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Parametric grinding wheel model for material removal simulation of tool grinding processes

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Abstract

Tool grinding is an essential process for the production of cemented carbide tools. In that context, the investigation of specific effects like the resulting surface profile and the fluid dynamic processes is of great interest, but requires microscopic modeling of the grinding wheel including its individual grains and bonding material. This paper introduces an approach for a parametric grinding wheel model, which provides a topography on microscopic scale depending on the grinding wheel specification and dressing conditions for subsequent use in material removal simulations. Scalable abrasive grains and variable distributions embedded in a shiftable bond layer are applied. Optical laser scans are used to derive surface parameters for an adaption and evaluation of the model. The prediction quality in terms of surface roughness is evaluated in surface grinding reference experiments.

Keywords: Grinding; Modeling; Material removal;

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1. Introduction

Grinding processes are essential for manufacturing of cemented carbide tools, as they define the geometric workpiece shape, influence the substrate properties and cause a majority of the costs. Process planning of flute, peripheral and face grinding influences the surface quality, shape deviation, surface layer properties, tool life and cutting performance of the tool significantly [1, 2].

Currently, extensive and therefore time intensive experiments are necessary to optimize process parameters, grinding wheel specifications or tool paths to achieve high quality parts in small lot sizes. To reduce the necessary time for optimization, accurate simulation methods and process models are required to predict relevant outcomes and to identify process parameters virtually [3]. Previous simulation studies have been implemented with a simplified representation of the grinding wheel to investigate the complex contact zone of the process. In this context, the material removal rate and geometric local cutting conditions were calculated [4, 5].

However, the grinding wheel topography has a significant influence on the surface quality, thermal effects and residual stresses. Thus, the grinding wheel topography should be considered in material removal simulations to allow more accurate investigations of these effects. Additionally, also bond layer modeling received little attention in previous studies, which would allow fluid dynamic simulation of cooling lubrication in the contact zone.

This paper presents a parametric grinding wheel model for microscopic and multi-scale material removal simulations in tool grinding. The aim is to investigate the microscopic scale considering typical grain sizes for further research on the quality of the curved tool surfaces.

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2. State of the art

Besides physical and empirical models as well as the finite element method (FEM), kinematic-geometrical models are used to predict the penetration of the grinding wheel into the workpiece. The large number of abrasive grains with an unknown geometry results in a complex material removal operation, which can be considered on different scales. Therefore, simulation approaches are divided in microscopic and macroscopic approaches [3].

2.1. Microscopic Approaches

In microscopic approaches, the individual shape of each grain is modeled and considered in a simulation. The grinding wheel modeling is based on statistical distributions [6] or measured grinding wheel topographies [7]. Warnecke and Zitt [8] have developed a kinematic simulation, in which the micro-geometry was investigated by modeling the topography of the grains and the back section of the bonding behind each grain. By fitting simple geometrical shapes such as octahedrons, cuboids or tetrahedrons in a randomized number of different planes, stochastic deviations from ideal crystal structure of diamond grain morphologies were modeled. Aurich et al. investigated chip parameters, dressing and process-machine interactions using such a grinding wheel model [9].

In order to analyze the loads on the bond, Li and Zhu [10] established a grinding wheel model, which consisted of modeled truncated octahedrons as grains and spherical binder elements. However, the resulting mesh-like surface of the model did not reflect the actual surface of grinding wheels correctly. Extended microscopic models of grinding wheel topographies can be used in kinematic simulations to predict the resulting workpiece surface roughness [11], the occurring process forces or the exact cutting conditions [12]. Sakura et al. also considered the effect of elastic deflections to calculate the kinematic grain behavior and to simulate the surface generation more accurately [13].

2.2. Macroscopic Approaches

Whereas microscopic approaches are focused on the grain-workpiece interaction, macroscopic simulations allow a fast calculation of the material removal, even for complex cutting conditions, e.g. in 5-axis machining or tool grinding. The information obtained from macroscopic simulation can be used to investigate the geometrical contact length or the material removal rates along the tool path and to model subsequent effects on the workpiece quality. For example, the authors could show that shape deviation in flute grinding can be compensated based on a numerical NC-simulation in combination with a dexel model and empirical models [5].

In addition to the calculation of cutting conditions, the literature describes the prediction of process temperature and occurring workpiece load. FEM-simulations by Weinart and Schneider [14] show that the choice of suitable process parameters, grinding wheel specification and process kinematics have a significant influence on the occurring thermal and mechanical workpiece loads.

2.3. Multi-scale simulation

The simulation of tool grinding is a multi-scale problem with different size and time scale effects. Multi-scale modeling approaches can also include micro-scale phenomena, which increases modelling accuracy significantly. Multi-scale simulations use locally constructed basis functions to enable a solution of the original microscale problems on a macroscale level. This reduces the computational effort compared to purely microscale approaches simultaneously [15].

In conclusion, many previous investigations on the microscopic scale were conducted for simple grinding processes. Most of them consider only a few individual grains in a kinematic-geometrical simulation. Furthermore, previous approaches investigated larger grain sizes compared to those typically used in tool grinding. The modelling of the bond layer has only been investigated rudimentarily so far. However, it could enable a detailed analysis of the contact zone and increase insight into thermal or fluid dynamic effects. Additionally, the integration of micro- and macroscopic approaches into multi-scale models offers the potential to simulate micro-scale phenomena, e.g. surface roughness, even for complex grinding processes. In this context, the article aims to investigate a parametric grinding wheel model for material removal simulations on a microscopic scale.

3. Parametric grinding wheel model

3.1. Concept

The parametric grinding wheel model predicts a topography on the microscopic scale. The topography depends on the grinding wheel specification and dressing conditions.

The grinding wheel model is characterized by four parameter categories (grain type and size, grain distribution, bond layer texture and bond layer diameter). Based on the selected parameters, a geometric model of the grinding wheel shape is generated, which can subsequently be used in a material removal simulation as the tool geometry (see Fig. 1).

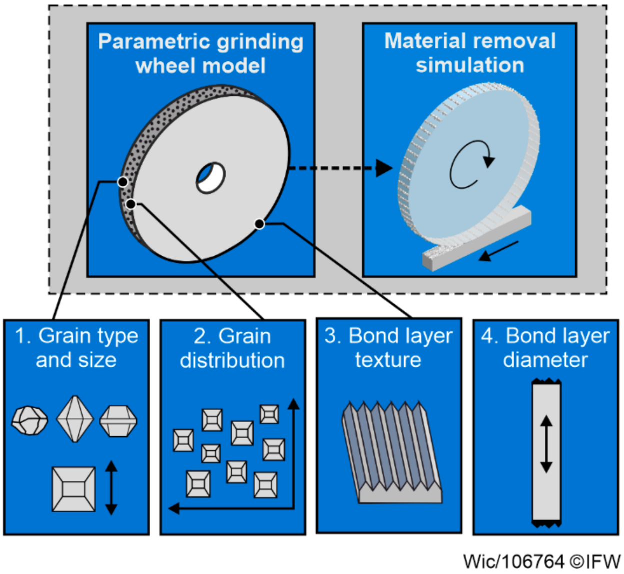

Fig. 1. Concept of parametric grinding wheel model

In order to establish a multi-scale material removal simulation for tool grinding processes, a concept for the combination of microscopic modelling and macroscopic process simulation was developed.

Both concepts were implemented using the kinematic simulation software IFW CutS [16]. The multi-scale simulation is set up using the original NC-code in a kinematic model of the tool grinding machine Walter Helitronic Vision 400 L. The workpiece is discretized using a cartesian multi-dexel model.

First, the material removal is simulated on macroscopic scale for the whole process using a simplified grinding wheel model to simulate the macroscopic geometry of the workpiece.

Secondly, an additional grinding wheel segment is added to the tool model to implement a multi-scale simulation. For that, the segment is modelled with reduced width and stochastic grain distribution on the microscopic scale. This segment should reproduce the wheel topography in a typical dressing condition.

In the next step, the macroscopic workpiece model is improved by simulating the resulting microscopic surface geometry. To reduce the necessary computing time for this process, the dexel model of the workpiece is focused just on a small workpiece element. The generated surface and calculated cutting conditions can then be transferred to the whole workpiece, as the process state is constant for most of the process time.

Fig. 2 shows the concept for the described multi-scale modelling approach. The difference between the structures illustrates how kinematic simulation on the microscale can increase the prediction quality. This concept establishes the first multi-scale material removal simulation for a tool grinding process.

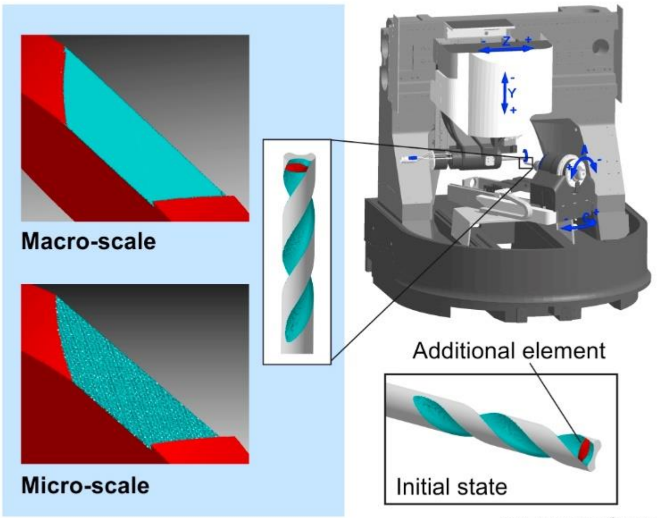

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Fig. 2. Concept of multi-scale material removal simulation for tool grinding

For the implementation of a multi-scale simulation in tool grinding, a parametric grinding wheel model is needed first. In the following, an exemplary grinding wheel analysis is shown.

3.2. Grinding wheel analysis

The model was parameterized based on optical laser scans of grinding wheel segments and derived statistical surface parameters (Ra, Sa, Sk, Spk). For that purpose, each grinding wheel was divided into five segments, whose surfaces were scanned after dressing. A selection of specifications, dressing conditions and surface parameters for the investigated grinding wheel types is given in Table 1. The arithmetic height Ra was determined based on the mean value of 3 profile evaluations.

Table 1. Grinding wheel specifications and surface parameters

Specification	Q-Flute^2	Q-Flute^2	Q-Flute EVO
Grain type	Diamond	Diamond	Diamond
Grain size	D54	D54	D33
Grain concentration	C100	C100	C100
Bond	Hybrid	Hybrid	Hybrid
Diameter [mm]	100	100	100
Truing tool	CVD disc	CVD disc	CVD disc
Dressing a_e [mm]	0.15	1	1
Dressing v_f [mm/min]	150	150	150
Arithmetic height Sa [µm]	3.84	5.46	3.63
Core height Sk [µm]	11.11	17.09	11.2
Peak height Spk [µm]	2.48	6.52	3.77
Arithmetic height Ra [µm]	2.77	4.43	2.55

It can be seen that the grain size as well as a changed dressing process by a lower depth of cut a_e have a significant impact on the surface parameters. In addition to that, measurements of the amount of grains and their mean distance were performed using a digital microscope to gain more information about the grain distribution.

The results have been analyzed visually to calculate the mean distance of the grains in horizontal and vertical direction, which can be seen in Fig. 3. The quantitative results are summarized in Table 2.

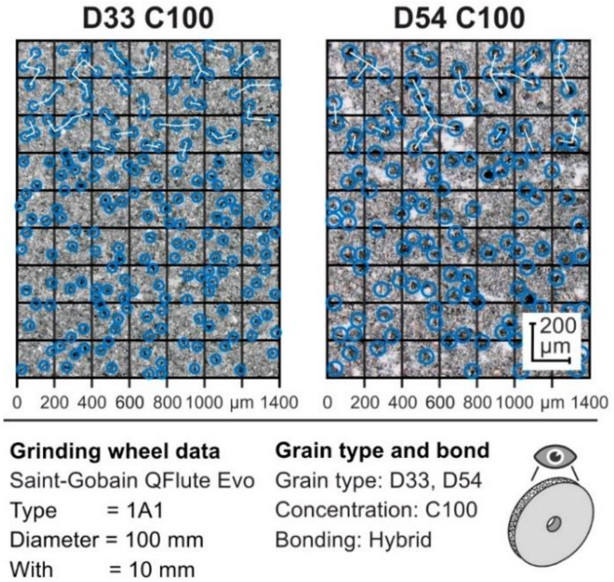

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Fig. 3. Grain amount and distance analysis

Table 2. Results of the grain amount and distance analysis

Measured value	Q-Flute^2 D54	Q-Flute EVO D33
Ø Grains on 200 x 200 µm	1.95	3.25
Ø Tangential distance [µm]	51	54
Ø Axial distance [µm]	54	73

Additionally, SEM pictures were analyzed to get a better impression of the bonding layer properties. As shown in Fig. 4, the hybrid bond, which consists of synthetic resin and metal, exhibits a rough or slightly porous structure with grooves after a few grinding passes. It can also be seen that a splintery grain was used, which supports the approach to model sharp-edged and pointed model grains.

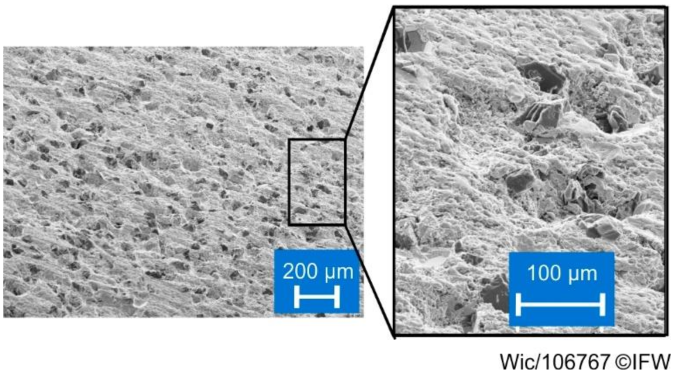

Fig. 4. Bonding layer analysis

3.3. Scalable abrasive grains in variable distributions

The shape of the abrasive grains corresponds to slightly truncated octahedrons, which are most similar to the splintery shape of the real grains. The grain size is scalable and can also be randomized in a user-specified range. This is important, because for example the typical grain size D54 for flute grinding can contain grains in a size range of 45-53 µm.

The distribution of the grains was modeled by two different approaches. First, a deterministic grain distribution was implemented (Fig. 5, left). In this case, the tangential, radial and axial distances are predefined. Nevertheless, the grain orientation and the individual grain size is randomized by a discrete uniform distribution.

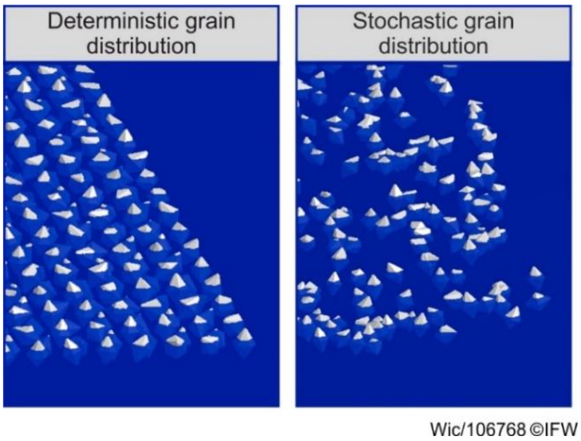

Fig. 5. Deterministic and stochastic grain distribution

For a first adaption of the parametric grinding wheel model, the measured tangential and axial distances were used for both grinding wheels, considering the individual range of grain sizes. Secondly, a stochastic grain distribution was applied. A discrete uniform distribution is used to define the tangential, axial and radial distances between the grains as well as the individual grain sizes and orientations (Fig. 4, right). Further parameters that must be defined include the number of grains, wheel diameter, angle of the segment, grinding wheel width and coating height.

3.4. Bond layer modelling

The scalable grains are embedded in a bond layer model to provide an improved representation of the entire grinding wheel surface for future studies regarding the fluid dynamics of the cooling medium or the dressing process. Previous SEM images showed that slight grooves emerged in the surface layer in cutting direction. However, these grooves are often interrupted due to grains or chipping out. Based on SEM images, it became also clear that the bond is characterized by a rough ground. In order to include the topography of the bond in the model, different metaphorical levels of complexity, which are shown in Fig. 6, were analyzed. Based on a visual comparison to SEM images, the surface structure c) (volcanic rock) was selected in further modeling.

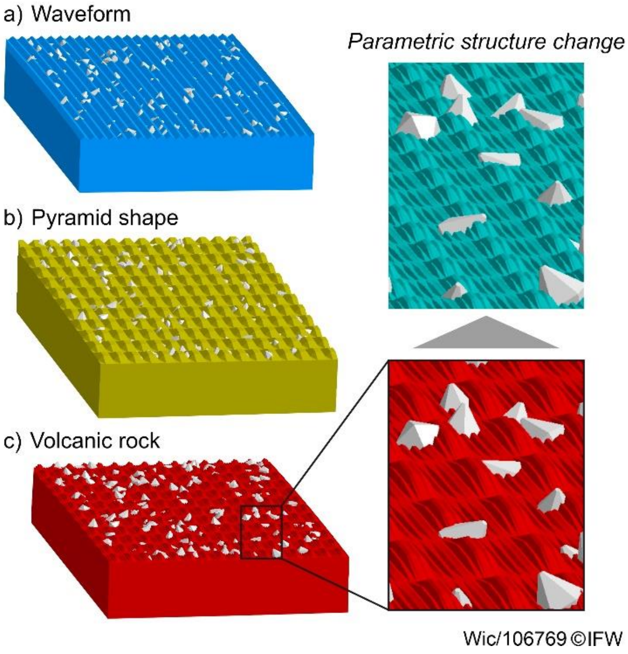

Fig. 6. Bond layer modeling

The surface profiles were generated by a script and saved in form of height data in a text file. The text file was then imported into the software IFW CutS and applied to the grinding wheel model. The grains were positioned within the shiftable bond layer afterwards. By changing the segments height or changing the diameter of the bond layer, it is possible to reproduce the dressing condition, in which the abrasive grains rise higher or lower out of the bond layer. Moreover, height and width of structures of the bond layer can be adjusted.

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3.5. Adaption by statistical surface parameters

In order to match the actual surface of the respective grinding wheel, the grain size, grain distribution and the bond structure must be parameterized accordingly. The statistical surface parameters from the laser scans (Keyence LJ-V7020 K) of the wheel segments are used to match the grinding wheel model to the measured one. The adaptation results were calculated for the D33 and D54 grain size in an industry typical dressing condition (Truing with CVD disc $v_c = 16$ m/s, dressing with corundum block $v_c = 16$ m/s, $v_f = 150$ mm/min, $a_e = 4 \cdot 1$ mm) as well as for the D54 grain size in a low-sharpened (LS) condition ($a_e = 4 \cdot 0.15$ mm).

In order to reproduce the individual condition, the correct size range of the abrasive grains were selected first. Then, the bond layer was shifted, until the grains were covered to half their size. Subsequently, the bond layer height h_{bl} was adjusted iteratively. Between each iteration, surface parameters of the modeled topography were calculated and compared to the measured ones by using an imprint in a material removal simulation. If the shift of h_{bl} was not sufficient for cases of very low surface roughness, the height of the elevations in the modeled bond structure h_{bs} was additionally reduced. This procedure was repeated until the difference of the Ra values was less than 0.1 µm to ensure that the topography corresponds to the measured dressing condition.

The deterministic grain distribution with the measured distances as well as the stochastic grain distribution were used for the investigations. The dexel density was set to 1,000 for a cuboid with a geometry of x = 0.1 mm, y = 3 mm and z = 0.5 mm. The cycle time was set to 0.005 s. Fig. 7 summarizes the results of the iterative adaption of the grinding wheel model parameters for the three grinding wheel conditions and both grain distribution approaches.

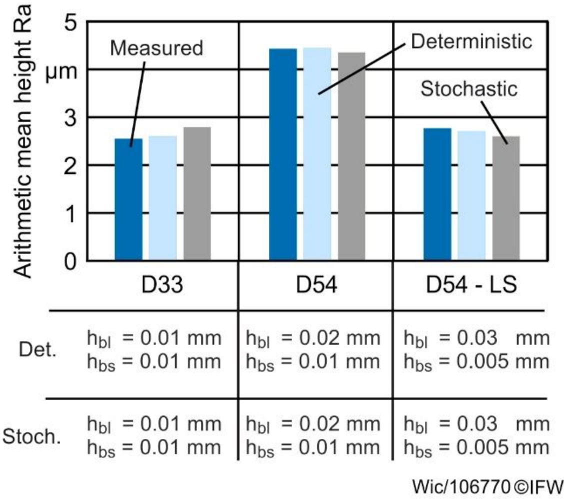

Fig. 7. Iterative adaption of the parametric grinding wheel model

4. Experimental validation

The resulting prediction quality was finally evaluated by comparing the simulated and measured workpiece roughness in surface grinding reference experiments. Therefore, cubic blocks out of cemented carbide (Tigra T10MG ISO: K10-K40) were used as workpieces. To investigate the influence of the grain size, two different grinding wheels (table 1) with the grain size D33 and D54 were analyzed. The cutting speed, feed rate and depth of cut were set to $v_c = 16$ m/s, $v_f = 100$ mm/min and $a_e = 0.2$ mm, respectively. The dressing process was carried out with the settings presented in section 3.5. The experiments were repeated three times. Fig. 8 shows the experimental setup.

The surface of the workpieces was measured afterwards with a confocal microscope to evaluate the arithmetic average roughness Ra. The average Ra value was evaluated for all workpieces (analyzed area: 800 x 350 µm). The experimental results (see Fig. 9) were compared to microscopic material removal simulation with the parameterized grinding wheel (see section 3.5). The relative differences between the simulated and measured Ra values are within 17-28%.

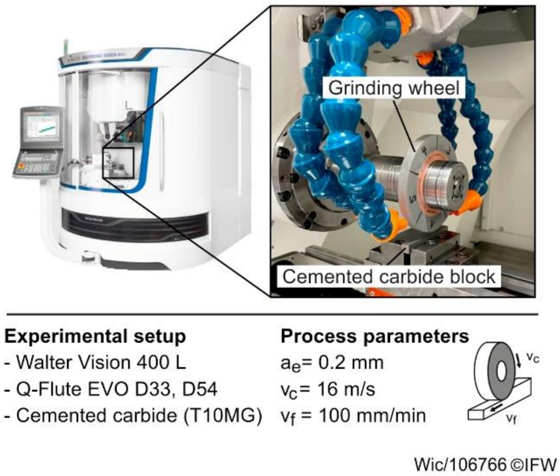

Fig. 8. Experimental setup of the validation

The remaining deviations can be explained as a result of stochastic effects and uncertainties. The kinematic simulation currently only reproduces the geometric effects. Additional effects due to material-specific chip-formation mechanisms should be taken into account by using an additional stochastic component to determine the resulting roughness. In the future, the prediction could be generated using a kinematic component from the geometric simulation and a stochastic component.

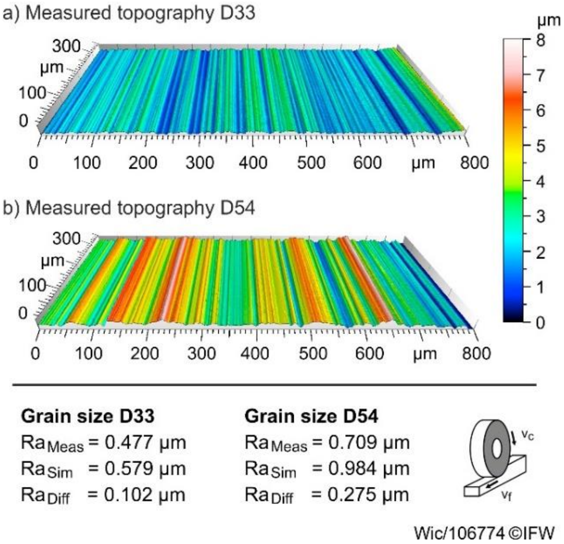

Fig. 9. Validation results

5. Conclusion and outlook

Tool grinding processes are essential for manufacturing of cemented carbide round tools, as they define the final shape and cutting edges. Currently, it is not possible to parameterize a grinding wheel model for material removal simulations on the microscale. However, this would allow further insight into the grinding process, such as fluid dynamics of the cooling medium, the resulting surface roughness or deeper understanding of force components and chip thickness in grinding. This article introduced a parametric grinding wheel model for material removal simulations on microscale. First, a concept for the parametric model was presented. The approach can be integrated into macroscopic simulations to implement a multi-scale material removal simulation. Next, the grinding wheel model was parameterized based on topography measurements of dressed grinding wheels. Afterwards, the grinding wheel models were applied in microscopic simulations of a surface grinding process. A comparison of the simulated and measured Ra values showed that the model reproduced the process conditions very well.

In future research, further analysis of the simulated surface will be carried out. Different grain concentrations and more grain sizes will be investigated to extend the applicability of the parametric grinding wheel model. Further simulation studies will also be carried out to apply the multi-scale material removal simulation in tool grinding in different cutting conditions of the grinding wheel and the workpiece. Moreover, research will be extended to fluid dynamics at the contact zone to gain insight into the thermal effects of grinding processes.

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