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Stochastic modeling of grain wear in geometric physically-based grinding simulations

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ABSTRACT

Grinding processes can be optimized by simulating the influence of individual grains on process forces and surface topographies. However, the process results are significantly influenced by tool wear. Simulating this effect allows, e.g., the prediction of necessary tool changes when manufacturing large forming tools. Therefore, a new point-based approach for modeling arbitrarily shaped grains in different states of tool wear was developed. Based on a small amount of representative wear investigations, a flexible tool model was defined, which can be used for various tool shapes without further experiments. This model can be applied for grinding processes with varying engagement situations.

1. Introduction

The manufacturing of forming tools is a large cost factor in many industrial sectors like the automotive industry. The wear-resistance of the forming tools can be increased significantly by applying thermally sprayed hard-material layers, e.g., HVOF (High Velocity Oxygen Fuel)-sprayed WC–Co coatings [1]. Due to the high surface roughness and form deviations, a subsequent finishing operation is required [2]. For this purpose, NC grinding on machining centers is a flexible solution for achieving a suitable surface finish [3].

The surface quality resulting from grinding operations depends on different parameters, e.g., grain shapes and distribution [4], but also on the tool wear. Therefore, the process design can be supported by simulation systems which allow the prediction of the resulting surface topographies. Different kinds of modeling approaches can be used to simulate grinding processes, i.e., kinematic methods, finite element analysis (FEA), molecular dynamics, analytical approaches, regression, fuzzy logic, or neural networks [5–7]. While FEA is, for example, used to simulate the complex chip formation of one single grain, geometric physically-based simulation systems [8] are required when the influence of all abrasive grains of a grinding tool on the process results, e.g., the resulting process forces and surface topographies, should be analyzed [9]. By taking the shape of individual grains based on measurements into account, thermo-mechanical effects and surface topographies can be predicted [10]. In order to model the tool wear in such simulations, the shape of the worn grains has to be considered [11]. For this purpose, geometric models, e.g., heightfields or triangle meshes [9,12], can be used to define arbitrary grain shapes.

At the TU Dortmund University, a simulation system based on the Constructive Solid Geometry (CSG) technique was developed [13], which allowed modeling the grain shapes simplified as the intersection of a hexahedron, an octahedron, and a tetrahedron. The workpiece surface, which changes due to the material removal process, was modeled by heightfields, assuming there were no undercuts. The movement of the grinding tool was determined by interpreting NC programs according to the kinematics of the machine tool. For each revolution of the tool, discrete simulation steps were defined. This approach allowed the calculation of the material removal process efficiently by reducing the height values of the workpiece model in each simulation step. Based on the resulting undeformed chip shape, process forces could be simulated using empirical force models [13].

However, the applicability of the CSG-based approach to model worn grains is limited, since the complexity of their shapes is significantly increased. In this paper, a new modeling approach is presented which utilizes the results of representative wear experiments to define a stochastic, wear-dependent grain model. This can be used to predict the surface topographies and process forces resulting from grinding processes with different states of tool wear. The new process model is based on point clouds for describing the grain shapes and is presented in detail in Section 2. In order to validate the simulation approach, it was calibrated for an exemplary grinding process as shown in Section 3 and applied to a grinding operation with varying engagement

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situations (cf. Section 4). Conclusions and an outlook for future investigations are given in Section 5.

2. Wear-dependent point-based model

The new simulation approach comprises a wear-dependent description of the grinding tool and an adapted process model as described in the following sections. The workpiece was represented by a heightfield.

2.1. Stochastic, wear-dependent tool model

In order to allow a flexible description of the complex grain shapes resulting from tool wear, a model based on unstructured point clouds was developed and used in the presented simulation system (c.f. Section 1). These point clouds were initialized by the results of experimental grinding investigations (c.f. Section 3). In Fig. 1a)–c), an electroplated grinding tool with B181 cBN grains is exemplarily shown. The measurements were conducted at different states of tool wear, where a new tool is labeled as "0%". "100%" corresponds to the end of tool life which was defined by the first occurrence of scratch marks in the bonding. From these measurements, 80 individual grains were extracted by thresholding and clustering the result as shown in Fig. 1d. For each of these grains, a point cloud was generated from the measurement information (Fig. 1e). Due to the high density of the resulting point clouds (approximately 10,000 points per grain), only a simplified subset of approximately 200 uniformly distributed points was used for the final model (Fig. 1f). Since a large number of points is required to model all grains on a grinding tool (3312 grains in the presented investigations), a database of 80 representative grains was created, which was used as a wear-dependent stochastic grain model in the simulation system. By using a sufficient amount of grains, this model comprises the stochastic distribution of the different wear mechanisms (76.92% abrasion and splintering, 21.54% almost unchanged grains, and 1.54% pullouts). Two exemplary grains from the database are shown in Fig. 1a)–c). This way, all 3312 grains on the tool could be modeled without storing the shape of each grain explicitly, using a limited amount of 80 grain shapes. The stochastic grain model can be used to simulate grinding tools with the same type of grains and bonding, but with arbitrary shapes, e.g., spheres or cones, without conducting further experiments. Different tool diameters can be modeled as well using the same grain database by distributing instances of grains from the database randomly on the surface of the tool. In order to ensure that there is no overlap between the grains and that the density of the distribution is homogeneous, a poisson-disk sampling [14] was used to position the grains according to the specifications of the tool. A generated distribution of grains for a cylindrical tool with a diameter of $d = 12$ mm and a width of $h = 8$ mm is shown in Fig. 2a. For each generated grain, the shape was chosen randomly from the database with uniform probability. This way, each grain shape was used multiple times, but its point cloud had to be stored once only. To reduce any repetitive patterns, each grain instance was rotated randomly around its normal direction. The resulting tool model is shown in Fig. 2b.

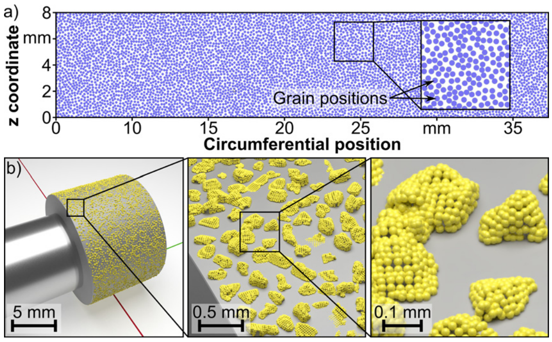

Fig. 2. Distribution of grains on a cylindrical tool using poisson-disk sampling (a) and the resulting point-based tool model (b).

2.2. Process model and calculation of process forces

In each simulation step of the time-discrete simulation system, the tool was moved and rotated according to the process parameters and the engagement situation was analyzed for each grain individually by calculating the intersection between the grain and the workpiece material. For the presented investigations, 360 steps per revolution were chosen, resulting in a relatively large movement of each grain between two simulation steps in order to reduce calculation time and discretization artifacts. To interpolate between these positions, a sweep volume was generated by duplicating the point cloud of the grain at multiple substeps as shown in Fig. 3a. In order to represent the sweep volume, a heightfield (called "sweep heightfield") with the same dimensions and resolution as the workpiece heightfield was created. Each point of a grain at different substeps was projected on this sweep heightfield and the maximum height value of all points in the same cell was stored. This is visualized in Fig. 3b. In most cases, there are some cells without any point and some cells are only containing points of a substep within the sweep volume. In order to fill these gaps, morphological filtering operations [15] were applied to the sweep heightfield, comprising an erosion and a dilation step. The result is shown in Fig. 3c. The material removal process was modeled by subtracting the sweep heightfield from the workpiece model by calculating the minimum height value for each cell.

In order to calculate the process forces in normal (F_n) and tangential (F_t) direction [16], the undeformed chip area was calculated for each grain in every simulation step. This was achieved by projecting the engaged points onto a plane with a

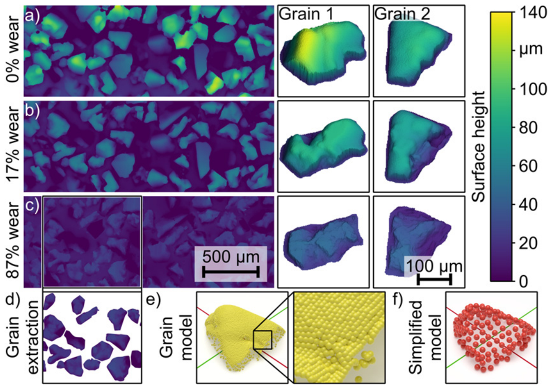

Fig. 1. Measured sections of an electroplated grinding tool with B181 cBN grains in three different states of tool wear (a, b, c). (d) Exemplarily extracted grains modeled as point clouds (e), which were simplified to reduce memory usage (f).

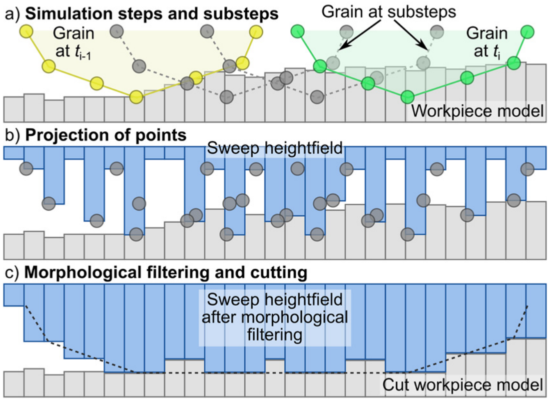

Fig. 3. Simulation step of the process model comprising a generation of substeps (a), the projection of points onto a sweep heightfield (b), and morphological filtering for interpolating between the points (c).

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