ÓBUDAI EGYETEM
ÓBUDA UNIVERSITY

PHD THESIS

(EXTRACT)

VARGA BÁLINT

Analysis of the micro- and macro-accuracy of the free-form milling surfaces

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Contents

1 Introduction

Freeform surfaces can be found in many places, almost everywhere from car parts to everyday objects. From tool design to mould design, from the shape of wind and hydroelectric turbines to aerodynamic design, these surfaces are used in a wide range of applications. However, machining free-form surfaces is one of the most challenging areas for the cutting industry. The parts produced must meet a wide range of user, technological and other requirements. Such requirements may be aesthetic, ergonomic, flow or design. The technological requirements are constantly increasing, and these surfaces must be produced with ever greater precision, both in terms of roughness and accuracy of shape. In addition to these requirements, productivity and economy must of course also be met.

Designing the production process is a complex task. The tools available for production and quality control must be taken into account. Some products are often made of difficult-to-machine materials and have complex geometries [1]. These factors make it difficult to plan production.

The free-form surfaces are produced by machining with a ball-end milling tool using 3 or 5-axis milling [2]. In all cases, the use of CAM (Computer Aided Manufacturing) software is essential to create the toolpaths required for manufacturing [3]. Different toolpaths can be produced with different machining strategies, which have an impact on productivity and accuracy [4]. The correct choice of machining parameters is also an important consideration, as they have a major impact on the properties of the surface created [5]. The accuracy of a surface is usually assessed in three aspects, namely dimensional accuracy, shape accuracy [6] and surface roughness [7].

2 Aims of the research

This thesis focuses on the theoretical and experimental investigation of the accuracy of free-form surfaces produced using a ball-end milling tool (Figure 1). There are many aspects of machining surfaces in this way, most of which have been investigated. The selection of the aspects studied was based on a search of the national and foreign literature.

In the thesis I describe the geometric characteristics of free-form surfaces. In this section their properties, creation and industrial applications are detailed. This is followed by the production of components with such surfaces and a characterisation of the technologies used.

In the literature review, after a classification, I will examine in detail the aspects, research directions and results related to the machining, measurement and accuracy of different free-form surfaces found in the literature.

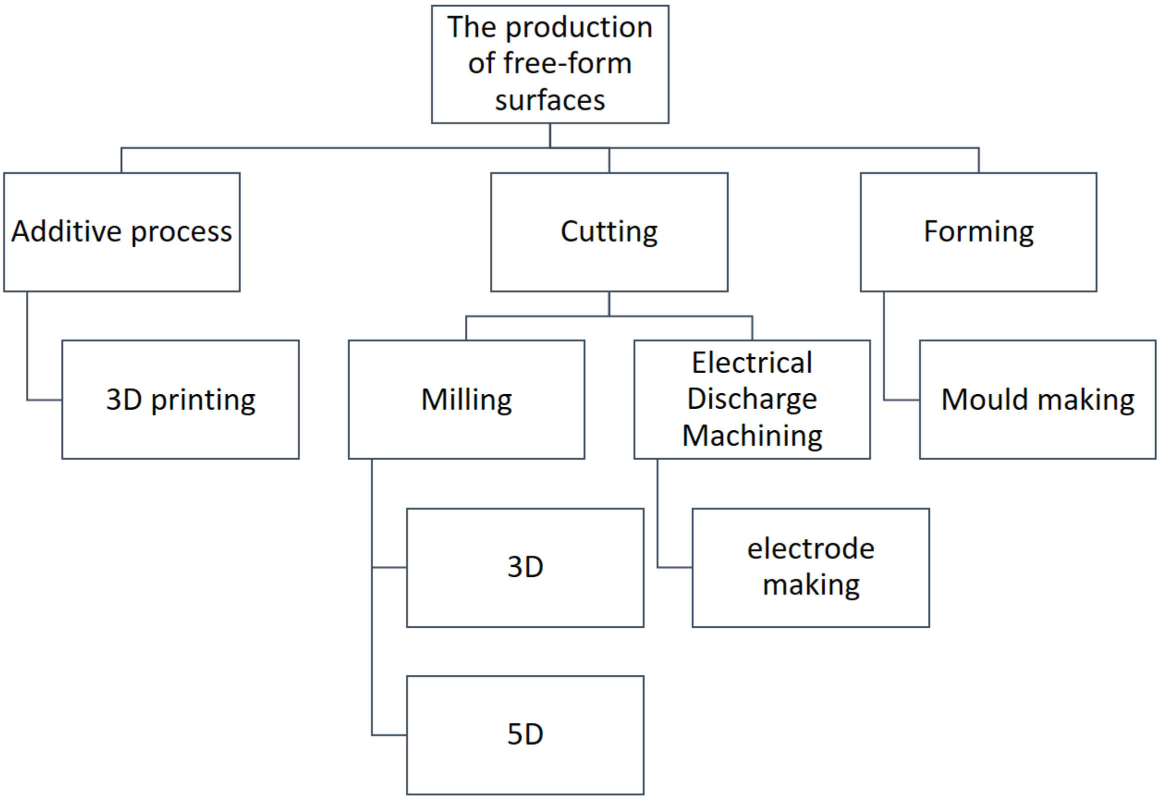

Figure 1: Production of free-form surfaces

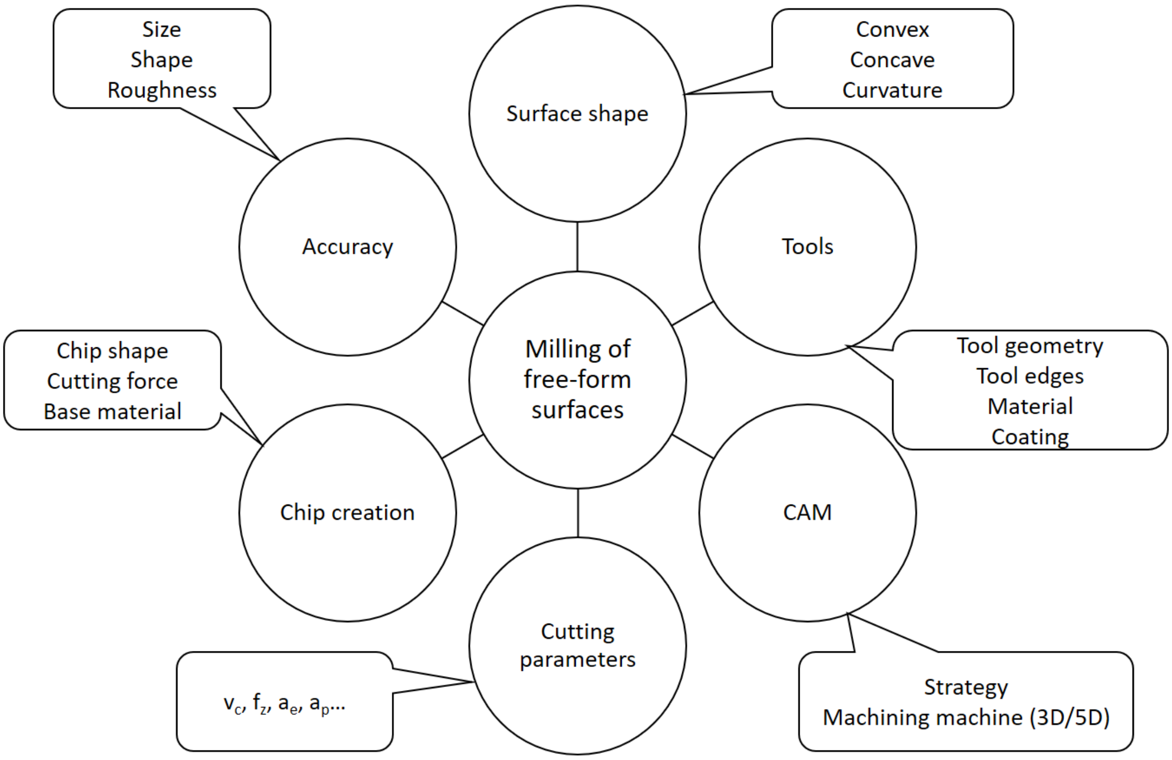

Figure 2: Classification of test aspects

Theoretical studies were carried out to analyse the theoretical chip properties that can be obtained by geometric modelling, the number of measurement points necessary and sufficient to establish the accuracy of the shape. During the experimental investigations, the main research focus was on the toolpaths and process parameters that can be set in the CAM system. I also analysed the forces generated during milling and their effects. All these were evaluated in terms of their impact on surface accuracy. The experimental phase was carried out in several phases over a longer period of time, which are not presented chronologically but in a logical order. The experiments were carried out at the Institute of Mechanical Engineering and Technology, Faculty of Mechanical and Safety Engineering, Bánki Donát (former Institute of Materials and Manufacturing Engineering). The thesis statement, the summary and the description of further research conclude my thesis.

The aim of the research is to investigate the technological aspects of machining free-form surfaces with ball-end milling cutters, including dimensional and geometrical accuracy of the surfaces, surface roughness. The technological approach means that during the research, investigations and analyses are carried out that help the technological design process, supporting the toolpath design work of the technological engineer in the CAM system. The results of the research will support the more efficient use of CAM systems, helping to select toolpaths that allow more accurate and efficient machining.

3 Methods

In the thesis I described the geometry, properties, creation and industrial applications of free-form surfaces. Theoretical and experimental studies were used to investigate the effect of different technological parameters and geometric characteristics on micro and macro accuracy.

Theoretical studies:

- I analysed the theoretical chip properties that can be obtained by geometric modelling.

- I have investigated the number of measurement points necessary and sufficient to establish the accuracy of the shape

- I carried out a time analysis for different tool paths.

Experimental investigations:

- I analysed the toolpaths (sweep, contour controlled, spiral) that can be set in the CAM system,

- machining parameters (feed per tooth vf, side feed ae),

- the influence of the geometric characteristics of the workpiece (convexity, curvature, surface normal) on the micro- and macro-accuracy of free-form surfaces (surface roughness, dimensional and shape accuracy).

- I investigated the forces (Fc, Ff, Fp, F) generated during milling and their effects. All these are also evaluated in terms of surface accuracy.

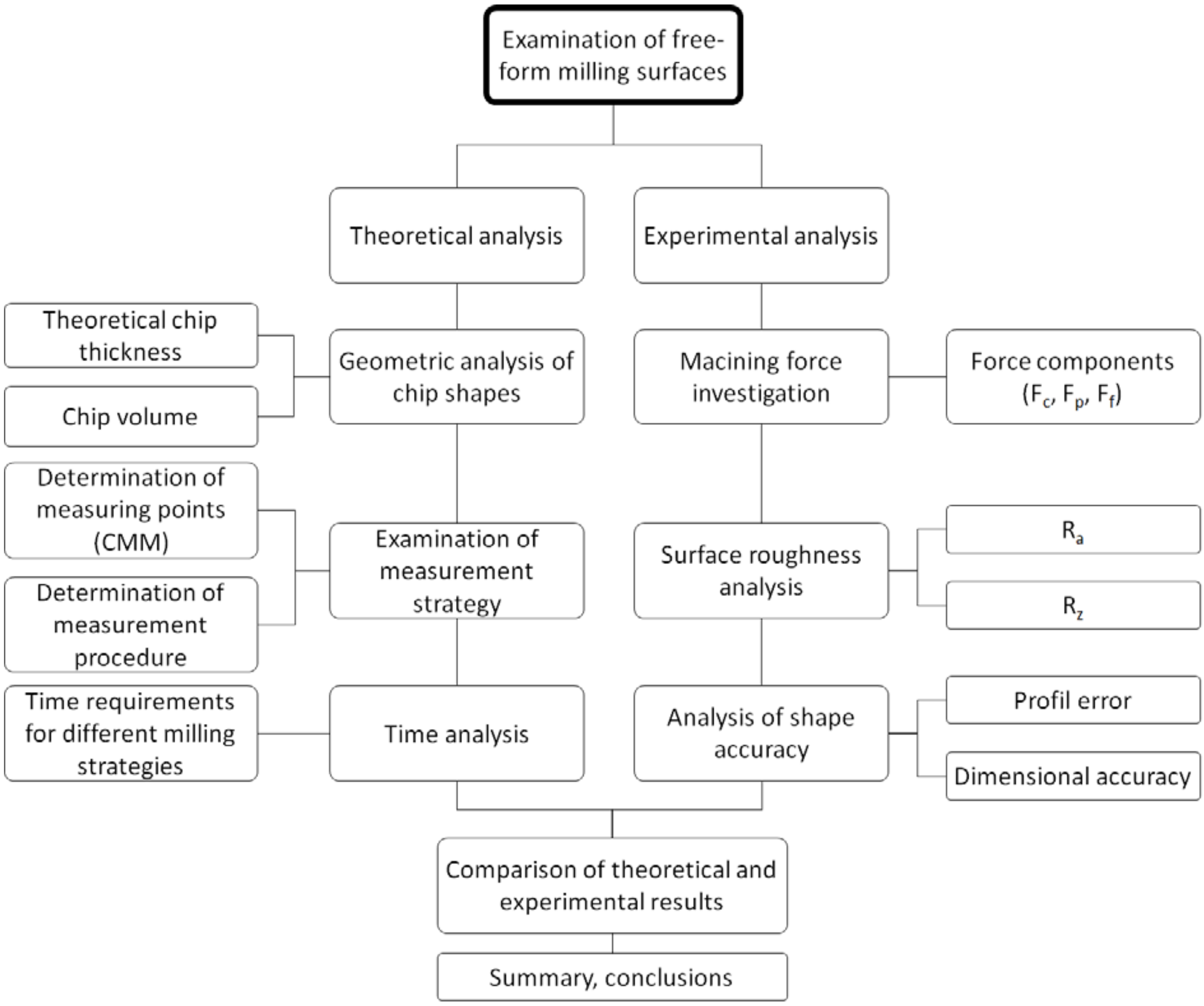

Figure 3: The investigation process

4 Új tudományos eredmények

1. Tézis

I have developed a CAD simulation method to determine the shape, volume and mean thickness of the resulting chips during ball-end milling of free-form surfaces (test parameters ranges: Dc = 10 mm; ap = 0.3 mm; fz = 0.08-0.16 mm; ae = 0.15-0.35 mm.)

Based on the simulation results, I found that for concave and convex surfaces, the chip volume and the mean thickness vary differently. The variation in the mean chip thickness along the path (standard deviation) is significant and depends on the milling direction, but the mean value is only slightly sensitive to the milling direction. The mean value and variance of chip volume are not sensitive to milling direction.

Based on the simulation data, I created a regression model that gives a good approximation of the theoretical mean chip thickness, taking into account the feed rate, width of cut, feed direction and surface normal. The presented simulation and regression method also provides the possibility to study tool load variations, to select the appropriate milling strategy and to determine the theoretical roughness.

2. Tézis

Surface measurements on a free-form surface coordinate measuring machine to investigate the ideal number of measurement points and the point sampling methods and their effect on the dimensional and shape accuracy under test (Test parameters: surface size 80 x 80 mm; surface type: concave and convex; point sampling strategy: matrix and Halton-Zaremba.)

The analysis shows that the number of points and the point sampling method have only a small influence on the measured values in the case of measurement error. In the case of rolling and surface profile defects, the nature of the surface (convex or concave) and the milling parameters affect the value of the defects. Increasing the number of points improves the accuracy of the values.

Based on the measured data, I have found that there is a limit to the number of points above which the surface profile error value increases only slightly, and this is the minimum value to be used in the measurements. The experiments show that this value is independent of the sampling methods considered.

3. Tézis

I have verified that the surface roughness of concave workpieces is better than that of convex workpieces by smooth milling experiments on free-form surfaces curved in one direction with a ball-end mill. This tendency is not influenced by the value of feed per tooth or the size of the side step (tooth width).

However, the surface roughness value is strongly influenced by the surface normal vector and the relative position of the tool axis. Where the vector is parallel to the tool axis (horizontal surfaces), the worst roughness values are found, because the contact between the ball-end milling cutter and the workpiece is smallest in surface area and tool diameter.

The roughness value is significantly influenced by the toolpath direction, so by choosing the correct toolpath direction, the surface roughness can be improved (test parameters: n = 5100 rpm; Dc = 10 mm; vf = 1650 mm/min; ap = 0.3 mm; fz = 0.08 mm; ae = 0.35 mm;)

4. Tézis

Using smooth milling experiments on free-form surfaces curved in one direction with a ball-end milling cutter, I have verified that the dimensional error varies with the toolpath direction, but is significantly affected by the nature of the surfaces. The experiments carried out show that the radius is larger than the nominal value for concave specimens and smaller than the nominal value for convex specimens.

The machining parameters and the scanning mode (toolpath strategy) have less influence on the dimensional accuracy than the nature of the surface in the case of triaxial machining (test parameters: n = 5100 rpm; Dc = 10 mm; vf = 1650 mm/min; ap = 0,3 mm; fz = 0,08 mm; ae = 0,35 mm;)

5. Tézis

I found that the surface profile error and the surface surface cilindricity are sensitive to the nature of the surface when testing the accuracy of a freeform surface milled with a ball milling cutter (test parameter ranges: Dc = 10 mm; ap = 0.3 mm; fz = 0.08-0.16 mm; ae = 0.15-0.35 mm.)

The value of the profile error is strongly influenced by the machining direction (scanning direction), as well as the feed rate and side step. For the same geometry, convex surfaces have a lower geometric error. For convex and concave specimens, the deviation can be up to twice as large.

Based on these tests, I found that the milling direction has a greater effect on the shape accuracy than the milling parameters. This is due to the distortion of the geometric relationships resulting from the nominal cutting parameters due to changes in surface and feed direction.

6. Tézis

I have demonstrated by milling experiments on free-form surfaces that the resultant cutting force and the individual force components (axial, feed direction, perpendicular to the feed) vary greatly during the machining process and that the change in resultant force is followed by a change in the geometric accuracy of the milled surface, but that the change in force is different from the change in theoretical mean chip thickness. For convex workpieces, the cutting force is higher and the force reaches its maximum value in the horizontal surface sections (test parameter ranges: Dc = 10 mm; ap = 0,3 mm; fz = 0,08-0,16 mm; ae = 0,15-0,35 mm).

I have shown that the force momentum can be used effectively to compare the effect of changes in force and machining time caused by machining parameters. The change in resultant force is determined not only by the change in chip cross-section, but also by the conditions of the actual machining section of the tool. When the tip of the tool is involved in the machining operation (surfaces close to horizontal), the cutting force increases significantly, together with the deflection.

Based on experimental results, I suggested that for smooth machining of free-form surfaces with a ball-end tool, a milling strategy should be chosen in which the tool tip is least involved in the machining to reduce cutting forces and misalignment. When determining the cutting force by calculation, the position of the tool's working section must be taken into account in addition to the chip cross-section, as this has a significant influence on the cutting force.

5 The potential of the results

In my PhD thesis, I carried out a theoretical and experimental investigation of the machining of free-form milled surfaces. The research investigated the causes of the geometrical accuracy of machined surfaces from a technological point of view, so that the results can be used in this field.

As a result of my research, I have identified correlations and conclusions that can be used in industrial practice and applied in process design. These provide a basis for the fast determination of the theoretical chip thickness, which is necessary for the estimation of the cutting force and the resulting surface profile error. The results will support the selection of the appropriate CAM motion strategy and the correct choice of the parameters that define the tool path, taking into account the surface tolerances.

There is potential for future research in several areas:

- Extending the regression model based on the CAD model to take into account the depth of cut and tool diameter.

- Detailed investigation of the effect of machining parameters on surface shape error.

- Development of a simulation application based on the mathematical model built using the experimental results, able to estimate the surface deformation deviation taking into account the surface shape, the cutting parameters and the tool path.

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7 Publication list

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[S-1.] Varga B., Mikó B. (2017) Szabad formájú mart felületek érdességének változása a simítási irány függvényében. International Engineering Symposium, IESB2017. (magyar nyelvű konferencia előadás és absztrakt)

[S-2.] Mikó B., Varga B. (2017) Forgácsolási paraméterek hatása gömbvégű maróval mart sík felület érdességére. International Engineering Symposium, IESB2017. (magyar nyelvű konferencia előadás és absztrakt)

[S-3.] Varga B., Mikó B. (2018) Curved surface roughness and cylindricity. Development in Machining Technology – Scientific Research Report Vol.8 pp.66-75 Ed.: W. Zebala, I. Manková; Cracow University of Technology, Cracow 2018. ISBN 978-80-553-2718-1 (idegen nyelvű konferencia cikk)

[S-4.] Varga B., Mikó B. (2018) Szabad formájú mart felületek érdességének változása a simítási irány függvényében. Bánki közlemények 2 pp. 85-90., 6 p. (magyar nyelvű folyóirat cikk)

[S-5.] Varga B., Mikó B. (2018) Investigate of geometric accuracy of free-form surface profile. Multiscience XXXII. MicroCAD International Multidisciplinary Scientific Conference, Miskolci Egyetem Paper D2, 8 p. (idegen nyelvű konferencia cikk)

[S-6.] Varga B., Mikó B. Zebala W. (2019) The Effect of the Feed Direction on the Micro- and Macro Accuracy of 3D Ball-end Milling of Chromium-Molybdenum Alloy Steel. Materials 12(24) p. 4038 (idegen nyelvű folyóirat cikk, Q2 IF3,057)

[S-7.] Varga B., Mikó B. (2019) Felületi érdesség változása szabad formájú felület marása során. Proceedings of the Engineering Symposium at Bánki (ESB2019) Óbudai Egyetem 94 p. pp. 49-54. (magyar nyelvű konferencia cikk)

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[S-9.] Varga B., Mikó B. (2022) CAD modelling of the chip shape in case ball-end milling. Engineering and IT Solutions 3(2) pp.30-38 doi:10.37775/EIS.2022.2.3 (idegen nyelvű folyóirat cikk)

[S-10.] Varga B., Mikó B. (2022) The effect of the point sampling to the result of coordinate measuring of free-form surface. Cutting & Tooling in Technological Systems

(Rezanie i instrumenty v tekhnologicheskih sistemah) (ISSN 2078-7405) 96 pp.89-98 doi: 10.20998/2078-7405.2022.96.10 (idegen nyelvű folyóirat cikk)

[S-11.] Varga B.; Mikó B. (2023) Investigation of the cutting force and surface profile error when free form milling. Acta Technica Jaurinensis, 16(1):27-33, 2023 DOI: 10.14513/actatechjaur.00685 (idegen nyelvű folyóirat cikk)

[S-12.] Varga B.; Mikó B. (2023) Regression model of uncutted chip thickness when ball end milling. Proceedings of Development in Machining Conference - DiM 2023 ; Crakow, Poland 27-28.04.2023. Development in machining technology 11:xx-xx Ed.: W. Zebala, I. Manková; Cracow University of Technology, Cracow 2023 (megjelenés alatt) (idegen nyelvű konferencia cikk)

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[S-5.] Mikó B., Tóth B., Varga B. (2017) Comparison of Theoretical and Real Surface Roughness in Case of Ball-End Milling. Solid State Phenomena 261 pp. 299-304., 6 p.

[S-6.] Mikó, B., Horváth, T., Varga, B. (2018) Cusp height and surface roughness in z-level milling. Development in Machining Technology – Scientific Research Report Vol.8

[S-7.] Czifra Gy., Varga B. (2018) Modern Teaching Methods in Today's Engineering Education. Konferencia Pécs