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Kinematic simulation to investigate the influence of the cutting edge topography when ball end micro milling

Katja Klauer[a,*,1], Nicolas Altherr[a,1], Matthias Eifler[b,c], Benjamin Kirsch[a], Volker Böß[d], Jörg Seewig[b], Jan C. Aurich[a]

[a]Institute for Manufacturing Technology and Production Systems, Technische Universität Kaiserslautern, Gottlieb-Daimer Str., 67663 Kaiserslautern, Germany
[b]Institute for Measurement and Sensor-Technology, Technische Universität Kaiserslautern, Gottlieb-Daimer Str., 67663 Kaiserslautern, Germany
[c]IU University of Applied Sciences, Juri-Gagrin-Ring 152, 99084 Erfurt, Germany
[d]Institute of Production Engineering and Machine Tools, Leibniz Universität Hannover, An der Universität 2, 30823 Gabsen, Germany
[1]These authors contributed equally

* Corresponding author. Tel.: +49-631-205-3386; fax+49-631-205-3238. *E-mail address:* katja.klauer@mv.uni-kl.de

Abstract

During the ball end micro milling of material measures, the cutting edge topography is imaged on the machined workpiece. The influence of the chipping on the resulting surface quality is much more dominant than other kinematic effects. In this simulative study, a model is built that is able to predict the correlation between the cutting edge topography and the resulting workpiece topography. Thus, the mentioned correlation can be investigated without overlaying effects of material separation or measurement uncertainties, which are unavoidable in an experimental study. The model has been validated based on four artificial chippings.

Keywords: micro milling, cutting edge topography, kinematic simulation, dexel model

Nomenclature

AC	Artificial chipping model
D_{eff}	Effective cutter diameter
f_t	Feed per tooth
$\Delta\varphi$	Angle that is exceeded in one simulation time step
n	Spindle speed
v_f	Feed rate
Rt	maximum peak-to-valley height (difference between highest peak and deepest valley of the simulated/theoretical calculated profile without filtering)
Rt_{sim}	simulative determined Rt-value
Rt_{theo}	theoretical Rt-value (approximation)
$std(\cdot)$	standard deviation
t_{sim}	Simulation time step
VM	Verification model

1. Introduction

In previous experimental studies, the authors investigated the manufacturing of areal material measures using ball end micro milling [1,2]. Due to increasing accuracy of modern measuring instruments, the highest demands are placed on the dimensional accuracy of the manufactured structures and on the short-wavelength roughness along the respective structures. In the experimental tests using single edged ball end micro mills, it was noticed that dominant characteristic structures occur in feed direction (figure 1a), 1b) & 1c)).

The commonly used tilt angle between the ball end mill and the workpiece in micro milling, causes the tool to only engage the workpiece with a specific area of the cutting edge (see figure 1d)). The topography of this area of the cutting edge is then imaged on the resulting workpiece surface. This means that the quality of the resulting workpiece surface is directly

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dependent on the topography of the cutting edge [3]. The kinematic structures in feed direction are due to the tool shape, as well as the cutting edge topography and overlaid by non-kinematic effects of material separation [4]. The topography of the cutting edge is determined by the cutting edge preparation and is changed during the cutting process by wear [3]. In experiments, the influences of chipping on the resulting surface quality cannot be fully separated from influences caused by chip formation or material separation. When observing the tool itself, chipping is very difficult to measure because the tools are very small, have steep flanks and, in the case of diamond, do not sufficiently reflect incident light from optical measuring instruments. The physical limitation even of high-resolution optical surface topography measuring instruments are spatial wavelengths in the scale of a few micrometers [4].

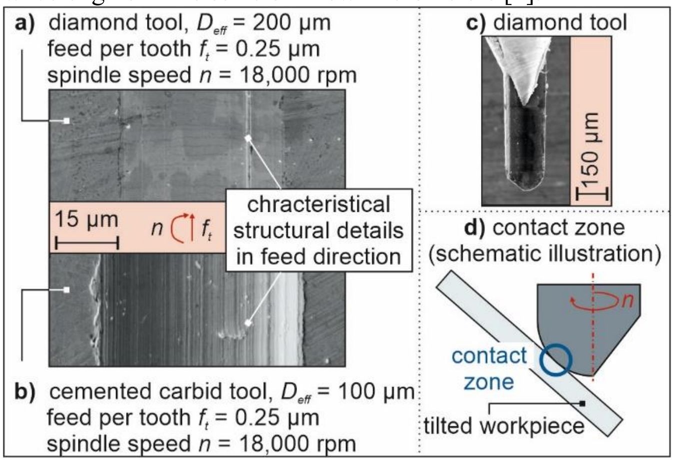

Figure 1: kinematic substructures influenced by the cutting edge topography

As it is not possible to separate the effects that can be attributed to the mechanisms of material separation or measurement uncertainties, kinematic simulations will be applied. Thus, it is possible to separately evaluate the influence of tool cutting edge topography on the resulting workpiece surface. Since no material deformation is considered, it is a purely kinematic simulation, unaffected by disturbances such as temperatures and forces. Within this study a simulation model was designed which can be used to examine the effect of cutting edge topographies on the workpiece surface in further studies. The aim of the present study was to implement and validate the kinematic model by comparing properties of the resulting surface topography with analytical estimations of the kinematic roughness.

2. Kinematic modelling – state of the art

The theoretical kinematic roughness for ball milling in the feed direction is geometrically approximated using the following formula [5, 6]. Here, effects such as spindle speed or depth of cut are not considered.

$$Rt_{theo} = \frac{D_{eff}}{2} - \sqrt{\frac{D_{eff}^2 - f_t^2}{4}} \tag{1}$$

When the actual kinematics of the milling process need to be investigated in three dimensions, kinematic simulations are used [7]. Although these simulations better represent the kinematics, they often use simplified tool models [8]. In most cases, either the rotational body of the milling tool or an ideal cutting edge [9] is considered. When simulated results are compared with experimental results, differences occur. These differences can be quantified, for example, by stochastic components [10], which can be iteratively adapted to the simulation. Especially in the field of conventional milling, the investigations of Lavernhe et al. showed, that the simulation results could be more realistic in comparison to the experiments if cutting edge chipping is considered [11]. For conventional milling tools the cutting edge can still be resolved with common measuring instruments [11]. In the field of micro milling, the measurement of the cutting edge chipping is a great challenge: usually the topography of the cutting edge can only be imaged with a scanning electron microscope [12, 13], which does not provide quantitative data.

The dexel model [14] is suitable for the investigation of the surface topography due to its data structure. For a kinematic simulation with dexel discretized workpieces, the simulation software IFW CutS (developed at the Institute of Production Engineering and Machine Tools, Hannover) is suitable. As it is a discrete simulation environment, only the state after a time step is calculated in the classical way [15]. For a rotating tool a certain angle is exceeded per time step. Subsequently the material to be removed is calculated at the new tool position. The relationship between the time step and the angle can be calculated using the following formula [16, 17]:

$$t_{sim} = \frac{\Delta\varphi}{n \cdot 360\,°} \tag{2}$$

More reliable results are possible when the calculation of swept volume [18] is activated within the simulation. With the swept volume, the connecting lines between two states of the corresponding time steps are calculated for all nodes of the tool [18, 19]. The methodology is subsequently applied to design a simulation model that kinematically matches the experimental micro milling process.

3. Model design for present task

The simulation was built in the software IFW CutS and was adapted to the experiments. The tilt angle between workpiece and tool was adjusted by tilting the workpiece and the cutting parameters were selected according to previous experiments ([2], [20]).

3.1. Tool model

The aim of this study was to investigate the influence of the cutting edge topography on the workpiece surface. Due to the small size and the steep flanks, cutting edge topography cannot be reliably measured with common optical measuring instruments. In addition, the transparent diamond tool causes problems with optical measuring instruments. Therefore, artificial cutting edge chippings were defined in the simulation. To achieve a model with realistic assumptions, geometrically well-defined and repeatable topographies were used to set up the simulation.

Four tools (cutting edges) were designed in CAD software and one additional tool was imported via a CSV file (see figure 2). All discrete tool models have in common that an ideal

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sphere shape is never imaged since an exact analytical sphere model cannot be mapped within a computer having limited memory: This leads to a tool model that is discretized depending on the type of import, associated with the import tolerances. In all models used the ideal sphere shape is approximated by secants. This interpolation of the shape is defined as artificial cutting edge chipping (see figure 3) within this study.

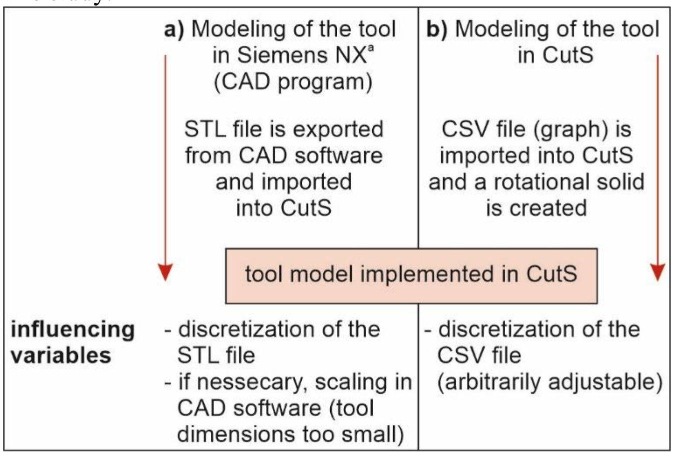

Figure 2: different methods for implementing the tool in CutS

The benefit of this artificial chipping caused by the discretization is the opportunity to specifically manipulate this interpolation.

In the standard setup of the CAD software used (Siemens NX 1904[a]), it is not possible to design in the required small dimensions of the tools (nominal diameter: 200 µm). Therefore, a scaling of the model was necessary. By default, the tool was modeled 1,000 times larger: in the dimension of 200 mm. The tool was then scaled down to its real size in CutS. In the used CAD software, the maximum resolution of the STL file export is limited by the input of the tolerances. The tolerances for model *AC1* to *AC3* were all set to the minimum value in NX[a] for the STL export: angular tolerance 1°, edge tolerance 0.0025 mm. However, the different scaling resulted in differences in meshing when the tools were all scaled back to their real size. Therefore, the three models *AC1* to *AC3* have different numbers of facets and different distances between the facet boundaries (see table 1).

Table 1: Properties of tool models *AC1 – AC3 designed in NX[a]*

Tool model	Scaling factor	Number of facets	Distance between two boundary lines / µm
AC1	100	6,896	1.7453
AC2	1,000	20,138	0.9942
AC3	10,000	195,666	0.3161

The last model *AC4* was performed by importing calculated points (profile curve) of the theoretical ball shape in CutS. In analogy to *AC2,* all these points have a distance of 1 µm to each other. After importing the profile, it was rotated in CutS to generate a volume. Under consideration of the scaling, the tolerance of rotation was set to $2.5 \cdot 10^{-3}$ mm, according to the STL export of the other models. Opposite to the tool generated in NX[a], this model only contains the cutting edge. However, it leads to a well-defined meshing and finer cross connections.

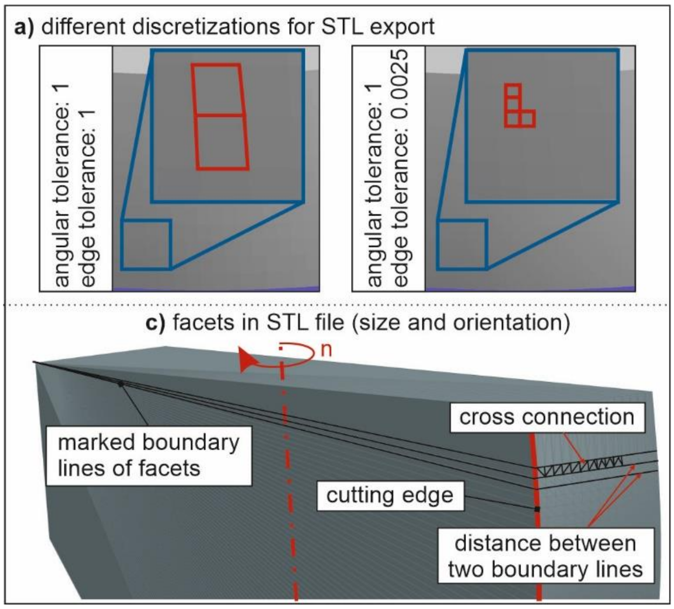

Figure 3: different tool discretizations within STL files

3.2. Workpiece model

To investigate the resulting topography of the workpiece, the simple dexel model, where dexels were only oriented in one direction was suitable. Since height differences of the topography of the workpiece (roughness parameter *Rt*, see nomenclature) were considered, the dexels were oriented perpendicular to the workpiece surface. The resulting data structure of the cut dexel then corresponds to the data structure of an experimentally measured surface.

A cuboid was selected as workpiece geometry and a translational axis was assigned, which enables the feed motion of the workpiece, similar to the experimental setup. In the simulation, only a single slot was considered. In kinematic simulations without environmental influences all slots with the same cutting depth are expected to be equal.

The workpiece width has been set so that the entire penetration of the milling tool could be simulated for a cutting depth of 1.159 µm. Considering the given cutting depth and the sphere shape of the tool, a geometrically necessary workpiece width of 30.4 µm was calculated.

3.3. Dexel discretization and simulation time step

All simulations were calculated with swept volume. The swept volume resolution was set to the value 1. This means that the tool positions between two consecutive time steps are interpolated without intermediate calculation points. Due to the high number of facets (see table 1) this procedure is essential. In preliminary investigations it was figured out that simulations without swept volume do not lead to meaningful results.

Throughout the simulation a distinction concerning the dexel resolution was made between two spatial directions. This difference was made because different effects occur in the two directions (see figure 4):

- In feed direction: The kinematic roughness caused by the feed per tooth is depicted on the workpiece surface (shown elevated in figure 4: profiles on the blue plane). The dexel grid has a distance between two dexels of 10 nm in this direction. The wavelength of the kinematic roughness is equal to the feed per tooth. The feed per tooth was varied in the simulations from 0.25 µm to 1.0 µm. Therefore, the chosen dexel mesh contains enough dexels in a wavelength of the kinematic roughness even under the consideration of the Nyquist sampling rate.

- Perpendicular to feed direction: Due to the position of the contact zone between tool and workpiece (figure 1d), the cutting edge topography leads to scratches on the workpiece surface in feed direction. Thus, surface profiles perpendicular to the feed direction depict the tool shape and the cutting edge topography (profiles on the red plane in figure 4). To map these effects, a coarser discretization in this direction was sufficient: the distance between two dexels was set to 40,5 nm. A discretization as fine as in feed direction was not possible due to limited computational resources. The coarser discretization was suitable because it was known from the preliminary experimental tests that the cutting edge chipping is of a larger order of magnitude than the kinematic roughness.

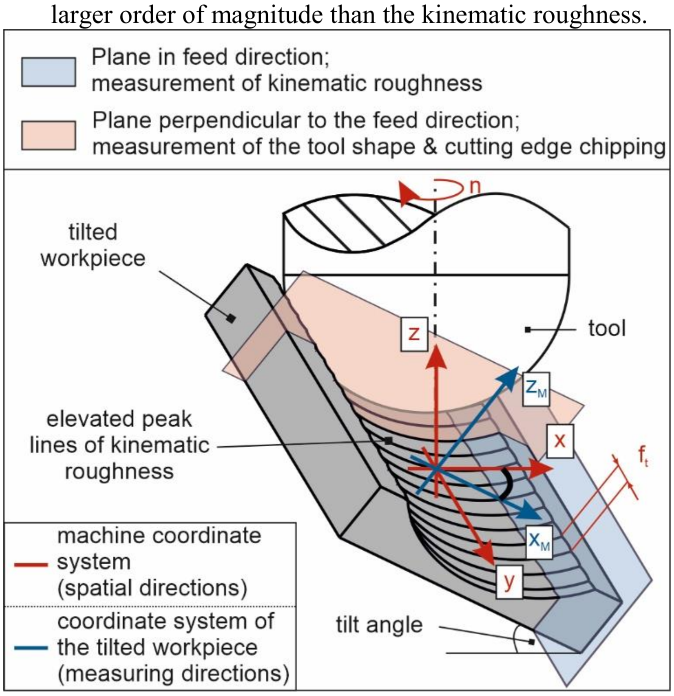

Figure 4: coordinate systems for the simulation model

3.4. Verification of the simulation model

For the verification of the model the simulated kinematic roughness was compared with the theoretically calculated kinematic roughness (equation (1)). A reliable comparison with experimental data is not possible because the relevant features of the machined surface cannot be measured with optical measuring instruments due to their small lateral scales down to the sub-micrometer range and amplitudes even in the sub-nanometer range. Additionally, kinematic effects are overlaid with effects of material separation in the experiments and cannot be separated.

Different cutting parameters were tested for the verification (see table 2).

Table 2: parameters for the different verification models

Nomenclature	*VM1*	*VM2*	*VM3*	*VM4*
f_t / µm	1.00	0.50	0.25	0.25
n / rpm	30,000	53,000	75,000	30,000
v_f / (mm/min)	30.00	26.50	18.75	7.50
t_{sim} / (10^{-8} s)	6.6	3.7	2.7	6.6

The same model was used for all simulations for verification:

- Tilt angle 20 °
- Tool model: tool designed in CAD software (1,000x scaling for STL file and backscaling to real size in CutS)
- Dexel only in z_M-direction; Dexel mesh (number of dexels in feed direction x number of dexels perpendicular to feed direction): 200 x 750; workpiece size (in feed direction x perpendicular to feed direction): 30.4 µm x 2 µm

The computing time for one simulation was about two days.

First, the resulting profile sections were considered (see figure 5a)). The course of the kinematic roughness looks as expected and the distance between two peaks is equal to the feed per tooth. The feed per tooth is the dominant wavelength which can also be seen from the discrete Fourier transform (figure 5b)). Also, the height difference between peak and valley corresponds very well with the calculated theoretical value (equation (1)) of 0.312 nm for the middle of the profile section. The slight deviations from the theoretical value are mainly due to the discretization of the tool and also, to a very small extent, due to superposition of the translational and rotational motion, which is not considered in the approximation formula (1).

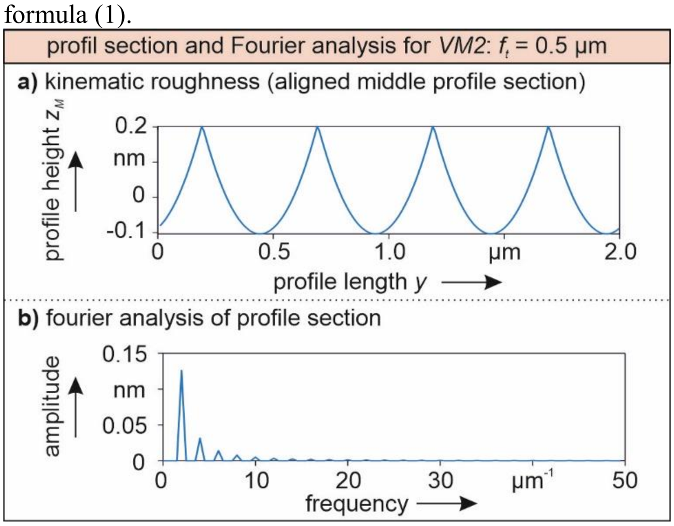

Figure 5: surface profile of a simulated kinematic roughness and Fourier analysis of the profile

To perform a quantitative comparison for all *VM*-models, the maximum peak-to-valley height *Rt* (see nomenclature) was considered. The peak-to-valley height depends on its position in x_M-direction within the slots. Therefore, the mean values and the standard deviations of *Rt* for both, theoretical roughness and simulated roughness were calculated (see table 3). This means that all 750 profile sections, resulting from the number of dexels, were considered in the numerical data Rt_{sim}. For the theoretical data Rt_{theo} (equation (1)) 17 profile sections were regarded with discretization in 1° steps along spherical contour.

Depending on the angle, the effective radius changes, which is used in equation (1).

Table 3 shows that the model used imaged the kinematic roughness very well. The deviations of the absolute values can be justified by the discretization of the tool. The models *VM3* and *VM4* should actually have the same roughness parameter values. If all roughness parameters *Rt* are considered for all 750 profiles, it is noticeable that one extreme outlier occurs with *VM4*. This outlier clearly affects the mean value and the standard deviation of Rt_{sim}. It is assumed that two planes intersect at this point, which are almost parallel to each other. This phenomenon occurs when different orders of magnitude are considered in one simulation (tool diameter 200 µm, dexel discretization < 50 nm, tool discretization nm- to µm-range). In general, however, the two mean values for *Rt* for *VM3* and *VM4* are very similar with a deviation of < 0.02 nm, so that a good agreement can be assumed. The model is therefore verified.

Table 3: numerically determined roughness compared with theoretical values

Simulation	Theoretical values		Numerical values	
	Rt_{theo} / nm	std (Rt_{theo}) / nm	Rt_{sim} / nm	std (Rt_{sim}) / nm
VM1	1.255	0.004	1.131	0.300
VM2	0.314	0.001	0.310	0.075
VM3	0.078	0.000	0.100	0.325
VM4	0.078	0.000	0.087	0.066

4. Simulation of cutting edge chipping

The cutting parameters (f_t, n and v_f) and the simulation time step t_{sim} were equal to *VM4* (see table 2). Also, the remaining parameters workpiece size, number of dexels and tilt angle, were set constant and were equal to those in the verification models (see section 3.4).

Before the investigations were carried out with real cutting motion (superposition of translational and rotational motion), a simplified simulation was performed: The model with standard scaling (1,000x scaling) was moved through the workpiece purely translational (see figure 6a)). Here, the distances of the polygon boundary lines are imaged on the workpiece.

In the simulation of the real motion, in which the translational and rotatory motion are overlaid, the distances between the boundary lines of the facets are still visible, but in simulations *AC1* to *AC3* they are overlaid with other wavelengths. It is directly noticeable that the model with the highest scaling (10,000x) shows the finest roughness perpendicular to the feed direction. With increasing distance between two boundary lines of the facets, the roughness also increases. This observation was to be expected and thus strengthens the plausibility of the model. The other wavelengths, which are not caused by the polygon rings, within the profile section are probably caused by the cross connections within the facets (see figure 3). Depending on how the individual edges cut the dexels, numerous intersections between the individual polygon rings are created. In order to be able to consider the existing wavelengths separately, a Fourier analysis was performed (see figure 7).

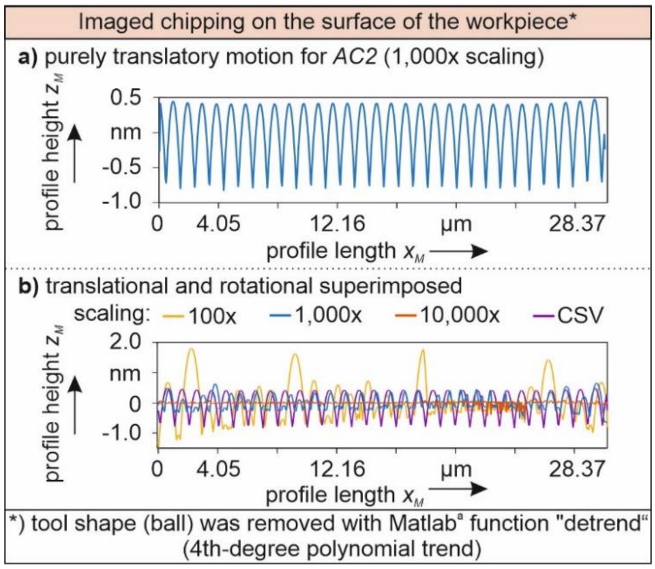

Figure 6: artificial cutting edge chippings imaged on the workpiece's surface – resulting surface topography from the simulation model.

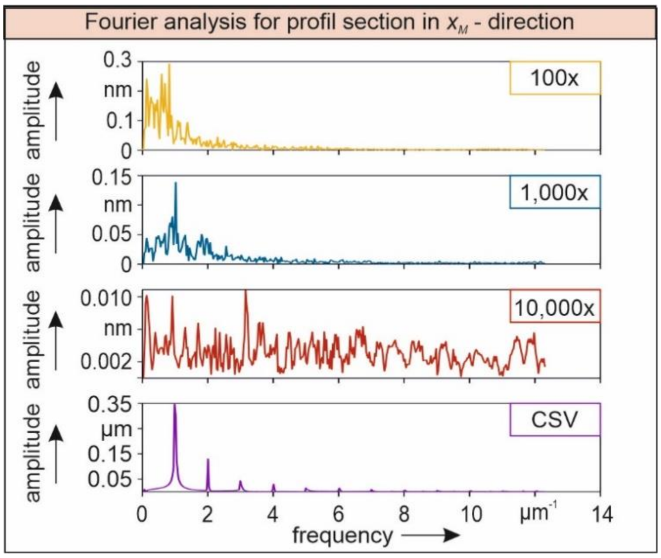

Figure 7: Fourier analysis for profile sections resulting on the surface topography when a different scaling of the tool is used in the model

For the standard model (1,000x scaling) and the finer model (10,000x scaling) the maximum amplitude in the Fourier spectrum is at the wavelength of the distance between two polygon rings. With the coarser model (100x scaling), the wavelength of the distance between the polygon rings is only the second strongest. The strongest wavelength is 1.216 µm. This wavelength probably results from the cross connections of the polygons. The profile and Fourier analysis of model *AC4* differ from the first mentioned model *AC2* (comparable meshing), even when they have the same distance of polygon rings. From the profiles it can be seen, that in *AC4* there are no overlaid wavelengths and amplitudes are higher in comparison to *AC2*. This is confirmed by the Fourier analysis which only exists of defined peaks at the wavelength of the polygon rings (1 µm). The differences are to be expected because of the finer cross connections of the model *AC4*.

In order to check the models in the other lateral direction, the kinematic roughness in feed direction is also calculated. For this purpose, the mean value and standard deviation of all 750 profile sections are calculated again (see table 4).

It is noticeable that the mean meshing (1,000x; *AC2*) leads to the results that are closest to the scale of the theoretical value (Rt_{theo} = 0.078 nm). Besides, the corresponding standard deviation of this simulation shows a low value. However, the simulation is not expected to match the exact theoretical value, since chipping is not considered within the formula.

A coarser meshing leads to more errors due to its more significant deviations from the ideal geometry of the cutting edge. However, even with very fine meshing, errors occur more frequently. These are due to other reasons: due to different orders of magnitude and the high number of cross connections artefacts occur in even greater numbers in the finer mesh. Model *AC4* is also very close to the theoretical value of *Rt* and has a smaller standard deviation than *AC2*.

Table 4: simulated roughness in feed direction and calculation time

Model	Rt_{sim}/nm	$std(Rt_{sim})$/nm	Calculation time/days
AC1	0.091	0.069	approx. 0.25
AC2	0.087	0.066	approx. 3
AC3	0.173	0.169	approx. 3
AC4	0.068	0.020	approx. 2.5

5. Conclusion and Outlook

A kinematic simulation in the software IFW CutS was built to investigate the kinematics of ball end micro milling. First, the simulation was verified on basis of the kinematic roughness in the feed direction.

For the verification model, the roughness was close to the theoretical value, but there were some outliers due to the simulation calculation which falsify the absolute values. These outliers are probably due to cross connections within the polygons of the STL file. Additionally, if very different orders of magnitude are considered, there can be intersections between two nearly parallel planes. Artifacts are created at this point. We assume that both effects occurred in the simulation.

The verified models were used to investigate the imaging of the cutting edge topography on the workpiece. Four different artificial chippings were tested, which were created by different meshing of the tool. As expected, the finest meshing, i.e. artificial chipping, led to the smallest profile amplitudes perpendicular to the feed direction. With correspondingly coarser meshes, the roughness perpendicular to the feed direction increased. The distances between the polygons on the cutting edge were also clearly visible in the profiles, which was also evident from the Fourier analysis. The smoothest profile was achieved by simulation model *AC4*.

Within this investigation, a simulation model was set up which enables to examine the kinematic influences of the cutting edge topography on the workpiece. This simulation will be applied in further investigations to consider real cutting edge topographies. Moreover, this investigation showed which challenges occur when several orders of magnitude are exceeded and how they are influenced by different meshing methods of the tool model.

Acknowledgements

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[a] Naming of specific manufactures is done solely for the sake of completeness and does not necessarily imply an endorsement of the named companies nor that the products are necessarily the best for the purpose.

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