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THE TASK OF 5-AXIS MILLING

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Preliminary notes

The article deals with 5-axis milling. This milling method is currently used in manufacturing of complex shaped parts. The 5-axis milling achieves increased accuracy of components because it is possible to mill a component from five sides at one clamp. The description of 5-axis milling machines structures is also mentioned as well as the equations for the calculation of important parameters of a hemispherical milling cutter. These parameters are adjusted for 5-axis milling. Finally, effective cutting speed and effective feed rates exploitation in practice are summarized.

Keywords: *effective cutting speed, effective feed rat, 5-axis milling, structures of milling machines*

Zadaća 5-osnog glodanja

Prethodno priopćenje

Članak se bavi 5-osnim glodanjem. Ova se metoda glodanja koristi u proizvodnji složenih oblikovanih dijelova. Njome se postiže veća točnost elemenata jer se element može glodati s pet strana kod jednog stezanja. Daje se i opis konstrukcije strojeva za 5-osno glodanje kao i jednadžbe za izračunavanje važnih parametara polukuglastog glodala. Ovi parametri su podešeni za 5-osno glodanje. Na kraju se upućuje na uporabu učinkovite brzine rezanja i učinkovitog posmaka u praksi.

Ključne riječi: *učinkovita brzina rezanja, učinkovit posmak, 5-osno glodanje, konstrukcije glodalica*

1 Introduction

In the past, parts were produced from stock with simple shape (cylinder, prism, etc.). Surfaces were machined on conventional machine tools. This often required a simple linear linkage of the two movements, which could be provided in a mechanical way (for example rotation and translation in turning of a cylinder). Today complex shaped surfaces are also machined [7]. These shapes are known in the literature as FFS (Free Form Surfaces). These shapes cannot be described analytically easily. Parts with FFS are effectively produced by production technologies like injection, blowing, precision casting, precision forming, forging, pressing and other. For these technologies it is necessary to produce tools. Those are: foundry models and molds, forging dies, forming tools and injection molds.

FFS are now produced on CNC milling centers, therefore it is possible to produce a whole shape on one machine tool in one clamping. The most widely used are 5 - axis milling centers. Components are designed in a CAD system.

Designing a part according to the application methods is important [5]. This relates to the possibility of component production, consequently to a tool moves during operation [1]. A program for the CNC machine tool is generated in a CAM system [6]. Machine tool, tools, or machined surface may be damaged, therefore the program must be simulated and debugged [3]. Thanks to that it is possible to avoid collisions.

The basic structures of 5-axis milling centers as well as equations for the calculation of important parameters of a hemispherical milling cutter are described in this article. These parameters will be applied to the 5-axis milling. Finally, effective cutting speed and effective feed rates exploitation in practice are summarised.

2 Structures of 5 – axis milling centres

All structures of machines are inventions which have started according to the industrial needs [4]. Tool movement in a space distinguishes two phases [9]:

1) positioning – it is the reference point displacement (e.g. centre of gravity) from one spatial position to another,
2) directioning – it is the spatial angular orientation of the tool eventually of the workpiece to a reference point.

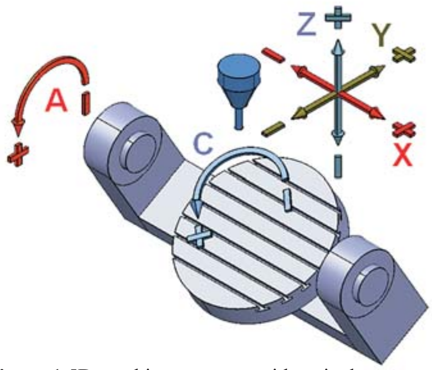

Figure 1 5D machine structure with swivel rotary table

Universal structure of a machine tool has six degrees of freedom [8]. It is possible to move the tool at any position in space. When rotary tool is used in machining (milling), the machine`s structure has five degrees of freedom. In practice it means the control of five (5D) machine's axes. In general, a 5D axis layout of the machine's structure can be realized in three ways:

- translational movement provides tool positioning and rotational movement provides the workpiece positioning. The tool moves translationally in axes X, Y, Z and the workpiece is rotated around two axes: A, C (Fig. 1),
- rotational movement provides tool directioning and translational movement provides workpiece

positioning. The tool is rotated around two axes B, C and the workpiece moves translationally in axes X, Y, Z (Fig. 2),
- various combinations of the two previous cases (Fig. 3).

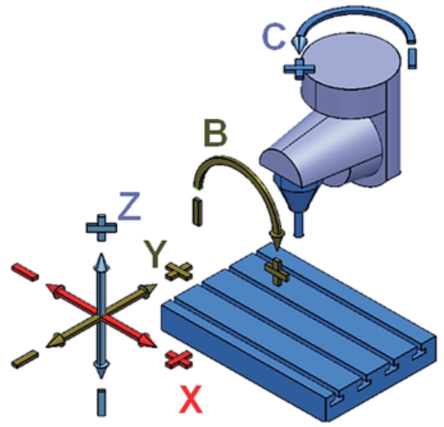

Figure 2 5D machine structure with tool rotation in two axes

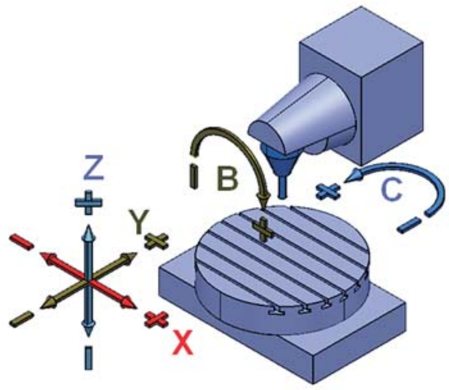

Figure 3 5D machine structure with tool rotation and workpiece rotation

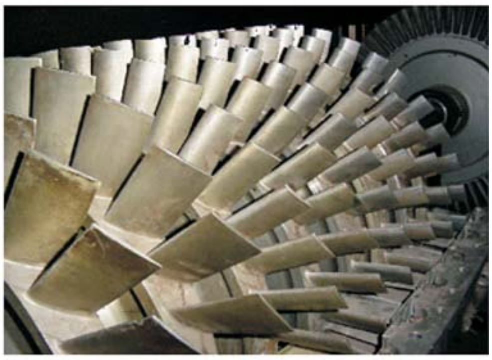

Figure 4 Turbine wheel blades

According to practice requirements, where more and more FFS are machined, application machines with 5D structure are also increasing. Various shapes, for example engine rotors, turbine wheels with blades of various shapes are produced on 5D machine tools (Fig. 4).

3
3 and 5 – axis milling with hemispherical cutter

When milling FFS, a combination of different surfaces is machined. Surfaces form the final shape of the product. Surfaces can be milled either upwards or downwards [2]. The most applied milling strategy in 5-axis milling is "constant Z". It is a longitudinal milling where the cutter can move up or down. Longitudinal upward milling is shown in Fig. 5.

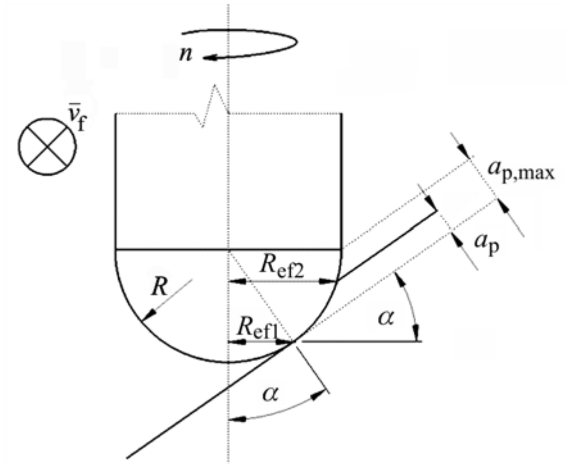

Figure 5 Longitudinal upward milling

The situation for longitudinal downward milling is illustrated in Fig. 6.

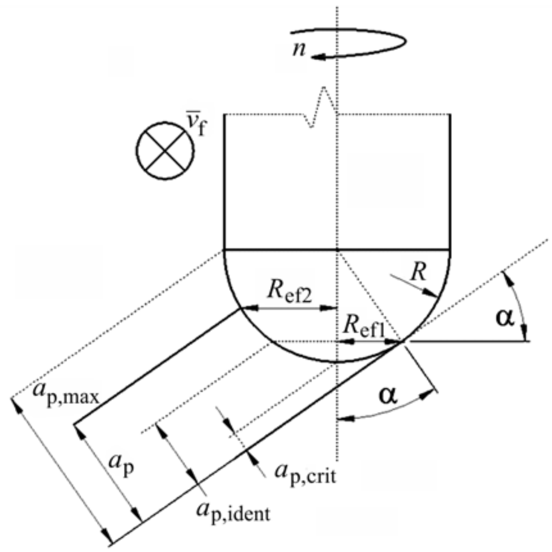

Figure 6 Longitudinal downward milling

The symbols in figures:
a_p – depth of cut, mm
R – radius of the cutter, mm
v_f – feed rate, mm/min
α – slope angle of milling surface, °
R_{ef1} – effective radius of the cutter at machined surface, mm
n – frequency of spindle rotation, 1/min
R_{ef2} – effective radius of the cutter at machined surface, mm
$a_{p,max}$ – maximum depth of cut, mm
$a_{p,ident}$ – identical depth of cut, mm
$a_{p,crit}$ – critical depth of cut, mm.

Equations for effective radius calculation were deduced from [2, 8]. These equations are valid for 3-axis machining. Machined surface is sloped and tool is in vertical position. Equation for calculation of R_{ef1} has the following form [10]:

$$R_{ef1} = R \cdot \sin\alpha \tag{1}$$

where:
R_{ef1} – effective radius of the cutter at machined surface, mm

R – radius of the cutter, mm
α – lead angle of milling surface, °.

In 5-axis milling a problem occurs. That is why it is important to analyse the situation for longitudinal upward milling with cutter lead angle (Fig. 7).

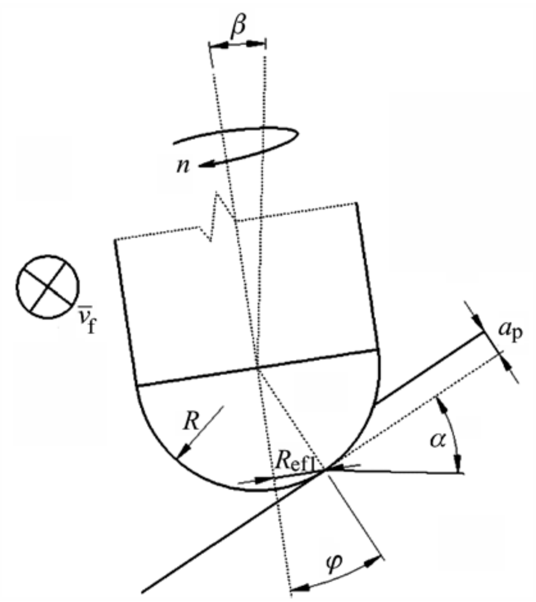

Figure 7 5 – axes longitudinal upward milling

Equation (1) for calculating R_{ef1} is not valid. It is necessary to add further parameters. It is lead angle from the vertical axis milling β, and the contact angle of the cutter with machined surface φ. Contact angle is calculated from the equation:

$$\varphi = \alpha - \beta \tag{2}$$

where:
φ – contact angle of the cutter with machined surface, °
α – slope angle of milling surface, °
β – lead angle from the vertical axis milling, °.

Then we can calculate the effective radius of the cutter at machined surface from equation:

$$R_{ef1} = R \cdot \sin \varphi \tag{3}$$

where:
R_{ef1} – effective radius of the cutter at machined surface, mm
R – radius of the cutter, mm
φ – contact angle of the cutter with machined surface, °.

4 Effective cutting speed and effective feed rate in practice

In technical practice it is common that parts have different surfaces, thus the value of effective radius will also change. This also changes the value of instantaneous effective cutting speed. We calculate this value from the equation:

$$v_{c,i} = \frac{2\pi \cdot R_{ef_i} \cdot n}{1000} \tag{4}$$

where:
$v_{c,i}$ – instantaneous effective cutting speed, m/min
$R_{ef,i}$ – instantaneous effective radius, mm
n – frequency of spindle rotation, 1/min.

In milling of FFS parts constant *instantaneous effective cutting speed* $v_{c,i}$ is required. Hence we need to formulate instantaneous frequency of spindle rotation n_i from equation (4). The equation is (5).

$$n_i = \frac{1000 \cdot v_{c,i}}{2\pi \cdot R_{ef,i}} \tag{5}$$

where:
$v_{c,i}$ – instantaneous effective cutting speed, m/min
$R_{ef,i}$ – instantaneous effective radius, mm
n_i – instantaneous frequency of spindle rotation, 1/min.

When programming the CNC machine tools in the NC code the frequency of spindle rotation is presented as S. If we know the value of instantaneous slope angle of milling surface α_i and lead angle from the vertical axis β, we can calculate instantaneous frequency of spindle rotation n_i that will be used in the NC program. Thanks to that constant cutting speed is achieved for whole surface milling and consequently the constant surface roughness is ensured.

Frequency of spindle rotation is closely related to the feed rate, therefore it is possible to calculate required feed rate at a moment according to equation:

$$v_{f,i} = f_z \, z \, \frac{1000 \cdot v_{c,i}}{2\pi \cdot R_{ef,i}} \tag{6}$$

where:
$v_{f,i}$ – instantaneous effective feed rate, mm/min
$R_{ef,i}$ – instantaneous effective radius, mm
$v_{c,i}$ – instantaneous effective cutting speed, m/min
f_z – feed per tooth, mm
z – number of teeth.

5 Conclusion

In the paper we have described the task of 5-axis milling. The 5-axis milling is a very wide topic. The structures of existing machine tools, calculation of effective radius of the cutter at machined surface and using of effective cutting speed and feed rates in practice are described. The next research will be focused on derivation of the equations for effective radius of the cutter in machined surface calculating. The current project will solve the impact of lead angle from the vertical axis milling on dynamic characteristics of the cutting process: cutting force and its components and vibration generated in the process of 5-axis milling. The result will be the derivation and experimental verification of equations for cutting forces calculation. We will also study the issues of structures of milling machines, CAM milling strategies and their impact on the accuracy and roughness of machined surfaces. Our research is realized in the "Centre of Excellence of 5-axis machining", (Fig. 8) where necessary machine tools and devices are located.

Figure 8 Centre of Excellence of 5-axis machining

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6 References

[1] Valentovic, E. Machining Strategy. Bratislava: STU 2007.
[2] Pokorný, P. Technological factors of CNC milling of free form surfaces – Habilitation work, Trnava, STU v Bratislave, 2009., 94.
[3] Jurko, J.; Džupon, M.; Panda, A.; Gajdoš, M.; Pandová, I. Deformation of Material Under the Machined Surface in the Manufacture of Drilling Holes in Austenitic Stainless Steel. // Chemické listy, 105, (S)(2011), 600-602.
[4] Pokorný, P.; Valentovic, E. What are hybrid structures? // Strojárstvo, Strojírenství, Február 2004., str. 52.
[5] Senderská, K.; Mareš, A.; Fabian, M. Practical application of ergonomic CATIA modules for the analysis of manual assembly workplaces. // IT CAD, 18, 2(2008), 18-19.
[6] Fabian, M.; Ižol, P.; Spišák, E. CAM a CNC: Theory of machining based on the virtual model. // Computer Design, 4(2006), 22-25.
[7] Valentovic, E.; Peterka, J.; Pokorný, P. The machining of the most complicated shapes. // MATAR Praha 2004 - Proceedings of Sections 2, 3, 4. Forming machines and forming production systems. Industrial robots and automation. Machining and forming processes / International Congres. Praha, Brno, 21.-23.9.2004. - Praha : Ceské vysoké ucení technické v Praze, 2004., 225-228.
[8] Peterka, J. 3D copy milling with copy cutter. Cutting process. // CO-MAT-TECH, 1996., 281-258.
[9] Valentovic, E.; Pokorný, P. The serial ortogonal structures of the tool machines. // CO-MAT-TECH, 2001., 391-396.
[10] Peterka, J. Analysis of the geometry and kinematics of copy milling. // Vedecké práce MtF STU v Trnave, zväzok 5, 1997., 53-58.

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