Simulation of Surface-Microstructures Resulting from Milling Processes

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Abstract

In addition to the prediction of whether a milling process is free of chatter or not, the resulting surface quality is of importance. This paper presents geometric models of the machined workpiece in order to predict the surface microstructures of the peripherally milled flank structures as well as the surface resulting from the slab milling process with end-mills. After a brief explanation of the time domain simulation system used to calculate the tool vibration patterns, a surface model is presented which is able to predict the roughness depending on the spindle speed. Results show that the best surface quality is achieved by milling with spindle speeds which are slightly lower than at the stability maxima.

Keywords:
Milling simulation, chatter, surface modeling

1 INTRODUCTION

For technical construction units predetermined surface qualities are often demanded. Seal faces need a certain surface roughness for the adhesive bonding compound to stick to the surface. Joining zones of parts which are assembled by force fitting also need predetermined surface structures to tighten the connection. There are several possibilities of producing surface microstructures by using the milling process. First, the choice of feed per tooth and tool path spacing influences the resulting surface roughness. These parameters affect the surface even in the ideal, non-dynamic milling process. Thus, these structures can be explained purely geometrically, though they are widely mistaken for chatter marks. Dynamic milling tool vibrations produce other types of surface structure, which can be induced by adjusting the spindle speed.

This paper presents a simulation system which is capable of predicting the geometric and dynamic effects of the milling process on the surface quality. It can be used as a tool for adjusting the process parameters in order to achieve desired surface microstructures.

The system uses arbitrary NC-programs as well as geometrical and modal descriptions of the used milling tool as input. It calculates the chip shapes along the tool path as a CSG (Constructive Solid Geometry) model for a precise computation of the occurring forces. This enables a feedback of tool deflections into the chip shape for the calculation of self-excited chatter vibrations. Thereby it is possible to apply a time domain simulation on the milling of free-formed surfaces.

After the calculation of the tool vibration plots a geometric model of the surface is presented, which can be used to analyze the surface roughness. Furthermore, high quality visualizations can be generated to intuitively compare the simulation results with real machined workpieces. This system can be used to evaluate a set of process parameters in order to optimize the surface structure to achieve the demanded quality. This is verified by comparing the simulation results with real experiments.

2 SIMULATION

In recent years different milling simulations based on various principles have been created [1, 2]. To get an exact model of the generated surface microstructure, the simulation must be able to simulate the movement of the tool as exactly as possible [3, 4, 5]. The calculation of self-excited tool vibrations demands knowledge of the acting forces, which can be deduced from the chip shape. In this paper a time domain, CSG (Constructive Solid Geometry) based simulation is presented.

2.1 Construction of the chip shape

NC programs consist of sequenced line segments. The tool position can be described as a pair (*s, p*), where s refers to the segment index and p to the distance from the starting point of segment *p*. Therefore the shape of the chip *C* at tool position (*s, p*) is given by:

$$C(s,p)=\left(W_0-\bigcup_{i=0}^{s-1}V(i)\right)\cap\left(T(s,p)-T(s,p-f_z)\right)$$

where W_0 is the initial shape of the raw material, $V(i)$ is the sweep volume of the tool along the *i*-th segment, $T(s, p)$ is the volume of the tool at position (*s, p*), and $T(s, p-f_z)$ is the volume of the tool at the previous cutting position (f_z = feed per tooth). The $V(i)$ can be constructed by uniting cutter models along the path. This formula is valid as long as the cutting velocity is much higher than the feed velocity. It can be used directly to build the chip with the CSG (Constructive Solid Geometry) method. With this method a volume can be formed by set operations (i. e. intersection or union) on primitives like boxes or spheres.

For the calculation of the chip shape it is sufficient to consider only NC paths in the region around (*s, p*) and therefore to model only the area of interest near the current tool position. These paths can be found faster if the path segments are stored in an octree data structure. Further optimizations lower the number of cutter positions used in the construction of the $V(i)$. Thus, the size of the generated CSG-tree data structure representing the chip can often be reduced by about 80% without altering the represented chip shape (fig. 1).

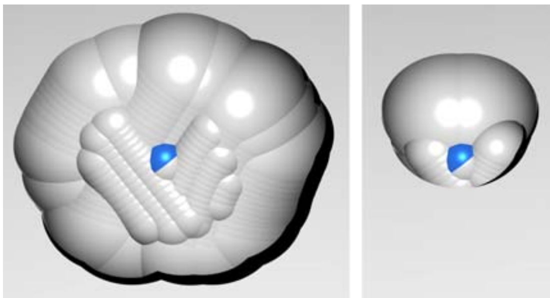

Figure 1: Local workpiece model without (left) and with (right) minimization of the CSG-tree

2.2 Calculation of process forces

The cutting edge, for which the forces are calculated, is discretized by segmenting it into several cutting wedges (fig. 2). A single wedge is determined by the offset point **p** relative to the tool tip, its width Δl, and the cutting direction $\mathbf{e_c}$, the cutting normal $\mathbf{e_n}$, and the tangential direction $\mathbf{e_t}$, which are specified in local coordinates.

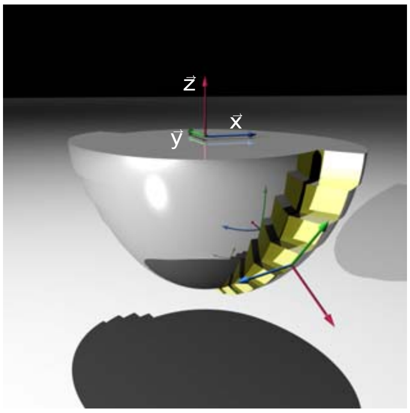

Figure 2: Cutting edge composed from single wedges

The calculation of the cutting forces $\mathbf{F_c}$, $\mathbf{F_n}$, and $\mathbf{F_t}$ in $\mathbf{e_c}$, $\mathbf{e_n}$, and $\mathbf{e_t}$ direction respectively is based on the Kienzle equation, extended by a term considering friction [1, 2, 6].

The chip thickness, which is an input parameter for the Kienzle equation, can be calculated from the representing CSG-tree. Intersections between a straight line and the volume described by a CSG-tree can be reduced to intersection computations between straight lines and the comprised primitives. Efficient algorithms for this task have been developed in the field of computer graphics, a triangulation of the object described by the CSG-tree is not necessary. The distance between the two obtained intersections corresponds to the thickness of the chip at the given position in direction of the straight line. The resulting force on the tool is the sum of all forces acting on each cutting wedge.

2.3 Tool vibrations and self-excited chatter

The forces acting on a tool are not constant. For each tooth engagement the forces depend on the surface which results from the previous cut. This behavior leads to self excited-chatter. To simulate self-excited chatter, it is necessary to incorporate a feedback of the forces into the CSG model of the chip shape and thereby influencing the calculation of the generated shape and forces in the following step.

Let $\mathbf{D}(\varphi, s, p)$ be the displacement of the tool tip at position (s, p) with the tool rotation angle φ. $\mathbf{D}(\varphi, s, p\text{-}f_z)$ is the displacement of the previous cut at the same tool rotation angle. These two deflections are to be applied to the tool positions $T(s, p)$ and $T(s, p\text{-}f_z)$ before the calculation of forces on the tool takes place and are reset afterwards. Since the structure of the CSG-tree representing the chip shape is not changed by this operation, it can be performed very efficiently.

2.4 Used oscillator model

The computation of the tool displacement adopts the model of a damped harmonic oscillator with two decoupled degrees of freedom; one in x and one in y Direction. The tool displacement is the superposition of the vibrations of both directions. The tool mass is assumed to be concentrated on a single point so that each dimension of the tool movement can be described by the following equation:

$$m\ddot{x}(t) + c\dot{x}(t) + kx(t) = F(x(t), x(t-T), t)$$

where $x(t)$ denotes the value for the tool displacement and T is the time difference between two tooth engagements. The self-excited behavior can be deduced from the dependency of F from the previous displacement $x(t\text{-}T)$. The approximative current deflection at time t of the tool for n known previous forces $F(t_i)$ of duration Δt is:

$$x(t) = \sum_{i=0}^{n-1} \frac{F(t_i) \cdot \Delta t}{m \cdot \omega} \mathrm{e}^{-\gamma(t-t_i)} \sin(\omega \cdot (t - t_i)).$$

Herein ω is the angular velocity, γ is the dampening constant and m is the modal mass. By this the feedback between force and deflection can be calculated in the time domain.

2.5 Time domain milling simulation

Now all requirements for the simulation of self-excited tool vibrations are fulfilled. This time domain milling simulation works in discrete time steps: first the chip shape gets constructed, then the forces acting on the tool are calculated and the displacement for the next time step gets calculated and stored. In the next time step the chip shape calculation is influenced by the previous calculated displacements and so are the calculated forces, which influence the next displacement. Self-excited chatter is the result.

3 EXPERIMENTS

To verify the simulation model, experiments were conducted. Within these experiments a two-fluted end-mill with a diameter of 8 mm and a length-to-diameter ratio of 12 was used. It has a eigenfrequency of 743 Hz, a modal mass of 0.02 kg, and a dampening constant of 63 1/s. The workpiece material was Aluminium 7075. The results shown in this paper were produced by a radial immersion a_e of 0.4 mm, an axial immersion a_p of 0.5 mm, and a feed per tooth of 0.12 mm.

4 STRUCTURES ON THE FLANK SURFACE

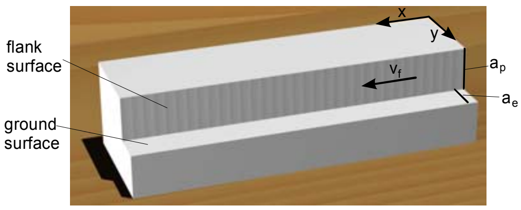

Figure 3: Model of a flank structure produced by low radial immersion milling

When milling with an end-mill at low radial immersion a_e, the surface structures of the flank and the location error of the flank are of interest. For an analysis of these quality features the simulated vibration trajectories are converted into a geometric model. Let φ_0 be the tool rotation angle in the instant, when the cutting edge normal first is perpendicular to the feed motion, and φ_1 the angle, at which the cutting edge normal at a height of a_p is perpendicular to the feed motion. Further, let $\mathbf{d_i}(\varphi)$ be the vibration trajectory along the *i*-th cut. Then the tool model T_i for the representation of the *i*-th cut can be described by a cylinder with the same diameter as the tool and running through the points $\mathbf{d_i}(\varphi_0)$ at height 0 and $\mathbf{d_i}(\varphi_1)$ at the height of a_p. This is necessary, because, when using helical cutting edges, the tool moves along the vibration trajectory while performing the cut. The entire flank surface created by n cuts can then be modeled by the subtraction of all tool models T_i from a box-shaped model of the workpiece. The structural formula of the related CSG-model reads as

$$F = S - \sum_{i=1}^{n} T_i \ ,$$

where *F* is the model of the flank, *S* is the workpiece and T_i is the tool model of the *i*-th tooth pass [7].

Each vertical structural element representing the surface microstructure of the flank in fig. 3 and 4 is created by one cylinder i.e. tool model. By calculation of a cross section through the flank, the surface location error can be determined.

4.1 Microstructures

The dynamic milling process creates different types of structure depending on the spindle speed. Chatter leads to a very rough surface because of the superposition of the chatter frequency and the eigenfrequency of the tool, resulting in alternating tool deflections when creating the surface (fig. 4, 8000, 12000, 13000 rpm). Non-chattering processes result in the theoretical roughness which is expected by an ideal non-dynamic process (fig. 4, 11000, 16500 rpm). The flip-chatter type (fig. 4, 15250 rpm) produces a roughness which seems to result from the double feed per tooth. Figure 5 shows the related real experimental surface structures. Except for some difference of the tilt in the structures, the sizes and types of structure are very similar to the simulated ones. A slight run-out makes the chatter-free surfaces (11000, 16500 rpm) look like the one created by flip-chatter (15500 rpm). The resulting roughness of the flank surfaces between 8000 and 17000 rpm and particularly the roughness of the flank surfaces in fig. 4 and 5 are shown in fig. 7.

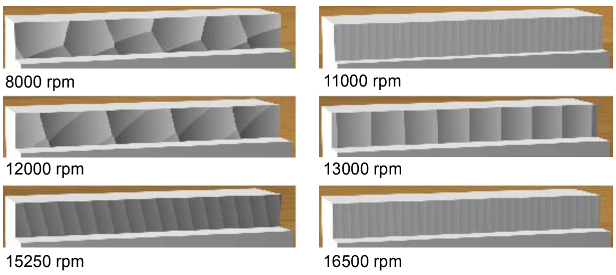

Figure 4: Models of flank structures milled at various spindle speeds

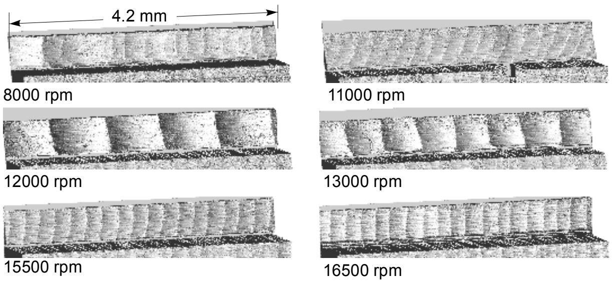

Figure 5: Real flank structures milled at various spindle speeds measured by a confocal white light microscope

4.2 Surface location error

It is often suggested to use a spindle speed which leads to a tooth pass frequency near the eigenfrequency of the tool to produce smooth surfaces and to maximize the axial immersion. Figure 6 shows the location error of the flank depending on the spindle speed. It can be seen that at 11000 rpm, where the surface roughness is minimal, the surface error becomes maximal positive. In case of chatter the surface error becomes negative i.e. too much material is removed. A second minimum appears at 15500 rpm where flip-chatter occurs. In the case of one dominating vibration mode, it is best to use a spindle speed slightly left of the stability maximum to achieve a minimum surface location error although the maximal axial immersion is lower [8].

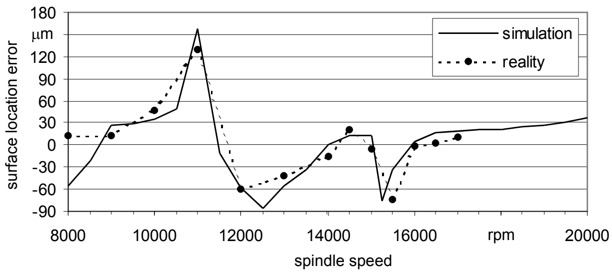

Figure 6: Simulated and measured surface location error as a function of the spindle speed

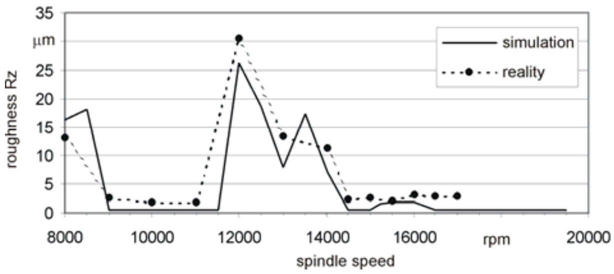

Figure 7: Simulated and measured roughness as a function of the spindle speed

5 GROUND SURFACE

Especially in slab milling the surface quality has to fulfill predetermined surface roughness properties. This applies e. g. for sealing surfaces to assure the bonding between the part and the sealing compound. To generate a certain surface roughness and structure of the ground surface, the dynamic milling process can be applied. For this, a geometric model is used to predict the resulting surface structure and adjust the spindle speed to produce the desired surface. Fig. 8 shows typical ground structures resulting from different process states.

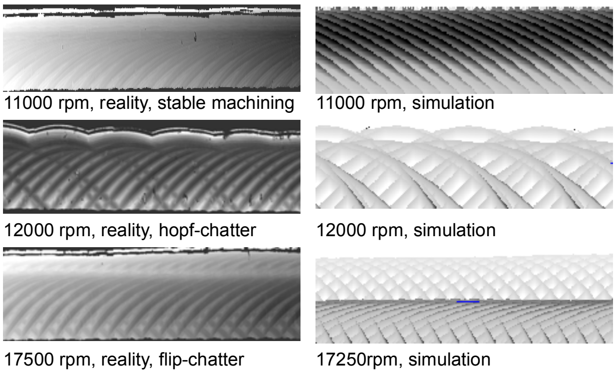

Figure 8: Real and simulated surface structures of the ground surface resulting from different spindle speeds

The structures result from the superposition of the time-varying bending of the tool and the tool rotation. E.g. a constant tool displacement in positive x-direction would cause a contact between the rotating cutting edge and the groove bottom at a negative x-position (fig. 9). Since in chatter-free (11000 rpm) and flip-chatter (17500 rpm) milling the eigenfrequency of the tool is a multiple of the tooth-pass frequency, the cutting edge contacts the ground at the same rotation angle at each respectively each second tooth pass. Therefore the structures are very smooth and periodic. In quasiperiodic (hopf) chatter the rotation angle with ground contact is different at each tooth pass. This results in the deep structures at 12000 rpm.

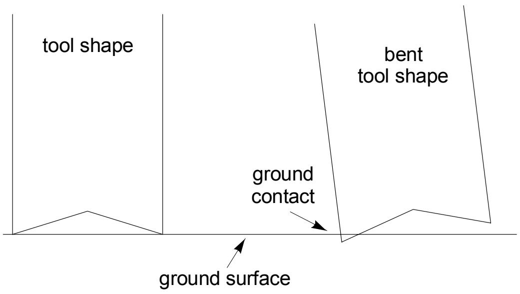

Figure 9: Cause of ground surface structures

To model the surface of the workpiece, the sweep surface of the cutting edges along the tool path is generated. To accomplish this, the cutting edges are represented by polygon curves. These polygon curves are rotated around the tool axis in discrete steps superposed by the feed motion of the tool and connected by triangles. Additionally, each polygon curve has to be rotated around the axis which is perpendicular to the tool axis and to the displacement vector to simulate the tilted position resulting from the tool bending. The angle for that rotation can be calculated from the length of the tool, which was 96 mm in the shown results.

The triangles are rendered into a depth buffer, which can be visualized and analyzed in order to compare the simulated and measured surfaces.

An interesting effect occurs on the surface generated by the flip-chatter type. The shades of gray in fig. 8 denote the height (the brighter, the higher) of the structural elements. As can be clearly seen, there is a step in the surface in the upper quarter of the real surface. This is caused by the period doubling where one tooth cuts with a positive tool displacement and the other one with a negative displacement causing two different tool bendings. The same effect, although much more distinctive, is covered in the simulation.

6 SUMMARY

This paper presents a time domain, CSG-based milling simulation that is able to simulate the trajectory of self-excited chatter by calculating forces based on a chip shape that is influenced by previous forces and adopting the physical model of a damped oscillator. The simulation includes a model for the workpiece that is capable of modeling the surface structures with very high accuracy. The generated surface microstructures can be visualized in photo quality, which enables direct comparison with real experiments.

Surface microstructures resulting from different chatter situations were produced in real experiments and compared to results of the simulation. Thereby it is shown that the simulation fulfills the requirement of showing the same effects as the real process and thus that it is capable of predicting the generated surface quality prior to real processing in the given cases.

In the future it is planned to verify the simulation on more complex surfaces with more complex engagement conditions. The main objective is to be able to adjust machining parameters to produce the desired surface structure.

7 ACKNOWLEDGMENTS

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