

9th CIRP Conference on High Performance Cutting (HPC 2020)

Optimization of Tool Axis Orientations in Multi-Axis Toolpaths to Increase Surface Quality and Productivity

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Abstract

This paper deals with a method to optimize tool axis orientations in multi-axis milling toolpaths. The method is based on calculation of the actual cutting diameter and the cutting speed during the toolpath. Subsequently, the NC code is processed by the interpolator with a machine tool kinematic model. The result is a visualization of the actual cutting speed and the real feed-rate on the toolpath. Based on these results, the vectors used to orient the tool axis along the toolpath can be effectively set up in several iterations. The toolpath are optimized to achieve a more constant cutting speed which lead to an improvement in surface quality and increase in productivity.

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Peer-review under responsibility of the scientific committee of the 9th CIRP Conference on High Performance Cutting.

Keywords: Milling; Surface quality; Computer aided manufacturing; Cutting speed; Tool axis vector

1. Introduction

Multi-axis ball-end milling operations are one of the most extensively used methods in machining of complex shapes, for example turbine blades, impellers or joint replacements. There is a growing demand for increased surface quality, geometric accuracy and machining efficiency in the manufacture of these high precision parts. Various targeting optimization methods are constantly being developed to meet these basic requirements. Many interesting analysis and optimization approaches have been designed to increase the productivity or accuracy of the machining process in terms of the required cutting conditions. Parameters which are often analysed include cutting forces and the speed of the cutting tool movement along the toolpath [1, 2]. Optimization interventions often involve correcting the feed rate in dependence on the force effect or the material removal rate [3, 4]. Other approaches include toolpath correction with respect to the required feed rate, especially at the pre-production stage [5]. Another group of optimization methods deals with creating optimized toolpaths. The main criterion of the new toolpaths is the reduction of machining time with the inclusion of the

kinematic and, in some cases, dynamic limits of motion axes [6, 7]. Other papers deal with creating entirely new toolpaths. The main benefit is functionality in specific areas, such as radius machining for impellers or machining of complexly shaped surfaces [8, 9]. No optimization methods that control tool axis vectors on a multi-axis tool path according to specified cutting conditions with respect to surface quality and productivity were found.

Adherence to the prescribed local cutting speed and inclination angle settings is very important in multi-axis point milling especially in difficult to cut materials, for example HRSA (Heat Resistant Super Alloys) or chromium-cobalt alloys and stainless steel (duplex or super duplex). The range of appropriate cutting conditions is very narrow in this materials and every larger deviation beyond this appropriate range of real cutting conditions can results in a rapid decrease in tool life, surface quality degradation, surface roughness non compliance or geometric inaccuracy.

When machining aluminium alloys, the cutting conditions, respectively the cutting speed, have a direct effect on adhesive tool wear [10]. Cutting speed also has a major impact on the microhardness of the surface when machining duplex stainless

steels [11]. This leads to overly conservative parameters being used in cutting complex parts to ensure that the local cutting velocity does not exceed some convenient value and thus production time of the part is unnecessarily prolonged.

For effective machining of complex shape parts, toolpaths and real cutting conditions must be analysed and then optimized.

This paper develops a tool path optimization method that ensures that local V_c keeps planned range using adjustment of inclination angle with respect an appropriate tool angle range. The goal of this method is to reduce the machining time, to lower the risk of damage of the tool and comply with the surface roughness requirements.

This paper focuses on the design of an analysis module developed to subsequently optimize the toolpath in multi-axis machining of complex parts in terms of adhering to the cutting conditions defined for machining. Process productivity and workpiece quality are key factors in controlling programmed cutting conditions. For ball-end machining complex parts that are machined on multi-axis machines such as turbines, it is difficult to maintain defined cutting conditions throughout the machining cycle. The required cutting conditions are usually not achieved due to the complex shapes and because the technologist lacks sufficient space to adjust the tool axis in the CAM (Computer aided manufacturing). This paper deals with optimization of machining in the CAM and the postprocessor. The main aim of this work is to propose a supportive optimization procedure that would help maintain the cutting speed when generating NC (Numerical Control) programs for CNC (Computer Numerical Control) machine tools.

Nomenclature

TCP	tool center point [-]
C_P	contact point [-]
R	tool radius of ball-end mills [mm]
R_R	real cutting radius of the tool [mm]
R_{Rc}	required radius of the tool increase [mm]
R_{Rn}	recalculated real cutting radius of the tool [mm]
\vec{e}	tool axis vector [1]
\vec{e}_n	recalculated tool axis vector [1]
\vec{n}_W	normal vector of machined surface in C_P [1]
\vec{n}_T	normal vector of tool “ball” surface in C_P [1]
v_c	cutting speed (nominal) [m/min]
v_{cR}	real cutting speed (calculated) [m/min]
λ_L	lead angle [°]
ft	feed per tooth [mm/min]
a_e	axial depth of cut [mm]
a_p	radial depth of cut [mm]
S	spindle speed [RPM]

2. Analysis of cutting speed

When machining with a circular cutting tool (inserts, toroidal cutters, etc.) the maximum diameter of the cutting tool is usually set during CNC machine programming. Unfortunately, in this case the cutting speed defined by the technologist is not observed. This is because the actual cutting diameter varies during the machining cycle depending on the

toolpath and the shape of the surface to be machined. The contact point moves along the cutting edge during machining. At a variable actual cutting diameter, the spindle speed would also have to be variable to achieve a constant cutting speed [12].

When programming toolpaths for multi-axis machining, the programmer has the option of selecting the tool axis vector in relation to a given location on the work surface. Therefore, the programmer has a direct impact on achieving the cutting conditions. The tool axis vector is adjusted in relation to the shape of the workpiece to avoid collisions between the tool and the tool holder and the workpiece with the clamping.

2.1 Test the effect of the lead angle on surface quality

The influence of γ_L on surface quality also needed to be tested to find out the suitable range for tool orientation adjustment. Two types of material, EN AW 7075-Dural and DIN 1.4462-hard to cut Duplex steel, were tested. Both materials are among the most commonly used materials in the energy and aircraft industries. Machining tests were proposed for mapping issues. The machined surface was planar. Machine tool was a MCV1000 (KOVOSVIT MAS, a.s.). The surface roughness was measured using a Surtronic 3+ according to EN ISO 4288 for a given range of R_a and R_z parameters. The tool was a ball-end cutter, $D=10$ mm 4-flutes, 30° of degrees helix angle with hard submicron carbide substrate (IC 908) and TiAlN PVD coating. The machining was performed under the same nominal cutting conditions; see Table 1. The lead angle varied from 0° to 14° for each experiment. In Fig. 1 we can see the influence of the particular lead angle vector on the resulting surface quality.

Table 1. Setting of cutting conditions

Material	S^* [rpm]	v_c^* [m/min]	ft [mm]	a_p [mm]	a_e [mm]
EN AW 7075	23,885	750	0.05	0.2	0.27
DIN 1.4462	4,777	150	0.05	0.2	0.27

*spindle speed was constant for each material for all tests; the cutting speed varied depending on C_P

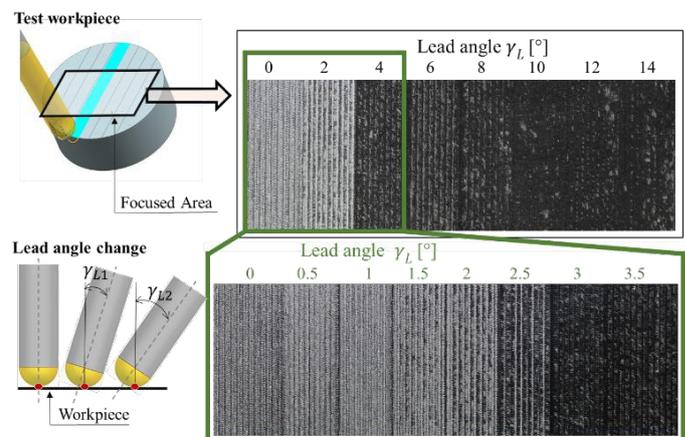


Fig. 1. Different surface quality when machining EN AW 7075 (microscope)

A comparison between the two tested materials is shown in Fig. 2. The graph shows a sharp drop in roughness with

increasing lead angle. The impact of a 0° or almost 0° lead angle is more significant in hard to cut material than in EN AW 7075. This is probably because duplex steel is tougher, which makes it less machinable, which in turn enables a deterioration of the surface quality that is more significant than in the case of EN AW 7075.

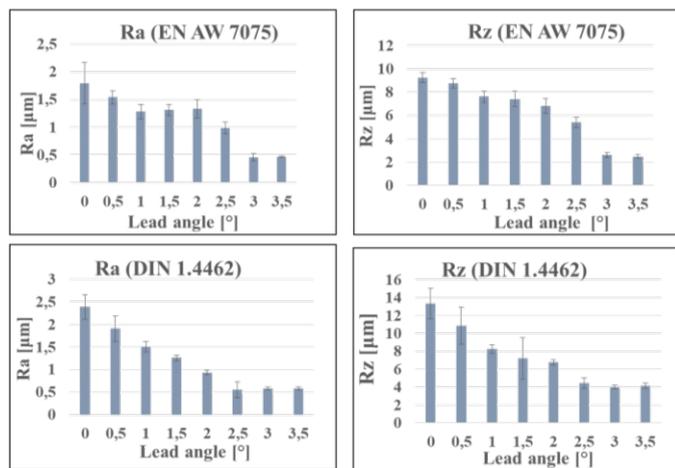


Fig. 2. Roughness results for the two test materials

The main purpose of these tests was to determine the problematic area of lead angle tool axis vectors in ball-end milling operations. With this knowledge it is possible to avoid the problematic area of tool axis vector adjustment. For EN AW 7075 it is the area between 0° to 3°, and for DIN 1.4462 it is the area between 0° to 2.5°. These observed intervals experimentally indicate the usable lead angle intervals in terms of surface quality.

2.2. Calculation of the cutting speed along the toolpath

Fig. 3 shows the calculation principle for the actual cutting diameter. This method depends on knowing the contact point CP between the cutting tool and the workpiece. The distance between \vec{e} and CP determines R_R . The CP is always determined by a match in the value of \vec{n}_W and \vec{n}_T .

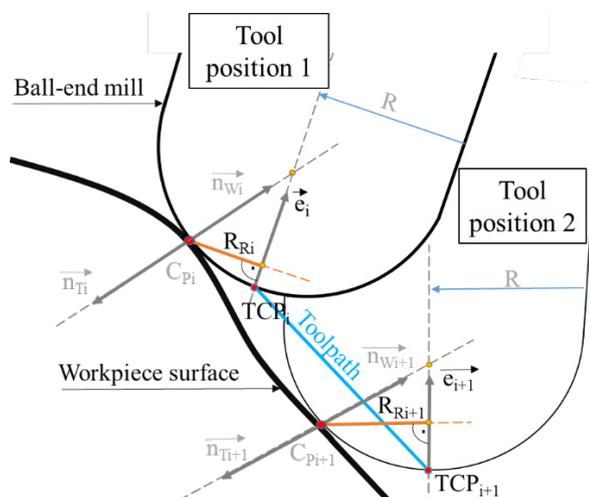


Fig. 3. Calculation of the actual tool diameter based on the CP

Calculation of the real tool diameter of the section is calculated according to formula (1). The $\vec{C}_P \vec{TCP}$ vector is calculated using formula (2).

$$R_R = \frac{\overline{C_P \vec{TCP}} \times \vec{e}}{|\vec{e}|} \tag{1}$$

$$\overline{C_P \vec{TCP}} = \{TCP_x - C_{Px}; TCP_y - C_{Py}; TCP_z - C_{Pz}\} \tag{2}$$

The analysis module works with the contact point without considering the material after semi-finishing machining operations. The presumption is, therefore, a small machining allowance for finishing machining, with an interval from one to several tenths of a millimetre depending on the size of the cutting tool and the shape of the surface. The adherence of cutting conditions at the contact point between the cutting tool and the workpiece has the greatest effect on the resulting surface quality after machining.

Now, there are two main options for optimizing finishing machining with a focus on cutting conditions. The first option is to actively control the spindle speed and the feed rate in dependence on the actual cutting diameter. However, this is limited by spindle dynamics and spindle speed control. The second option is to recalculate the tool axis vectors in relation to the machined area when preparing the toolpaths in the CAM with the aim of moving the contact point on the cutting tool as close as possible to the maximum value of the cutting tool diameter. This second solution can be easily implemented in the postprocessor and is potentially widely applicable. For these reasons, an optimization approach based on recalculation of tool orientation will be proposed.

3. Optimization of tool position

Based on the calculation of the real cutting radius and experimental mapping of areas with deteriorated surface quality, the optimization module was approached. This optimization module was implemented in the postprocessor for more efficient use. The calculation principle is shown on Fig. 4.

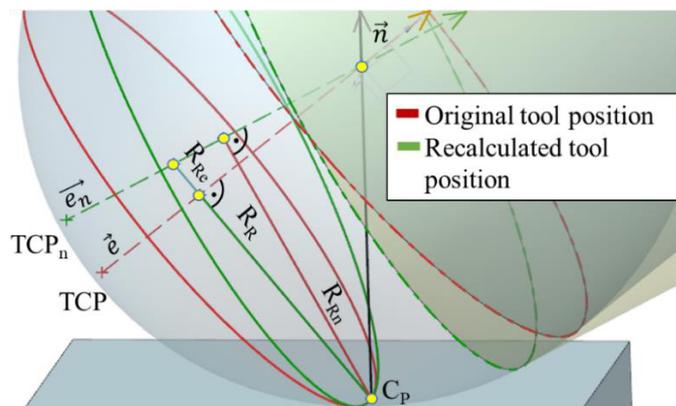


Fig. 4: Scheme of recalculation of new tool position

The optimization is based on the conversion of individual NC blocks in the NC code, where the input is a requirement for minimum cutting speed. Based on this value, NC blocks are

converted which do not correspond to the real cutting speed is shown on Fig. 5.

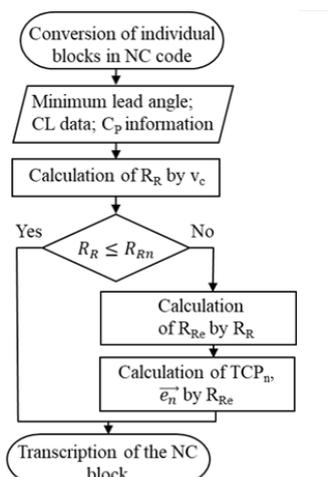


Fig. 5. Flowchart describing the calculation algorithm

The developed method was used in the preparation of the production of the water turbine hub and was tested on a representative segment of Francis turbine with a diameter of 650 mm. Before optimization, the average cutting speed was increased from 47.5 % to 69.5 % from a nominal value of 150 m/min. Thus, it was possible to increase the programmed working feed by 46 % and even narrow the actual cutting speed interval in one operation from (2 % to 93 %) to (39 % to 100 %), see Fig. 6. This shortened the operation time from 93 to 54 minutes. This resulted in significantly reduced finishing time and improved quality as well as savings on tools due to the elimination of excessive wear of the cutting edges of the tool due to non-compliance with the technological conditions during tool travel. However, the selection of the tool axis vectors is primarily limited by the shape of the machined area, machine kinematics and the shape of the machined part with respect to collisions. Therefore, it is not always possible to achieve the ideal maximum value of the actual cutting tool diameter on the entire machined area.

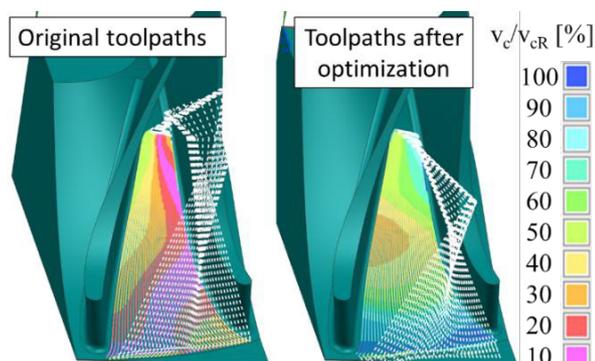


Fig. 6. Colour visualization of the expected cutting speed - nominal cutting speed (v_c)/calculated cutting speed (V_{cR})

4. Conclusion

The proposed method focuses on analysis of the actual cutting speed in finishing machining with circular cutting edge tools. The cutting speed changes during the process depending on the

contact point between the tool and the workpiece. The effect of adherence to the prescribed cutting speed was proven through machining tests on two materials, EN AW 7075 and DIN 1.4462. The evaluated surface roughness makes apparent the need for post-adjustment of the tool axis orientation in places where the desired cutting speed is not achieved. Based on the analysis, a procedure was developed to optimize the lead angle in terms of improved compliance with the prescribed cutting speed in complexly shaped toolpaths. The optimization module was implemented in the postprocessor and can be used for three-axis and five-axis operations. The optimization process was successfully used in the production of large-scale water turbines representative segment. The newly developed optimization method resulted in production time savings and tool life and surface quality increasing.

Acknowledgements

This work was supported by the Grant Agency of the Czech Technical University in Prague, grant no. SGS19/165/OHK2/3T/12.

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