MODIFICATION OF THE 5-AXIS TOOLPATH TO INCREASE THE TURBINE HUB SURFACE QUALITY

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This industrial article focuses on the finishing machining of workpieces made of aluminium alloy EN AW 7075 with a freeform shape, utilizing minimal material stocks. These workpieces are widely used in sectors like aviation and the energy industry. In these sectors, there is a pressing demand for high-quality production in the initial attempt, eliminating the need for subsequent post-processing operations. The reason for this is to save material and reduce production time. The paper, therefore, deals with a method that involves analysing the shape of a spherical end mill in relation to surface roughness and quality, followed by a mathematical recalculation of the tool path. This approach allows to adjust the machining settings during the preparation phase in order to achieve satisfactory surface quality across the entire machined surface. This method was successfully validated during the final surface treatment of the turbine hubs.

5-AXIS, FREEFORM, MACHINING, TOOLPATH

1 INTRODUCTION

The demands on the efficiency of 5-axis milling of freeform surfaces such as turbines hub with ball-end mill are constantly increasing. These demands can be met through various optimization methods and approaches. This article focuses on enhancing the surface quality of turbine hubs during the pre-production phase within the toolpath and cutting tool area. Surface quality, represented by surface roughness and optical quality, has a significant impact, for example, on the efficiency of the turbomachine, and even on the marketability of the part [ZARIATIN 2017, SAGOL 2013]. It is therefore desirable to set the machining so that the surface quality is satisfactory after milling and it is not necessary to include post-processing adjustments such as manual grinding.

Increasing the quality of 5-axis machining on already set tool paths is possible for example by applying force models and subsequent optimization of cutting conditions [GUZEL 2003, OZTURK 2007]. However, it is more advantageous to set the toolpaths and cutting conditions in the pre-production phase so that the resulting surface has desired quality without additional optimizations. During 5-axis milling the contact point between the tool and the workpiece changes. That results in changes of the effective cutting diameter (D_{eff}) and it is necessary to correctly set the nominal cutting conditions [MIKO 2014, CORRAL 2011, VARGA 2023]. Another effect on the quality of the surface has the choice of the position of the tool relative to the workpiece marked by tilt and lead angle also resulting in specific effective cutting diameter - D_{eff} [GDULA 2020, POLZER 2020, SADILEK 2009]. Tilt and lead angle can be optimized for example on the basis of a surface roughness model [LAYEGH 2017] or on the basis of the effective cutting diameter and the change of the tool axis vector [STEJSKAL 2021]. When machining hub turbines the D_{eff} varies due to avoiding collisions with the blades and due to avoiding machining with the tip of the tool [PESICE 2023]. The mentioned approaches were applied in limited ranges of tilt and lead angle and only on ball- end mill with two tooth. In the case of machining larger turbines on large machine tools with low spindle speeds it is necessary to choose multi-edged tools to achieve effective machining at higher feed-rates. It is also possible to use a larger range of tilt and lead angles than in the mentioned research. Therefore, this article focuses on the effect of setting the position of the tool axis vector in relation to hub turbine shape and effective cutting diameter. Based on this, the tool path will be modified to achieve a higher surface quality.

2 APPROACH TO INCREASE THE SURFACE QUALITY

The finishing machining of parts with a complex shape, especially the hub of turbines, is a demanding task from many points of view. The narrow space between the complex shape of the blades reduces possibilities for adjusting the tool path on the hub. Often, tool paths are adjusted solely considering the avoidance of tool-holder-workpiece collisions and the machine tool's kinematic ranges. In such cases, the tool axis position fluctuates from normal to the surface during the turbine hub passage. This results in a constantly moving contact point between the tool and the workpiece, leading to a variable effective diameter. As a consequence, constant cutting conditions are not ensured, leading primarily in the case of aluminium alloy material to a deterioration in surface quality. The proposed approach to improving surface quality involves an analysis of the relationship between the tool position relative to the surface at each NC point of the tool path and the surface quality represented by roughness and optical appearance. Furthermore, these findings are applied to the real tool path, where the standard tool path is modified by redistributing the tool axis to equalize the surface quality turbine hub, as shown in Fig 1.

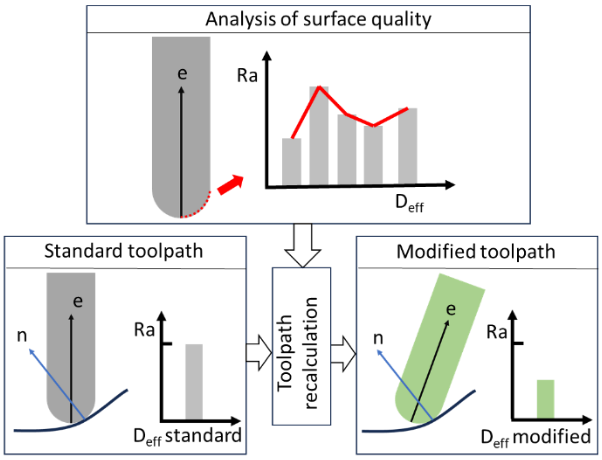

Figure 1. Approach to increase the surface quality

The first step is to analyze the course of the surface quality depending on the position of the contact point on the cutting edge of the tool. This position gives the real D_{eff}, see formula 1.

$$2\cos^{-1}(n \times e) = D_{eff} \tag{1}$$

Different values of D_{eff} will result in different surface quality especially for multi-edged tools. On the basis of this analysis the D_{eff} intervals satisfying the surface quality are determined. The second step is to recalculate the toolpath or tool axes and programmed tool tip (T_T) maintaining the contact point so the D_{eff} falls into the desired interval. The last step is to write the recalculated NC block into the NC code, see Fig 2.

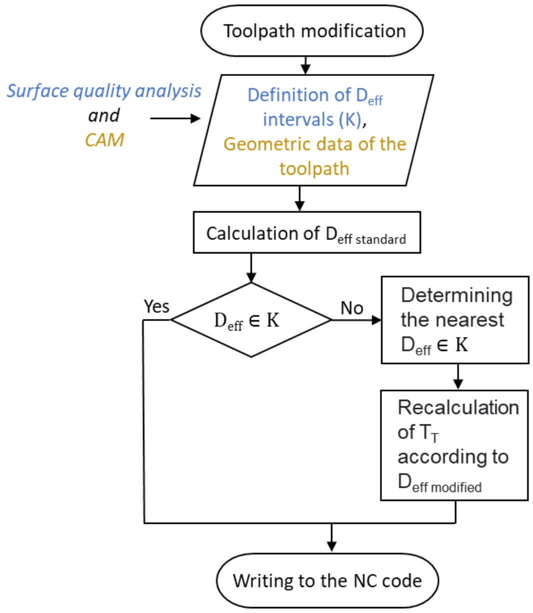

Figure 2. Toolpath modification scheme

3 ANALYSIS OF SURFACE QUALITY

Determining the D_{eff} interval where the surface quality is satisfactory is based on a basic measurement experiment, see Fig. 3.

3.1 Experimental setting

NC code was generated using the Siemens NX CAM software for the MCU 700 VT-5X multifunctional CNC machine tool from KOVOSVIT MAS Machine Tools, a.s. which was equipped with the HEIDENHAIN TNC640 control system. Ball-end mill was diameter of 10 mm, four teeth, a helix pitch angle of 30°, blade radius of 18,7 µm, TiAlN PVD coating. The cutting conditions were set with regard to large machine tools, i.e. spindle speed S = 14000 RPM, feed per tooth F_z = 0.06 mm.

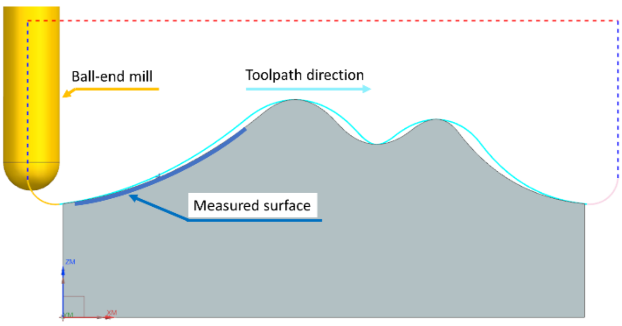

Figure 3. Test workpiece with toolpath set

3.2 Measuring of surface roughness

The roughness of the testing workpiece surface was measured using a roughness tester from Mahr LD130 using a measuring sensor LP C 25-15-2-90, see Fig. 4. The evaluation was performed according to the ISO 4287 standard, using a Gaussian filter ISO 16610-21 with limiting wavelength LC of 0.8 mm. Roughness measurement was performed by pulling in the direction of tool movement, i.e. along the contact points. The measurement was repeated five times.

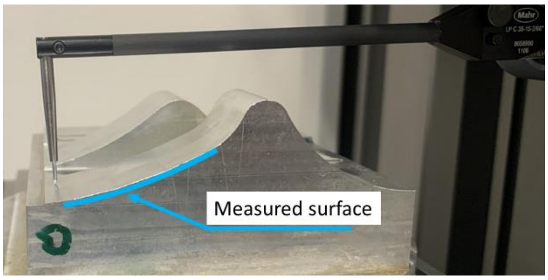

Figure 4. Roughness measurement on the test workpiece

The position of the measurement was further divided into areas according to the effective diameter of the tool. Machining near the tool tip has been described in previous research and is not the subject of this paper. The experiment is primarily focused on the D_{eff} area greater than 2.8 mm, which is close to the values used for machining of hub turbines, see Tab 1. The variance of all the measured values was a maximum of 4%.

Area [-]	1	2	3	4	5	6	7	8	9
D_{eff} [mm]	2,8-3,1	3,1-3,4	3,4-3,7	3,7-4	4-4,3	4,3-4,6	4,7-4,9	4,9-5,2	5,2-5,5

Table 1. Distribution of areas

The evaluation of the measured roughness Ra and Rz shows a local increase in roughness in area 4, see Fig 5.

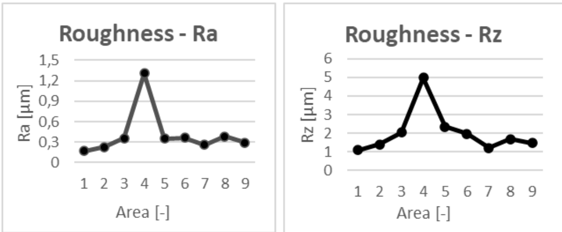

Figure 5. Measured surface roughness in the direction of ball-end mill toolpath

To detect the local deterioration of the surface quality in area 4 a 3D scan of used finishing ball-end mill was performed on an Alicona InfiniteFocus G5 scanning device. The reconstruction of the tool teeth geometry and their re-measurement led to identifying the measured area 4 as the place where the secondary teeth start to come into contact with the workpiece. This location (CP_{MS}) is established, based on measurements, at D_{eff} = 3.912 mm. From these findings, it is necessary to consider two critical areas of the position of the contact point (CP) on the cutting edge of the tool. These are the area near the tip of the tool (CP_{TS}) and the area near the beginning of the secondary teeth (CP_{MS}) see Fig 6. An area instead of a specific point was chosen for the reliability of the solution. An additional imprecise influence can be, for example, imbalance of the tool or minimal addition of material.

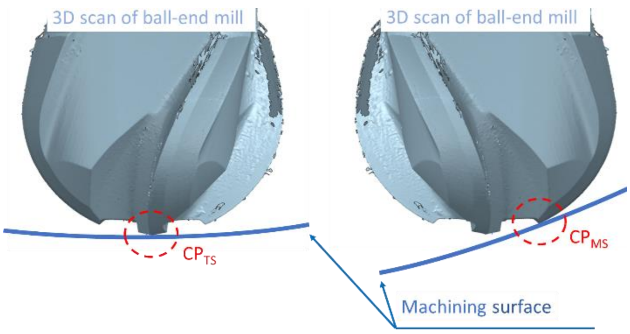

Figure 6. definition of two areas with deteriorated surface quality

4 CASE STUDY

The proposed approach was applied to a 490 mm diameter Francis turbine made of EN AW 7075 material. The cutting tool was identical to the tool from the previous experiment. The machine tool was a FRF 350/8, ser. no. 3317 head-to-head kinematics with Sinumerik 840D sl. The spindle head was marked VKE from TOS KUŘIM – OS, a.s. A total of two hub turbines were machined for testing see Fig 7. The machining strategy was zig in the direction of the streamlines. The first hub was machined with standard settings, i.e. settings without knowledge of the course of the D_{eff}. The second turbine hub was machined with a modified tool path according to the proposed and described approach.

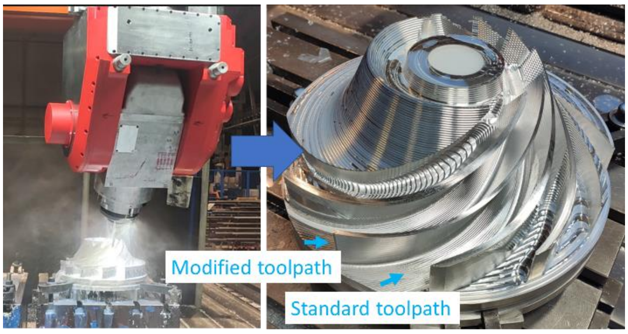

Figure 7. Machining of turbine hubs on the FRF machine tool

Fig 8. shows the difference by color visualization in the distributed D_{eff} along the toolpath with respect to the CP_{TS} and CP_{MS} areas.

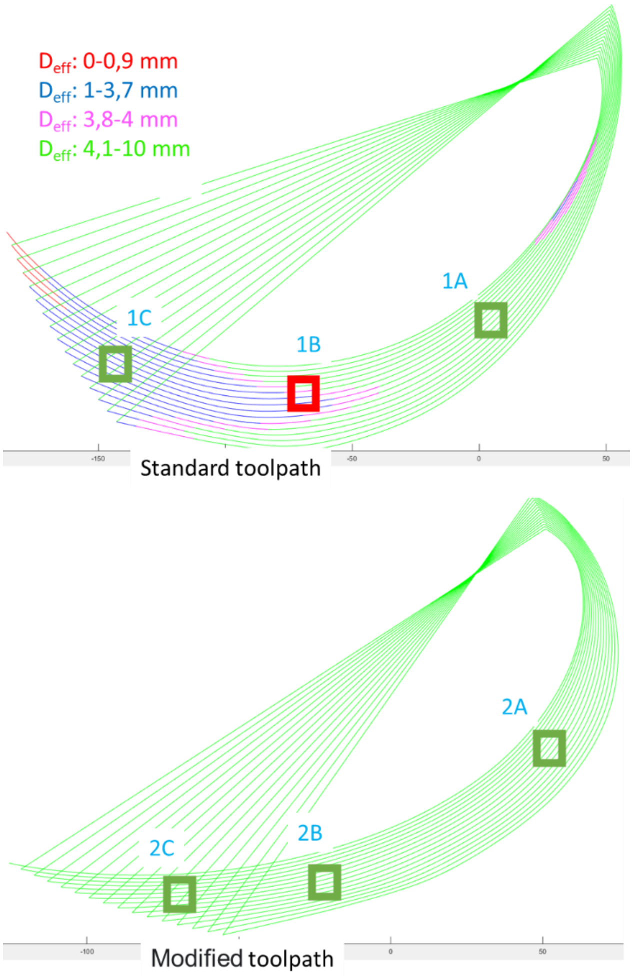

Figure 8. Visualization of areas on the hub toolpath with the risk of workpiece quality deterioration

When evaluating the optical quality in the measured areas a deteriorated texture can be seen in the standard tool path marked 1B, i.e. in the area where the secondary teeth (CP_{MS}) entered the cut, see Fig 9. For the other measured areas, the optical quality is satisfactory.

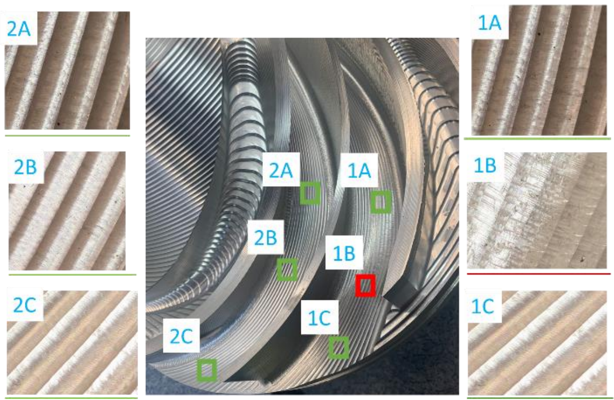

Figure 9 Optical quality of the measured areas on the turbine hub

Furthermore, the roughness was measured in the evaluated areas. The measuring direction was feed direction considering the supposed influence from the D_{eff} difference (and cutting conditions change) to the groove bottom surface. Measurement was repeated 5 times, average values are given in Tab 2 along with the corresponding D_{eff} parameter interval. According to the measured data, the improvement is acquired especially by the elimination of machining in the CP_{MS} area.

Area	1A	1B	1C	2A	2B	2C
Ra [µm]	0,354 ±0.03	1,173 ±0.15	0,276 ±0.02	0,339 ±0.03	0,325 ±0.03	0,333 ±0.03
Rz [µm]	1,448 ±0.13	4,854 ±0.24	1,316 ±0.05	1,348 ±0.11	1,672 ±0.07	1,486 ±0.09
Rsm [µm]	420 ±35	511 ±52	283 ±21	342 ±29	387 ±37	299 ±41
Interval D_{eff} [mm]	1 – 3,7	3,8 - 4	4,1 - 10	4,1 - 10	4,1 - 10	4,1 - 10

Table 2 Roughness measurement in selected areas after machining

5 CONCLUSION

An approach to tool path modification was designed and verified in order to enhance the surface quality during the machining of hub turbines. Through the analysis of the effective cutting diameter's impact on the ball-end mill concerning roughness, an additional critical area, apart from the area near the tool tip, was identified as susceptible to surface quality deterioration. Thus the surface roughness can be locally worsened up to three times the nominal value within one machined surface. This finding played a pivotal role in the tool path recalculation process, achieved by adjusting the tool axis vector while preserving the precise position of the contact point. Subsequently, the proposed approach was validated in the machining of hub turbines. The obtained results clearly demonstrated substantial improvements in optical quality and surface roughness, significantly attributed to the successful implementation of the modified tool path as compared to the standard tool path. These results now pave the way for more in-depth research into this issue, focusing on the generalization of the relationships between the cutting tool and the workpiece.

ACKNOWLEDGMENTS

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