ÓBUDAI EGYETEM
ÓBUDA UNIVERSITY

Dissertation Summary

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Thesis Title: Optimization of ball end milling tool path in case of free form milling

1. Introduction

1.1 Overview

In the ever-evolving landscape of advanced industries, free-form surfaces have become ubiquitous, finding applications in aerospace, automobile, consumer products, and die and mould manufacturing. These complex surfaces require advanced machining techniques to achieve the desired precision and surface quality. One of the most versatile tools for this purpose is the ball-end mill, which is capable of machining intricate geometries with high accuracy. However, machining free-form surfaces with ball-end mills presents a significant challenge due to the dynamic change in the tool's working diameter as a result of variations in surface inclination [1].

When a ball-end tool is used, the machining process does not utilize the entire tool diameter uniformly, leading to the concept of the "effective diameter." This effective diameter varies because different parts of the cutting edge are engaged with the material depending on the tool's orientation and the surface slope. Consequently, the effective diameter is not constant and changes dynamically during the machining process, which complicates the determination of optimal cutting parameters.

The effective diameter is influenced by several factors, including the depth of cut (ap), the nominal diameter of the tool, and the slope of the machined surface. As the depth of cut increases, the effective diameter also increases, approaching the nominal diameter when the depth of cut equals the tool's radius. However, in many finishing operations, the depth of cut is relatively shallow (typically between 0.1mm to 0.3mm), resulting in an effective diameter that is smaller than the nominal diameter. This variation in effective diameter leads to inconsistent cutting speeds and milling parameters, even if the spindle speed remains constant. As a result, the surface finish of the machined part can be uneven, which is undesirable in high-precision manufacturing [2].

One potential solution to this problem is the use of simultaneous five-axis milling, which can adjust the tool orientation continuously to maintain a more consistent effective diameter. However, the high costs and complexity associated with five-axis milling systems can be prohibitive for many applications. Therefore, this thesis explores alternative methods to address the challenge of varying effective diameter in three-axis milling machines, which are more commonly used in industry.

This research investigates two primary approaches to mitigate the effects of effective diameter variation. The first approach involves the development of an algorithm that continuously calculates the working diameter in real-time and adjusts the spindle speed and feed rates accordingly to maintain a consistent cutting speed. This method leverages the geometric information from the STL file representing the machined surface and the APT format for the tool path to dynamically recalibrate machining parameters.

The second approach focuses on optimizing tool path planning. Unlike conventional tool path strategies, the proposed method calculates the working diameter at each adjacent point along the tool path and guides the tool towards points where the changes in the effective diameter are minimal. This strategy aims to reduce fluctuations in cutting speed and improve the homogeneity of the machined surface.

By addressing the challenge of dynamic changes in the working diameter, this thesis aims to enhance the precision and quality of free-form surface machining using ball-end mills in three-axis milling machines. The proposed solutions have the potential to significantly improve manufacturing efficiency and surface finish quality, contributing to advancements in various high-tech industries.

1.2 Objective of the thesis:

The principal objective of this thesis was to optimize the tool path for end ball milling of free-form surfaces. The specific goals were pursued through two distinct strategies:

1. Dynamic Spindle Speed Control:
   i. Investigated the impact of dynamically changing the spindle speed during the milling process, taking into account the milling diameter at each point.
   ii. Assessed how varying the spindle speed influenced the cutting speed, with the aim of ensuring minimal changes in the working diameter throughout the machining operation.
   iii. Developed and implemented a methodology, utilizing a Python program, to dynamically adjust the spindle speed along the tool path for optimal milling performance.
2. CAM System Tool Path Optimization:
   i. Explored the utilization of a Computer-Aided Manufacturing (CAM) system to generate a tool path that minimizes the change in the tool's effective diameter.
   ii. Investigated the selection of appropriate milling directions from point to point on the path to achieve a smoother and more consistent machining process.
   iii. Developed a systematic approach, possibly through the enhancement of a Python program, to integrate CAM-generated tool paths that prioritize minimal changes in the tool's effective diameter.

To visually illustrate the concepts of these two strategies, Figure 1-1 presents a schematic representation of the dynamic spindle speed control and CAM system tool path optimization methods. As shown in the figure, a key step in both strategies involves calculating the working diameter for each point. In the context of spindle speed control, this calculation aids in determining the spindle speed required to maintain a constant cutting speed. Conversely, in tool path planning, this calculation assists in selecting the next point on the path, ensuring minimal changes in the working diameter and, consequently, minimizing variations in cutting speed.

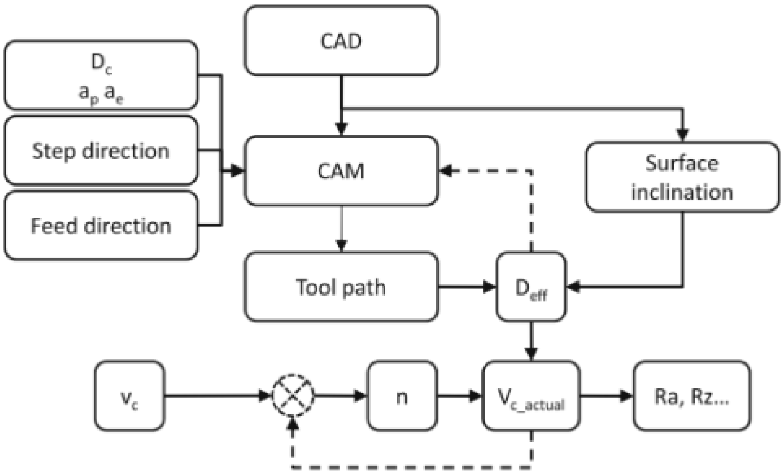

Figure 1-1:Illustrating the Concept of Tool Path Optimization Strategies.

1.3 Scope and limitation

1.3.1 Scope

The scope of this thesis encompasses the optimization of tool paths for end ball milling of free-form surfaces, focusing on two primary strategies: dynamic spindle speed control and CAM system tool path optimization. The research aims to advance understanding and implementation in these specific areas, contributing insights and methodologies for improving machining efficiency and surface quality.

1.3.2 Limitations:

1. Experimental Validation: While the dynamic spindle speed control strategy has been fully implemented and analysed, the CAM system tool path optimization is conceptual, lacking experimental validation in the current study.
2. Specific Milling Context: The findings and recommendations are tailored to the context of end ball milling for free-form surfaces, and their direct applicability to other milling processes or machining contexts may require further investigation.
3. Software and Hardware Constraints: The effectiveness of the proposed methodologies is influenced by the capabilities and limitations of the software tools and CNC hardware used in the study. Generalization to different platforms may necessitate adjustments.
4. Material Specificity: The research primarily considers the milling of free-form surfaces in various materials. The applicability of the proposed strategies may vary based on specific material properties and cutting tool considerations.
5. Single-Tool Focus: The study predominantly concentrates on optimizing tool paths for end ball milling using a specific type of cutting tool. The extension of findings to other tool types may require additional exploration.

By acknowledging these limitations, the study ensures a focused and realistic approach while providing valuable insights within the defined scope.

1.4 Revised research gap:

1. Sparse Attention to Dynamic Spindle Speed Control: While various tool path optimization methods have been discussed, there is a scarcity of research specifically addressing dynamic spindle speed control in the context of end ball milling. This study aims to fill this gap by investigating the implications and benefits of adjusting spindle speed dynamically during the milling process.
2. Limited Insight into Working Diameter Calculation and Its Impact: Existing literature lacks in-depth exploration of the working diameter calculation and its direct impact on tool path optimization. This research addresses this gap by delving into the intricacies of working diameter calculations, emphasizing their role in determining optimal spindle speeds and influencing overall machining efficiency.

By identifying and addressing these research gaps, this thesis aims to contribute a more nuanced understanding of tool path optimization for end ball milling of free-form surfaces, with specific emphasis on dynamic spindle speed control, CAM system tool path optimization, and the intricate effects of working diameter calculations on machining outcomes.

1.5 Structure

This summary is organized as follows:

1. Literature Review: An examination of existing research on ball-end milling, the concept of effective diameter, and current methods for handling variations in cutting parameters.

2. Methodology: A detailed description of the research design, including the development of the real-time adjustment algorithm and the optimized tool path planning method.

3. Results: Presentation and analysis of the findings from applying the proposed methods to free-form surface machining.

4. Discussion: Interpretation of the results, implications for theory and practice, comparison with previous studies, and identification of research limitations.

5. Conclusion: A summary of the main findings, contributions of the research, and suggestions for future research directions.

By addressing the challenges associated with the dynamic change in working diameter, this thesis aims to contribute to the field of precision machining and improve the quality and efficiency of manufacturing processes involving free-form surfaces.

To provide a visual overview of the comprehensive work done, Figure 1-2 represents a roadmap outlining key milestones throughout my research. Each node represents a pivotal step, interconnected to trace the path of my contributions. As we delve deeper into the following chapters, this graphical representation will guide the reader through the dynamic landscape of my work.

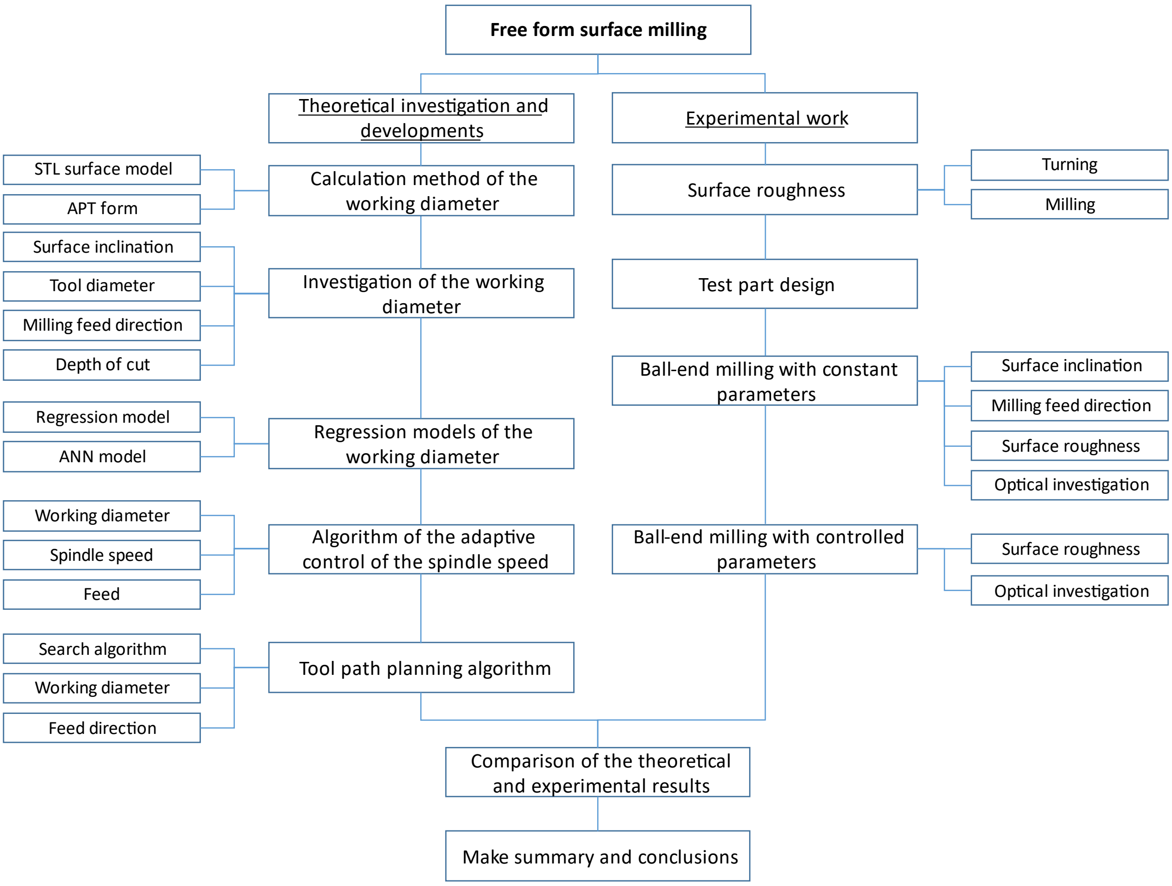

Figure 1-2: Graphical overview of PhD research progress.

2 Results:

2.1 Spindle speed control

2.1.1 Concept

To calculate the spindle speed and ensure effective machining, the working diameter of the ball-end milling cutter needs to be determined point-by-point. This calculation relies on a geometric model proposed by Mikó and Zentay [3], necessitating the description of the free-form surface, the cutting tool path, and cutting data.

To calculate the working diameter, both surface data and tool path data are essential. The STL file format is commonly used for describing free-form surfaces, while the APT language is utilized for describing tool paths. Briefly, the STL file format represents objects in CAD systems by defining the surface geometry using a mesh of triangles. On the other hand, the APT language provides a means to describe tool paths, including tool movements, feed rates, and spindle speeds.

By utilizing the STL file format for surface geometry and the APT language for tool path data, the algorithm can calculate the angle of surface inclination at each cutting point, facilitating the determination of the working diameter of the ball-end milling cutter. This comprehensive approach ensures accurate spindle speed control and effective machining, independent of the CAD/CAM system used.

To achieve the objective of this study, an algorithm has been developed to control and adjust the spindle speed point-by-point to maintain a constant cutting speed. Figure 2-1 illustrates the functioning of this algorithm in calculating the spindle speed required at each point of the surface.

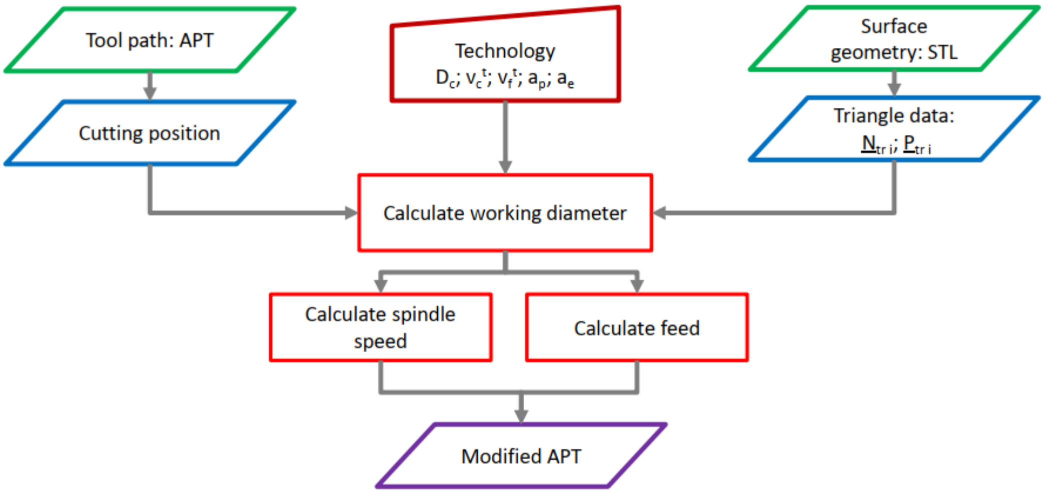

Figure 2-1: Diagram illustrates the algorithm

2.1.2 Main findings:

To validate the introduced algorithm, a series of rigorous tests were conducted. The results of machining a free-form surface using ball-end milling with five different feed directions are presented. Two test series were executed: one with constant spindle speed and the other with controlled spindle speed. The surface roughness of these parts was then compared to assess the effectiveness of the proposed adaptive spindle speed control method in the context of 3-axis milling.

Figure 2-2 compares the average values of surface roughness Rz for each milling direction. The difference between the Rz surface roughness values after modification is small (2.0 µm in the case of milling direction 0° and 1.6 µm in the case of 45°) compared to milling under a constant spindle speed (ranging from 4.5 µm in the case of feed direction 67.5° to 3.7 µm in the case of milling direction 0°). Maintaining a constant cutting speed reduces the effect of milling direction on surface quality, ensuring similar surface roughness under different milling directions and a more homogeneous surface regardless of surface inclination.

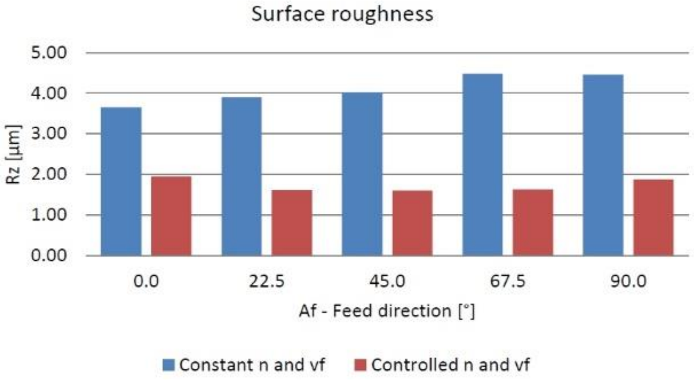

Figure 2-2: Average values of the surface roughness (Rz).

As depicted in Figure 2-3, the Rz parameter ranges (defined as the difference between the maximum and minimum values) from 1 µm to about 2 µm in the case of controlled surface, varying based on feed direction. In contrast, with conventional milling methods (constant spindle speed), the ranges are between 3.7 µm and 5.3 µm in each direction. The smaller range in controlled milling indicates a more homogeneous surface quality.

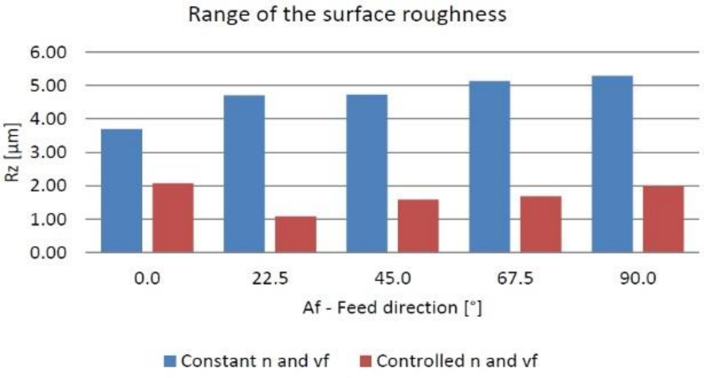

Figure 2-3: The ranges of the surface roughness (Rz).

In Figure 2-4 the standard deviation of the Rz surface roughness is depicted for each milling direction, comparing constant and controlled spindle speed conditions. The standard deviations of workpieces machined with controlled spindle speed are smaller (less than 0.5 µm) compared to those machined without optimization, which range from 1 to 1.5 µm. This minimal standard deviation implies that the surface maintains consistent roughness after the machining process, regardless of milling direction. Conversely, similar values of standard deviation across different milling directions underscore the effectiveness of the suggested method in mitigating the impact of milling direction on surface quality.

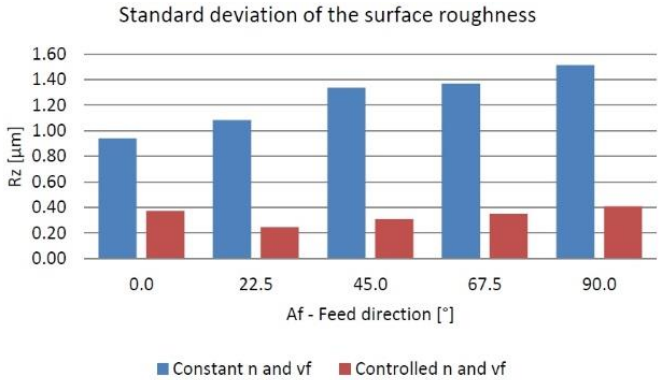

Figure 2-4: Standard deviation of Rz surface roughness.

2.1.3 The tool path planning as a search algorithm

2.1.4 Concept

The algorithm has been developed with a specific focus: generating an optimal tool path for milling free-form surfaces. The primary objective is to minimize variations in the working diameter of the ball-end tool during the machining process. By achieving minimal changes in the working diameter, the resulting reduction in cutting speed fluctuations ensures a more uniform and homogeneous machined surface.

The core objective of the algorithm is to perform path planning for CNC machining. This involves determining the sequence of points (toolpath) that the CNC machine should follow while milling the freeform surfaces. The developed algorithm solves the tool path re-planning as a search algorithm. The algorithm uses the pre-generated NC code in APT form. The code contains the points of the toolpath. The search algorithm reorders the points in order to equalize the value of the working diameter and reduce the dynamic load of the spindle. The algorithm implements a path planning that takes into account the difference in the effective diameter between the current point and its neighbour points. Once a point is processed, it is marked as visited (tabu) to prevent the algorithm from revisiting it. The overarching goal is to ensure that the algorithm systematically covers all points without duplication while minimizing fluctuations in the working diameter.

The algorithm begins by reading and processing data from an STL file, which represents 3D models using triangular facets and contains vital geometry information. Subsequently, it extracts tool position coordinates from an APT file, a format used in CNC machining. To enhance precision, the code generates additional tool positions as needed and calculates normal vectors at each position based on facet data from the STL file. It also determines neighbour points and computes the working diameter using an established mathematical model. Finally, the code's core objective is path planning for CNC machining, aiming to optimize toolpaths by considering variations in the effective diameter while efficiently covering all points on the surface.

The developed algorithm uses APT file to determine the tool position coordinates at each point of the surface. An APT (Automatically Programmed Tool) file is a file format used in computer-aided manufacturing (CAM) and computer numerical control (CNC) machining. APT is a high-level programming language specifically designed for defining toolpaths and machining operations for CNC machines. By reading the file, the algorithm extracts tool position coordinates.

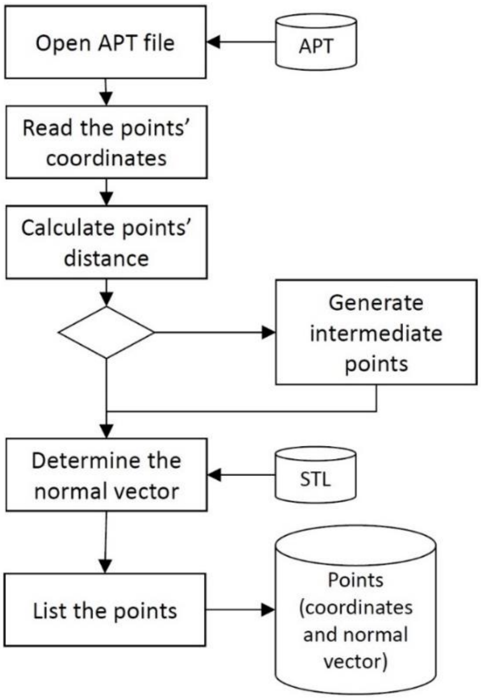

Figure 2-5 Pre-processing of the tool position and surface data.

The algorithm calculates the normal vectors at each tool position using the facet normal obtained from the STL file. These normal vectors are associated with the corresponding tool positions by identifying the nearest in-center point. Essentially, this process ensures that at each position, the tool aligns with a specific triangle and adopts the same normal vector as that triangle.

The search algorithm of the reordering the points of the tool path is started by the selection of the starting point (Figure 2-6). It must be on the border of the machined surface. The point can be defined by rules, like the lowest or the highest point of the contour or it can be a random point.

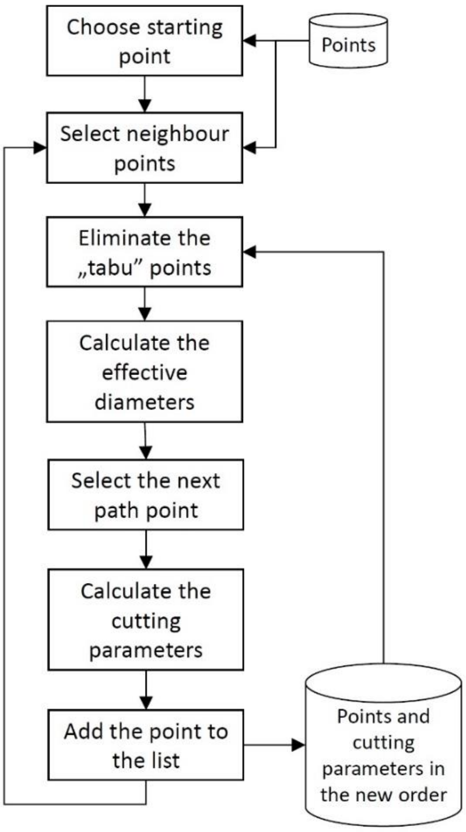

Figure 2-6 Search algorithm.

The next step is finding the neighbor points. Because of the non-uniform and non-regular distribution of the tool points, an adaptive method has to be used. This code then performs some neighbor point calculations based on a distance threshold R. It iterates over tool position elements and checks for nearby points. If the count of nearby points is less than a specific number, it incrementally increases the distance threshold R until it reaches or exceeds a specific number of points. The resulting points are stored in a list. If a point was chosen previously, it is deleted from the neighbor set, as a taboo point.

The algorithm calculates the milling direction for each tool position based on the slopes between the tool position and its neighbor points. Then it calculates the working diameter of each neighbor point using a mathematical model presented by Mikó and Zentay [3].

At the last step, the point is selected, which has the smallest difference value in the working diameter. If there is no difference in the working diameter because the surface is horizontal, the next point is selected in the feed direction.

The modified cutting parameters (cutting speed and feed) are calculated and added to the list of the points of the new tool path. The algorithm starts again by the selection of the neighbor points. The reordering of the points of the tool path ends when all points are selected.

2.1.5 Main findings:

Figure 2-7 and Figure 2-8 provide a visual representation of the change in the working diameter when employing two different milling strategies: the traditional down milling tool path and an optimized tool path. The working diameter, a critical parameter in machining operations, is analyzed to understand its variation and impact on the machining process.

In the case of the traditional down milling tool path, Figure 2-7 illustrates a significant range of change in the working diameter, spanning from 0 to 0.9155. This wide variation suggests that the machining process under traditional down milling conditions results in a less consistent effective diameter throughout the operation.

On the other hand, Figure 2-8 highlights the working diameter variation when utilizing a modified tool path. In this scenario, the effective diameter fluctuates within a narrower range, specifically between 0 and 0.6. This narrower range indicates that the proposed tool path leads to a more controlled and predictable working diameter during the milling process.

The observed difference in the effective diameter range between the two milling strategies has noteworthy implications, particularly in terms of surface homogeneity. A smaller variation in the working diameter, as achieved with the modified tool path, contributes to enhanced surface homogeneity.

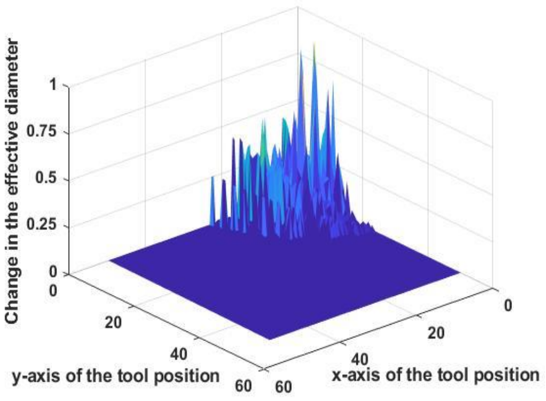

Figure 2-7 The change in the working diameter in the case of original tool path

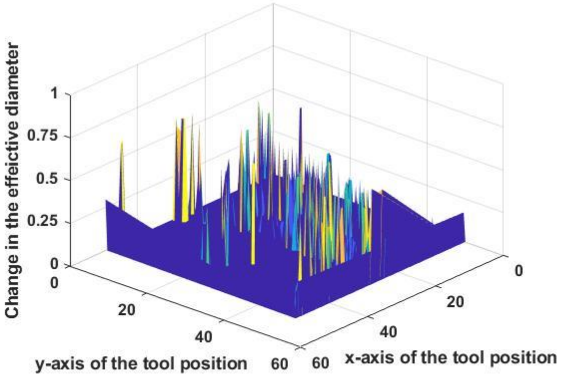

Figure 2-8 The change in the working diameter in the case of optimized tool path

Figure 2-9 illustrates the spindle speed change in the case of the traditional down milling approach, showcasing a wide range from 0 to 622. This broad variation implies that under traditional down milling conditions, the spindle speed undergoes significant changes throughout the machining process. Such fluctuations may introduce challenges such as tool wear, vibration, and inconsistent cutting conditions, potentially impacting the overall quality of the machined surface.

Conversely, Figure 2-10 represents the spindle speed variation for the optimized tool path. In this case, the spindle speed changes within a smaller range, specifically from 0 to 128. The narrower variation indicates that the proposed tool path leads to a more controlled and stable adjustment of spindle speed during machining.

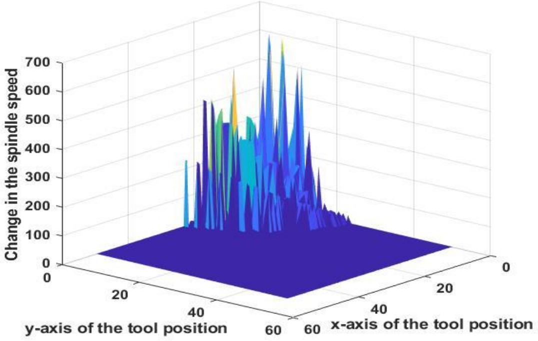

Figure 2-9 The change in the spindle speed in the case of original tool path

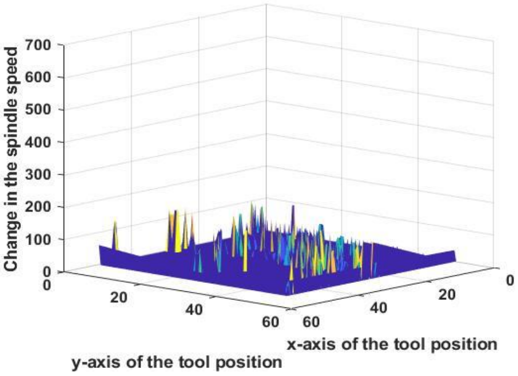

Figure 2-10 The change in the spindle speed in the case of optimized tool path

The presented algorithm was developed for improving toolpaths in CNC machining, with a primary focus on minimizing variations in the working diameter of the ball-end tool during milling of free-form surfaces. The algorithm reorders the tool points of the CNC program and functions as a search algorithm. It systematically calculates the working diameter of neighboring points and directs tool movement to points with minimal diameter differences, ensuring minimal changes in the working diameter and the adjustment of the spindle speed to maintain a constant cutting speed.

Key steps involve reading and processing data from an STL file to extract surface geometry and tool position data from an APT file. Normal vectors are calculated and associated with tool positions, aligning the tool with specific triangles of the STL file.

Neighboring point calculations consider a distance threshold, and working diameters are determined for each point. The core path planning algorithm minimizes working diameter fluctuations, preventing point revisits for efficiency.

The comparative analysis between the original and improved tool paths highlighted the nuanced impact of starting points and neighboring points on the resultant tool path. Successfully achieving the primary optimization goal - reducing the change in effective diameter and moderating spindle dynamic loads - was evidenced in the controlled working diameter variation observed in the improved tool path, contributing to enhanced surface.

3 Summary of new scientific results

The dissertation findings are summarized in seven thesis points. In square brackets are the author's works in which the actual thesis points were published:

Thesis 1

I have created a simulation model to compute the working diameter of the ball-end milling tool in a broader context. This simulation approach has allowed for a more comprehensive examination of each tool and cutting parameters. I have found that the working diameter and therefore the cutting speed varies during the chip removal. This variation is larger for larger nominal tool diameters and down milling technology. Based on the simulation, I have found that the feed direction has a significant effect on the value of the working diameter, therefore this parameter is suitable for controlling the milling process from the point of view of the working diameter.

The parameters of the simulation were: Tool diameter: D_c = 6-8-10 mm; Depth of cut: a_p = 0.1 – 1.0 mm; Width of cut: a_e = 1 mm; Feed direction: A_f = 0-180°.

Related publications: [1]

Thesis 2

I have made a regression model for the calculation of the working diameter of free form ball-end milling. I have demonstrated that to create an accurate regression model, it is essential to include the first, third, and fifth powers of both the surface inclination and the relative feed direction. I suggest a separated regression model based on tool diameter, which results in higher accuracy. The general form of the proposed regression model is:

$$D_{eff} = \sum f_i(D) \cdot C_i$$

where: the $f_i(D)$ is a linear function of the tool diameter, and the C_i is the influential parameter.

Related publications: [4]

Thesis 3

I have designed a method for maintaining a constant cutting speed by regulating the spindle speed, independent of any CAD or CAM system by using standard STL file for surface representation and APT file for toolpath description. The algorithm utilises the standard STL file format to calculate the normal vector at each surface point considering the tool position from the APT file. It establishes a connection between cutter positions and triangles within the STL file, subsequently computing the working diameter at each point. Following the desired cutting speed, the spindle speed is determined for each point. The algorithm then produces a new NC file with adjusted spindle speed values.

I have verified that implementing controlled spindle speed introduces greater dynamic stress to the machine tool. The integral value of spindle speed along the tool path serves as an indicator of dynamic load, making it a useful parameter for selecting the most efficient milling direction. It allows for the compensation of cutting speed, leading to improved surface quality and visual appearance.

Related publications: [2]

Thesis 4

By milling experiments, I have demonstrated that at a controlled variable spindle speed, taking into account a constant cutting speed, the surface roughness is significantly improved in the case of ball-end milling of a free-form surface compared to constant speed milling. Depending on feed direction, the average values of Rz surface roughness parameters are 36-56% of the original values, in the case of controlled spindle speed. The surfaces are more homogenous, which is indicated by the values of the range and standard deviation of the surface roughness. The ranges of the Rz values are 23-56% and the standard deviation are 23-39% of the original values.

The parameters of the experiments were the next: workpiece material: C45 steel; Nominal cutting speed: $v_c = 63$ m/min; Feed per tooth: $f_z = 0.125$ mm; Depth of cut: $a_p = 0.3$ mm; Width of cut: $a_e = 0.25$ mm; Feed direction: $A_f = 0 - 90°$; Spindle speed: $n_{constant} = 1845$ 1/min; $n_{controlled} = 3002\text{-}8066$ 1/min.

Related publications: [3][7]

Thesis 5

I have developed a novel approach to plan a milling toolpath for free form ball-end milling, focusing on variations in the effective diameter. The developed approach solved the tool path-planning problem by searching algorithm. The algorithm aims to find an optimal solution, ensuring minimal changes in the working diameter. It reorders the points of the milling toolpath considering the changing of the working diameter of the tool. Therefore, it minimizes the spindle speed compensation in order to reduce the dynamic load of the spindle. The results show that by adjusting the spindle speed, the optimized toolpath notably reduces the range of spindle speed values. The implementation of this method involves developing an algorithm that utilizes standard STL files and APT.

Related publications: [8]

4 References:

[1] C. X. Yue, F. G. Yan, L. Bin Li, H. Y. You, and Q. J. Yu, “Parametric Design of Ball-End Milling Tools for High Speed Milling,” *Materials Science Forum*, vol. 800–801, pp. 484–488, Jul. 2014, doi: 10.4028/www.scientific.net/MSF.800-801.484.

[2] L. Norberto López de Lacalle, F. J. Campa, and A. Lamikiz, “Milling,” in *Modern Machining Technology*, J. Paulo Davim, Ed., Elsevier, 2011, pp. 213–303. doi: 10.1533/9780857094940.213.

[3] B. Mikó and P. Zentay, “A geometric approach of working tool diameter in 3-axis ball-end milling,” *The International Journal of Advanced Manufacturing Technology*, vol. 104, no. 1–4, pp. 1497–1507, Sep. 2019, doi: 10.1007/s00170-019-03968-9.

5 Publication list

Journal articles with impact factor

1. Mgherony Abdulwahab; Mikó Balázs (2022) *Simulation of the working diameter in 3-axis ball-end milling of free form surface.* Tehnički vjesnik 29(4):1164-1170 (**IF 0.9**) https://doi.org/10.17559/TV-20210719181212
2. Mgherony Abdulwahab; Mikó Balázs (2023) *Controlling the spindle speed when milling free-form surfaces using ball-end milling cutter*. Acta Polytechnica Hungarica 20(6):135-149 ISSN 1785-8860 (**IF 1.7**) https://doi.org/10.12700/APH.20.6.2023.6.8
3. Mgherony Abdulwahab; Mikó Balázs (2024) *The effect of the spindle speed control when milling free-form surfaces.* The International Journal of Advanced Manufacturing Technology; 130(3-4):1439-1449 (**IF 3.4**) https://doi.org/10.1007/s00170-023-12811-1
4. Mgherony Abdulwahab; Mikó Balázs (2024) *Regression analysis and neural network model of working diameter of ball-end mill.* Acta Polytechnica Hungarica xx(x):xxx-xxx ISSN 1785-8860 (**IF 1.7**) 10.12700/APH.xxxxxx (***under review***)

Journal articles whithout impact factor

5. Mgherony Abdulwahab; Mikó Balázs; Drégelyi-Kiss Ágota (2020) *Design of experiment in investigation regarding milling machinery.* Cutting & Tooling in Technological Systems (Rezanie i instrumenty v tekhnologicheskih sistemah) 92:68-84 https://doi.org/10.20998/2078–7405.2020.92.09
6. Mgherony Abdulwahab; Mikó Balázs; Farkas Gabriella (2021) *Comparison of surface roughness when turning and milling.* Periodica Polytechnica - Mechanical engineering 65(4):337-344 https://doi.org/10.3311/PPme.17898
7. Mgherony Abdulwahab; Mikó Balázs (2021) *The effect of the cutting speed on the surface roughness when ball-end milling.* Hungarian Journal of Industry and Chemistry 49(2):9-13 https://doi.org/10.33927/hjic-2021-14 hjic.mk.uni-pannon.hu
8. Mgherony Abdulwahab; Mikó Balázs (2024) *Tool path planning of ball-end milling of free-form surfaces as a search algorithm.* Acta Technica Jaurinensis, 17(2):75-83, 2024 https://doi.org/10.14513/actatechjaur.00736

Conference proceedings

9. Mgherony Abdulwahab; Nagy János; Mikó Balázs (2022) *Application of the regression method in case of the free-form surface error.* Proceedings of Development in Machining Conference - DiM 2022; Crakow, Poland 18-19.05.2022. Development in machining technology 10:63-73 Ed.: W. Zebala, I. Manková; Cracow University of Technology, Cracow 2022 ISBN 978-80-553-4133-0