complicated; however, offers satisfactory results in the case of analysis of five-axis milling process of sculptured surfaces [6, 10].

2.2. Cutting tool model

Cutting tool model in dynamic analysis should be formed using the activity surface (Figure 7).
This is a surface which creates the cutting edge by the movement about the axis of the main spindle of the machine. Cutting tool moves relatively to the workpiece’s motion kinematics, resulting from the real spindle feed with a set step. The step is defined in accordance with the technological parameter of feed per tooth \( f_z \) [6].

![Figure 7. Toroidal cutter action surface](image)

2.3. The accuracy of the direct mapping action of surface of tool

The accuracy of the obtained surface and mapping of the removable layer of material as a result of the simulation is dependent on several factors. The first is the manner of modeling of cutting tool. It impacts the reception of machining traces consistent with the real traces. The second factor is the step of discretization which is defined by geometric construction of tool and machining parameters. The third factor is the numerical error of spatial transformations, which is negligibly small.

The machined surface, the surface’s layer parameters, as well as the removable layer of material in reality differ from the assumed geometry. This is due to phenomena occurring in the real machining process, such as: deformation (including thermal), vibration, and due to the geometrical accuracy of machine and tool.
3. SIMULATION STUDY

In order to perform computer analysis of the effect of axis orientation of toroidal cutter and variable radius of curvature of the machined surface in the area of cut in the process of simultaneous of five-axis face milling, adapted was a test model reflecting concave and convex surface of the turbine blade (Figure 8). For simulation, used were: a modeled action surface of toroidal cutter R300-016B20L-08L Sandvik Coromant with two round inserts R300-0828E-PL made from carbide S30T and PVD coated. Ranges of the studied parameters of axis orientation and radii of curvature of the sculptured surface is shown in Figure 8. Simulation parameters for the assumed mapping tools were similar as during real machining process:

- feed per tooth \( f_z = 0.1 \) mm/tooth,
- cutting width \( a_e = 1.5 \) mm,
- depth of cut \( a_p = 0.25 \) mm.

The first step in the analysis was to develop the movement’s trajectory for toroidal cutter in the face milling and 3D dynamic simulation of machining in CAM system. For this purpose, Siemens NX software was used [1, 6]. As a result of this simulation, a cross-section of cut for the convex surface at the point of maximum radius of curvature (Figure 9) and the minimum radius of curvature (Figure 10) were illustrated.
Due to the fact that the 3D dynamic simulation of CAM does not allow for the assessment of real cross-sectional shape of cut with the definition of the volume of the removable second layer of material, the next stage of research was performed.

Using the CAD environment, a machining system was modeled, such as during the real process of simultaneous five-axis milling. In this system a solid model of the subject of research (turbine blade) was included, as well as a solid model of the toroidal cutter.

In order to process the object of study, the strategy of separating the lines of sculptured surface was adapted, namely concave and convex surfaces, where discrete movements that simulate the real machining process take place after the outlining of the turbine blade’s profile. This will allow to easily interpret the impact of parameters such as the lead angle $\alpha$ and variable radius of curvature $r_k$ on the area of cut.

### 4. RESULTS OF SIMULATION STUDY AND ANALYSIS

Histograms of the area of cut $A_{Ap}$ obtained from the simulation of the selected parameters are shown in Figure 11 and 12. Values of area of cut were determined
in the plane of feed in the action surface of toroidal cutter. Figure 13 and 14 show the histograms of the volume of the removable layer of material $Q_{Ap}$.

Figure 11. Histogram of the values of cross sectional area of cut for the concave sculptured surface

Figure 12. Histogram of the values of cross sectional area of cut for the convex sculptured surface
Analysis of the histograms of sectional area of cut, as well as the volume of the removable layer of material presents a conclusion that there is a correlation between the lead angle $\alpha$ and radius of curvature $r_k$ of sculptured machined surface, as well as the area and volume of the cut. The correlation is that with the increasing value of the radius of curvature, the area and the volume of cut decrease. The same relationship exists in case of increasing the value of the lead angle $\alpha$. 
Thus it can be concluded that better accuracy can be obtained on the profiles where the degree of curvature is small. Better accuracy can also be obtained by use of greater tilt axis of the toroidal cutter in the feed direction.

Smaller values of area of cut contribute to a smaller influence of cutting force components on deformation of the workpiece and the tool which also affects the machining accuracy. Greater values of area of cut will result in an increase of the value of the cutting force’s components acting mainly on the tool, causing the displacement of the point and the contact area from programmed movement trajectory.

It should be noted that in simulations, beyond the lack of strain, vibration, or influence of temperature, uniform distribution allowance is also ideal in terms of digital compared to the sculptured machined surface. In a real processing, a high impact on the process of five-axis machining has also the accuracy of forming of machining sculptured surface. Thus, there may occur, in extreme cases, the uniqueness of the experimental results on the elements of varying degree of geometrical complexity.

5. CONCLUSION

From the simulation study it can be concluded that during the simultaneous five-axis face milling, the applied lead angle $\alpha$ has a significant influence on the area of cut of sculptured surface. Furthermore, the area and the volume of cut are variable depending on the radius of curvature $r_k$ in the direction of feed. This indicates that it is possible to develop a method consisting of matching the orientation of the lead angle $\alpha$ to the machined sculptured surface, which will allow for machining of this type of surface with acceptable accuracy.

ACKNOWLEDGMENT

Research carried out in the framework of the project “Investigation of high performance machining of sculptured surface parts of the difficult to machine materials”, No. WND-EPPK.01.03.00-18-017/13 co-financed by the European Union from the European Regional Development Fund under the Regional Operational Programme Podkarpackie Province for the years 2007-2013.
REFERENCES


PRZEKRÓJ WARSTWY SKRANANEJ
W SYNULTANICZNEJ PIĘCIOOSIOWEJ OBRÓBCE POWIERZCHNI ZŁOŻONYCH

S t r e s z c z e n i e


Key words: symultaniczne pięcioosiowe frezowanie, powierzchnie złożone, przekrój warstwy skrawanej