GEOMETRIC SIMULATION OF THE MILLING PROCESS FOR FREE FORMED SURFACES

K. Weinert, T. Surmann

Department of Machining Technology, University of Dortmund

Abstract

In optimization of milling processes the modeling of engagement conditions is a basic feature to be implemented. This paper presents a technique for creating high-precise geometric models of undeformed chips. These models offer the possibility of an accurate process force prediction.

1 Introduction

Simulation based optimization systems for the milling processes have spread throughout various fields of application in production technology. Since they are capable of predicting faults and quality deficiencies in advance to the process itself, they offer an easy and reliable way to reduce the production costs [1, 2, 3]. The process models have the one disadvantage, that they can either model the cutting process analytically for simple engagement conditions or model the process for free formed surfaces but in a less precise way [4]. To build up process models for the machining of free formed surfaces it is necessary to use a geometric simulation, which produces accurate results even on complex tool paths. For this a modeling technique is presented, which enables the calculation of geometric models of undeformed chips, which show a high precision, for the milling simulation of free formed surfaces. This modeling is based only on the NC-programs generated by standard CAM-systems. Therefore no other information is needed, as the dimensions of the raw material, NC-files and cutter data. Furthermore the further processing of the modeled engagement conditions, the process force calculation, and the analysis of complete NC-programs are treated in this article.

2 Modeling Undeformed Chips

The process forces result from the rotating tool cutting chips out of the material. The value and the progression of the occurring forces depend on the thickness and width of these chips. The distribution of these values along the cutting edge and for one tool rotation, the so called undeformed chip has to be known for the calculation of process forces [5]. This chapter deals with the geometric modeling of the undeformed chip for one specific position within a NC-program.
2.1 Used Modeling Concept

To use a simplification, the feed rate is considered small in comparison to the cutting speed. So the milling process can be derived from the set theory. The work piece and the rotating tool are considered as sets of points in $\mathbb{R}^3$. The machined surface results from a successive subtraction in discrete time steps $\Delta t = 1 / (n \cdot z)$ sec. ($n=$revolutions per minute, $z=$number of cutting edges) between the work piece and the cutter. Thereby the tool $C_t$ is placed in the position, where it would be at the particular point of time $t$ in the real process. The following set formula describes the work piece $W_T$ immediately after the time $T$:

$$W_T = W_0 - \bigcup_{t=0}^{T} C_t$$

The undeformed chip $S$ at the time $T$ then is the intersection between the work piece at time $T-\Delta t$ and the tool at time $T$:

$$S_T = W_{T-\Delta t} \cap C_T = \left( W_0 - \bigcup_{t=0}^{T-\Delta t} C_t \right) \cap C_T$$

![Figure 1: Two dimensional example of the modeling concept](image)

The sum in the above formula delivers a perfect description of the undeformed chip for discrete time steps of $\Delta t = 1 / (n \cdot z)$ sec.. Figure 1 demonstrates the concept of modeling the chip with a two dimensional example.

For a concrete implementation within a simulation system the Constructive Solid Geometry (CSG) [6,7] is well suited. This modeling concept allows the assembly of complex objects by simpler ones, which are combined by Boolean operations. A CSG object consists of a tree structure in which the inner nodes represent the Boolean functions, and the leaves consist of the primitive geometric objects. Hereby a geometric model of the engagement condition can be derived directly from the above mentioned formula. The work piece and the tools at the various positions are the leaves and are represented by simple geometric form. I. e. a box is used for the work piece and cylinder, sphere or torus for the tools.
Figure 2: By CSG modeled local work piece cutouts

Figure 2 show examples from the simulation system. In the left picture one can see on the left most side a surface already machined by the pre finishing step. The right picture illustrates a more complex situation, where the cutter is engaged near its equator. The colored faces are those surfaces, which result from the last cut.

2.2 Local Work Piece Modeling

Since the union in the above formulas can reach a high cardinality when modeling realistic machining processes and so the CSG tree would reach a high number of nodes, conditions have to be considered, which simplify the geometric model, without influencing the shape of the resulting object. For the rendering of the chip it is sufficient to use only those $C_t$, which possibly contribute to its form. With this the description of the work piece is extended to:

$$W_T = W_0 - \bigcup_{t=0}^{T} C_t \mid C_t \cap C_{T+\Delta t} \neq \emptyset$$

This modification causes the effect of modeling only the local work piece directly around the actual cutter position. So the number of nodes in the CSG tree is reduced to a number of 500 to 1000 independent of the location within the NC program.

A further simplification of the model lies in using existing knowledge about the generation of the NC program. By knowing the distance between the NC paths within a parallel semi finishing strategy the above criterion can be strengthened, by using only those cutter positions in the work piece model, which have less or equal distance to the actual tool position than the distance between the parallel paths. This further reduces the size of the CSG tree.

2.3 Undeformed Chip

After building the intersection between the tool at the actual position and the local work piece, one is in possession of an exact description of the undeformed chip form, whose
accuracy is only influenced by the choice of $\Delta t$. By defining $\Delta t = l / (n \cdot z)$ the model reaches highest accuracy and is almost free of errors, if the assumption $V_c \gg V_f$ is true.

![Image](image_url)

**Figure 3:** Modeled work piece extract and corresponding uncut chip for a toroidal cutter

Since the chip is a three dimensional model, it can be further processed in many ways. It may be triangulated and rendered graphically for a visual analysis of the engagement condition. The main application lies in an analysis of the processes, which occur at the cutting edge during a complete rotation of the tool.

## 3 Analysis of the Chip

For an accurate analytic calculation of the occurring process forces it is necessary to take the rotation of the tool into account and to take a look at the processes, occurring at the cutting edge. Therefore the chip is converted into a chip grid [8]. The chip grid is a two dimensional array whose entries carry the process data for the relating point on the cutter hull. The two directions of the grid regard the angle $\phi$ and the bow length of the cutting edge. So one entry $E(\phi,l)$ carries the process information at angle $\phi$ and distance $l$ along the cutting edge measured from the tip of the tool. Figure 3 shows the scheme for the mapping of cutting edge points into a chip grid.

![Image](image_url)

**Figure 4:** Scheme for mapping the cutting edge point into a chip grid (l) and chip grid with grey value coded chip thickness (r)
3.1 Sampling the Chip Thickness

The chip thickness $h$ is the dominating factor for the cutting forces. To determine the chip thickness at a point $P=(\phi,l)$ on the cutting edge, the chip model is intersected with a ray, which is orientated in the normal direction of the cut. The distance between entry and exit of the ray is then the chip thickness and is stored in the entry $E(\phi,l)$ of the chip grid. This calculation of an intersection between a ray and a CSG model is efficient, if it is efficient for the primitive objects forming the leaves, which is given here. Figure 4 shows a projection of an engagement condition (l) onto the cutter hull (r).

Figure 5: Modelled engagement condition (l) and its projection onto the cutter hull (r)

3.2 Parameters of the Cut

Additional to the chip thickness $h$ each chip grid entry carries the following process parameters:

- the length of the arc segment around the tool axis, for which this entry is valid
- the length $b$ of the cutting edge segment
- direction of the cut
- rotation speed
- velocity of the cut $V_c$
- velocity in normal direction of the cut $V_{c,N}$
- velocity in tangential direction of the cut
- overall velocity of the cutting edge segment

These data allow an efficient implementation of various models for the calculation of cutting forces. Possible are cutting force models, which make use of the Kienzle equation or those who deal with friction models or simulate the chip formation itself.

3.3 Calculation of the Process Force

By using the chip grid, it is possible to reduce the overall force calculation to the calculation of the cutting force for each single chip grid entry. After that the forces along one column and the relating columns which belong to the other cutting edges are added to
get the overall process force at one angle $\varphi$. Note that a column in the chip grid does not necessarily mean a straight cutting edge. The angle $\varphi$ refers to the rotation of the cutter itself. The additional process parameters in a chip grid entry even allow a cutting force calculation for twisted cutting edges.

**Figure 6:** Chosen extract from the semi finishing program used for a force calculation. The dots mark the selected positions ($r$)

The advantage of this kind of process modeling is that by the geometric modeling of engagement conditions the effects of e. g. up and down milling automatically are simulated. Figure 5 shows an extract (red) of a semi finishing program, in which up and down milling alternates. The small pictures show the engagement conditions at the yellow dotted points. You can obviously see the different material distribution around the tool tip.

For the calculation of the time series of figure 6 based on the engagement conditions shown in figure 5 the Kienzle equation [9, 10] was applied to each segment of the cutting edges for the cutting force $F_c$ and the normal force of the cut $F_{cN}$:

$$F_c = b \cdot k_c \cdot \left( \frac{h}{h_0} \right)^{1-m_c}$$

$$F_{cN} = b \cdot k_{cN} \cdot \left( \frac{h}{h_0} \right)^{1-m_{cN}}$$

The vectorial description of the force results from multiplying the absolute values by the respective unit vectors and adding them:

$$\vec{F} = ||\vec{V}_c|| \cdot F_c + ||\vec{V}_{cN}|| \cdot F_{cN}$$
Figure 7: Typical time series for up (l) and down milling (r) for one rotation

4 Process Force Calculation for Entire NC-Files

Until now we have dealt with the analysis of single engagement conditions at single positions of an NC program. For a simulation based process optimization whole NC programs have to be analyzed. For this, starting at the first NC set, each path segment is divided into intervals in such a way, that each interval length is equivalent to the relating feed per tooth. Figure 7 shows some NC paths with various feed rates. The marks on the paths point out the positions to be analyzed.

Since all of the previous NC sets have to be read for the modelling of one chip, the run time of the simulation of an entire NC program would be a function of $n^2$, when $n$ is the number of NC sets. For an improvement the NC sets are divided hierarchically into an octree. So the test, if an NC set is important for the actual chip model, is with $O(n \log n)$ very efficient. The time series of figure 8 are computed by this scheme and belong to the selected extract of a program shown in figure 5. The high peeks in the force at some critical positions are obvious.
5 Results

For the validation of the force model experiments were made. Figure 9 demonstrates one engagement condition, which was used next to others for the validation. Figure 10 compares the measured forces with the calculated ones. Besides the height of the forces the phase shift between the single components in each coordinate direction fits perfectly. This indicates the correctness of the used model consisting of forces in cutting direction and normal direction of the cut. Only the values for the x components show slight deviations from the measured ones. This may result from using a cutting force model for a non twisted cutting edge but using a twisted one in the experiment.

Figure 10: Used engagement condition for validation of the force model

The coefficients used in the Kienzle equation where $k_c=1600$, $m_c=0.35$, $k_{cN}=1500$, $m_{cN}=0.25$ for the used material and tool combination.
Figure 11: Comparison between measured and calculated cutting forces. The smooth graphs refer to the calculated forces. The x-axes of the diagrams refer to time and the y-axes refer to the forces.

6 Summary and Outlook

This paper presented a very accurate concept for the geometric modelling of engagement condition for the machining of free formed surfaces. The engagement conditions are modelled mathematically precise, so that they can be analyzed without having the problem of raster effects. This helps setting up and validating the process force models because errors no longer result from the geometric modelling. The run time of this simulation model is not as bad, as thought of in the beginning of the implementation. Actually the simulation runs on modern PCs as fast as the real process does.

In future this modelling approach will be extended to the calculation of tool vibrations, so that a prediction of chattering will be possible for the machining of free formed surfaces. With a process model, which predicts the tool vibration, an optimization of the process parameters feed, spindle speed, tool path, etc. will be possible.
7 Literature


