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Procedia CIRP 4 (2012) 41 – 45

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3rd CIRP Conference on Process Machine Interactions (3rd PMI)

Contact Zone Analysis Based on Multidexel Workpiece Model and Detailed Tool Geometry Representation

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Abstract

A new method for analyzing the tool-workpiece-contact area in cutting processes is presented. To gain enhanced knowledge about tool-workpiece interaction, determination of chip thickness, contact length and resulting cross-section area of the undeformed chip is of major interest. Compared to common simulation approaches, where rotation-symmetrically constructed tool geometry is used, the new method uses a detailed three dimensional tool shape model for an extended and more accurate contact zone analysis. As a corresponding representation of the workpiece and its time dependent shape-changes a multidexel model is used.

To prepare the geometric tool model, the contained BREP topology is built up within the simulation system using data from a STEP-file. First of all functional parts of the tool like rake and flank faces and cutting edges are labeled for further processing.

In a second step the identified NURBS-faces are discretized for the application in material-removal calculation. This way a mesh is built-up based on triangle elements which maps the geometry of each cutting edge into a 2D parametric representation. In relation to rake face, each node is described by its position on the cutting edge and its perpendicular distance to this edge.

To perform contact zone analysis each cutting geometry and a multidexel model are intersected in discrete time steps corresponding to a tool rotation of about three degrees. The intersection point of each dexel and the cutting geometry is calculated. Parametric cutting geometry allows for a direct computation of local cutting depth and contact length for each involved point. Based on the local values of contact length and cross section area of the undeformed chip the characteristic values for the entire contact zone are calculated and used to predict mechanical as well as thermal loads caused by the cutting process.

To demonstrate the application of the novel approach, prediction of forces in slot milling of 1.1191 steel is presented.

Keywords: Multidexel Model; NC-Simulation; BREP Model; Graphics Hardware (GPU); Tool Stress; Force Calculation

1. Introduction

In milling, geometric analysis of the contact zone between tool and workpiece is an important means to gain knowledge about the process and to calculate specific values. Commonly used simulation methods for computing the contact zone consider the motion of the tool relative to the workpiece in discrete time steps. For each step the removed material is calculated by intersecting the geometric models of the workpiece with either the tool at its current position or its trace during the time step.

To perform further analysis, geometric results are used for physical approaches, e. g. mechanical or thermic models. According to literature, a common approach to increase precision of calculation is to split the geometric object into smaller parts and to calculate values separately while merging them to gain the intended value. In most cases computing local conditions is based on investigating the wedge which refers to considerations along the cutting edge in perpendicular

doi:10.1016/j.procir.2012.10.008

direction. Many approaches use the depth and width of cut as input for calculation of specific values [1, 4, 6]. For determining these, calculation of the shape of the contact zone and knowledge about the position of the cutting edge is necessary.

This paper introduces a new method for mapping data of the removed material to different functional faces of the tool by using positions along the cutting edge as reference. In the next section a brief overview of methods in cutting simulation and contact zone analysis is given. It is followed by a description of the new approach for considering functional faces within cutting simulation and some details about the necessary phases to perform analysis.

2. State of the art

A common structure for modeling the shape of the workpiece in cutting simulation is the so called dexel model. It is comparable to a plain grid of parallel nails of different length which are refreshed in start and end point to modify the shape of the object. Earlier approaches used elements of only one direction which is for example the approach of graphics rendering in graphics processor units (z-buffer) [9]. To decrease the dependency between the chosen dexel-direction, the shape of the workpiece and the resulting accuracy, multi-dexel-models have been introduced [3, 7]. Usually three grids are used in direction of the main axes of a cartesian coordinate system.

Another common method for modeling the shape of geometric bodies to be modified uses the shell of the object. This approach is called Boundary Representation or BREP. It is widely used within Computer Aided Design or related software. A special variant of this uses only simple elements for surface representation, i. e. flat polygons or even solely triangles.

Computational Solid Geometry (CSG), another Representation from Computer Aided Design, is as well used in process simulation [10]. It defines models by combination of primitive volumetric elements using geometric addition, difference or intersection.

Depending on the data structure which is used for calculation of the part that is cut off in a specific time step, different methods are known from literature that perform an analysis of the geometric shape for determining physical data, in most cases process forces. Usually classical calculation methods which reference additional input, e. g. the position of the tool axis, the speed and direction of cut etc. are applied to the chip data. Because these methods only approximate the real value by assuming simplified shapes, the overall error can be reduced by dividing the investigated object into smaller parts and calculating the values separately. This is comparable to nested intervals in approximating integrals.

The approaches to determine geometrical data for calculation input can be divided into volumetric methods, projective methods and contact zone diagrams. Volumetric methods calculate data by summation of values from smaller volumetric elements which arise from the single elements of the used discrete approach for material removal calculation. An example for this approach can be found in [8]. Projective methods use a surface perpendicular to the cutting direction to calculate the cross-section of the undeformed chip. In most cases the projection of the single discrete elements is calculated and investigated with further methods. An example for projective methods can be found in [5].

The approach of contact zone diagrams is similar to projective methods but the projection is performed onto the surface of the rotational shape of the tool. Analysis is performed by considering the contact length of the cutting edges and the estimated depth of cut [2].

3. Approach

In many calculation approaches the rotational axis of the tool is used as reference to estimate direction of width and depth of cut. Calculation errors are made depending on the actual angular between the axis and the local tangent of the cutting edge. Thus, the conventional approach of using the volumetric model of the tool without knowledge about the function of different parts is not sufficient. A known solution for this is using general descriptions of the shape of the cutting edge and fitting it onto the calculated chip shape.

The basic principle of the approach presented here is the preparation of the tool data prior to performing cutting simulation. For each face within the used geometric model its function is declared and transferred while transforming the model into a triangulation. This way the trace of each functional surface and edge is considered separately within the simulation and the connection between the discrete elements of the workpiece model and the faces of the tool is kept. This enables a more detailed analysis of the contact zone

The parts of the tool to be allocated prior to simulation are the rake face and the flank face. Additionally it is important to distinguish between the different teeth. The depth of cut is defined using the distance to the cutting edge and the width using the distance in parallel direction to the edge. This procedure implies that the cutting edge is also known prior to calculation. Moreover it is a suitable approach to define a coordinate system upon the rake face using the position along the curve of the cutting edge as abscissa and the perpendicular distance as ordinate.

It is a common method in calculation of technological values to partition objects into smaller ones and to considere each separately. The method presented here uses a multi-dexel structure for workpiece representation. This model assumes each dexel to be a representative for a prismatic element with the size of the grid distance of the dexel field. Thus the prismatic elements of a single dexel grid form a continuous object without intersections. Each dexel is assumed to be a ray, intersecting the cutting part at a certain point. To calculate the tool load the points of all grids are mapped to the prepared tool faces and considered with respect to the cutting edge.

To consider its position concerning the cutting edge, geometric calculation is necessary to determine the perpendicular distance to the cutting edge. To avoid effort in performing this calculation for each dexel in each time step, a mapping is established between the points of the functional faces of the tool and the cutting edge. As a preprocessing step this mapping is initialized once and is used in each time step during simulation run. Moreover by using a perpendicular structure concerning the cutting edge, determination of depth and width becomes more precise. This is done by creating elemental surfaces with edges perpendicular to the cutting edge and using these as edges for the necessary triangulation of the tool faces.

4. Preparing the Tool Model

To perform cutting simulation including consideration of the cutting edge and the functional faces the common approach of using a body of revolution as substitute of the tool is not sufficient. Instead a full three-dimensional model is required. If analysis of the process shall be done without big effort, a preparation of the model is important prior to simulation. We assume that the tool model is stored in a Boundary Representation (BREP) which is the most common, like in file types as IGES, STEP and most CAD-systems.

First step in model preparation is to assign technological properties to the corresponding geometrical objects of the model claiming them as rake surface, flank surface or a face not involved in the cutting process. Additionally, the cutting edge has to be defined and – if the model includes a fillet at the cutting edge – this has to be identified, too. To do this the topological structure of the CAD-Model is used. Depending on the mathematical representation (e. g. freeform or ruled surface) the technological face may consist of more than one geometric surface. To gain a complete description, it is necessary to assign the type interactively by the user. For further use this assignment information is saved in a special file.

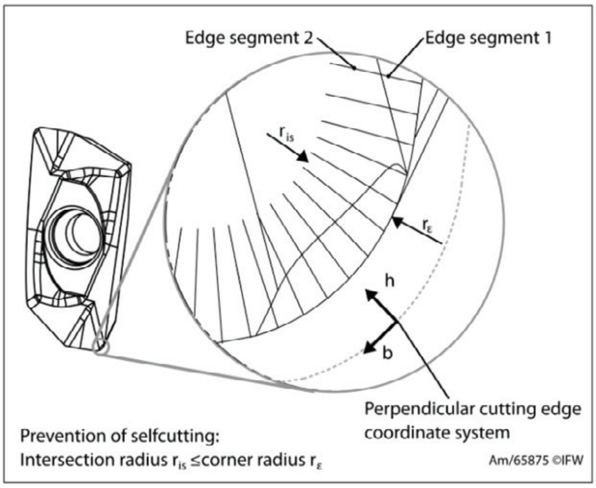

Figure 1: Segmentation of the rake face by perpendicular lines

As an example, processing of the rake face is presented in detail. The surface description is mapped into a coordinate system which describes all surface points by its position concerning the cutting edge. Thus the next step in tool model preparation is building up a unique description of the curve representing the edge. Similar to the technological faces the cutting edge will consist of more than one geometric edge segment in most cases. Thus these segments have to be sorted and normalized to introduce a function that continuously maps a numerical value to a point upon the edge.

Each point of the surface to be transformed is mapped to its foot of perpendicular onto the cutting edge. Because the edge is not a linear curve, this mapping is not unique. Thus it is necessary to find a definition which point shall be used in case of more than one solution. Obviously the point with the smallest distance should be chosen if possible. If the radius of the cutting corner is greater than zero it can be assumed that the curve representing the cutting edge is continuous in the first derivation, which means that the radius of curvature is greater than zero in all positions. In this case a unique mapping can be found for all surface points with a distance to the cutting edge which is smaller than the minimal radius of curvature. The above presumption usually is met if the radius of the cutting corner is greater than the depth of cut per tooth. If this is not the case, for example if a radius near zero is specified for the cutting corner, the mapping has to be adapted to ensure uniqueness. To prepare analysis for each point concerning its distance to the cutting edge rectangular areas within the introduced coordinates are used. Actually this means that perpendicular lines are laid upon the surface in equidistant distances along the cutting edge (Figure 1). These lines are used as basis for a triangulation of the face. Concerning the introduced coordinate system (position at cutting edge/distance) the elements are vertical. Thus the mapping of each knot of the triangulation is included in the transformation between the coordinate systems used. Figure 2 (top left) shows the resulting triangulation. The pseudo-color representation of the rake face visualizes the undeformed chip-thickness which results from the transformation.

5. Analysis of the contact zone

To perform an analysis of the contact zone, each functional part of the tool surface is investigated separately. Each face is cut with the multidexel model and each intersection point of dexel triangulated surface is analyzed without updating the length of the dexel. To map each intersection point to the coordinate system of the cutting edge, transformation data of the triangulation nodes are applied. The corresponding position on the cutting edge (b) as well as the perpendicular distance (h) is calculated using a linear interpolation. For this purpose barycentric coordinates with regard to the nodes of the triangle are applied. Thus parameters b and h values of the intersection point are calculated based on their known values stored with each triangle node.

For further processing each intersection point is registered within a map using the cutting edge coordinate system. The bottom left part of Figure 2 shows the distribution of the intersection points on the rake face for a multidexel approach. The colors of the points correspond to the directions of the intersected dexels.

Further calculations based on the cutting points aim at the evaluation of contact length and especially cross-section of undeformed chip. The multidexel model provides maximum accuracy by the combination of three independent dexel models. To gain the accuracy in the evaluation of the undeformed chip cross section area it is calculated based on the intersection points of all dexel directions. To do so, a polygon is created bounding the intersection points. Considering the line segments of this polygon, crossing each element of the rake face, the cross-section of undeformed chip *A* of each element is calculated. The contact length succeeds from the cutting edge coordinates of the elements intersected by dexels.

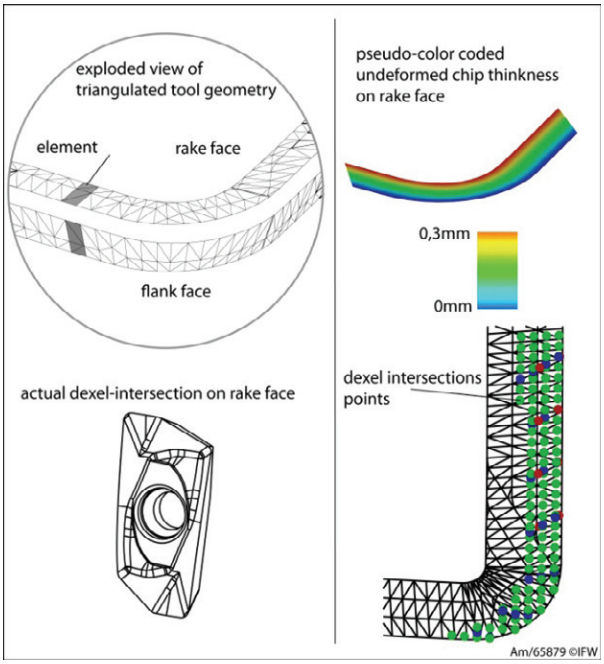

Figure 2: Dexel-Intersection on rake face

Following the analysis of the contact zone the multidexel model is updated using sweep representations of the tool faces. The start and end position of the prepared triangulation is calculated and each knot of the mesh is connected with its corresponding target point. By this a suitable approximation of the sweep body is created.

6. Application of the method

The method for contact zone analysis is used to consider mechanical and thermal effects caused by a cutting process. Especially the thermal load and the resulting heat flow into the workpiece require a precise local distribution. The local distribution of the cross-sectional area and the contact length from the contact zone analysis are basic input information for the calculation of cutting forces. Based on the distributed forces the heat flow is calculated. To compute cutting forces the empirical model of Altintas is applied [1]. To examine model parameters K_t and K_e cutting experiments at different feedrates per tooth are carried out recording the process forces (Equation 1).

$$\begin{pmatrix} F_x \\ F_y \\ F_z \end{pmatrix} = T \cdot \left(\begin{pmatrix} K_{tc} \\ K_{rc} \\ K_{ac} \end{pmatrix} \cdot A + \begin{pmatrix} K_{te} \\ K_{re} \\ K_{ae} \end{pmatrix} \cdot b \right) \tag{1}$$

A 3-component dynamometer (Kistler Type 9257B) was used to measure the forces during the process in the 3 orthogonal directions. For the experiments a KENNAMETAL 90° shell-type milling cutter (Type 40A04RS90ED14D) with inserts (EDPT140404PDERHD/KCPK30) for machining of 1.1191 (C45EN) steel was used. To avoid the effects of interaction of different teeth the number of inserts was reduced to one. To prevent disturbances of tool-runout slot milling has been chosen as reference process.

After determining the cutting force parameters the cutting forces are calculated using *A* and *b*. A transformation into the workpiece coordinate system using matrix T enables for the comparison to the measured data (Equation 1).

Figure 3 shows the variation in time of both, measured and simulated forces. Only forces in the x and y-direction are considered, where x denotes the feed direction. It is shown that the signals correlate in magnitude and characteristic very good. The difference

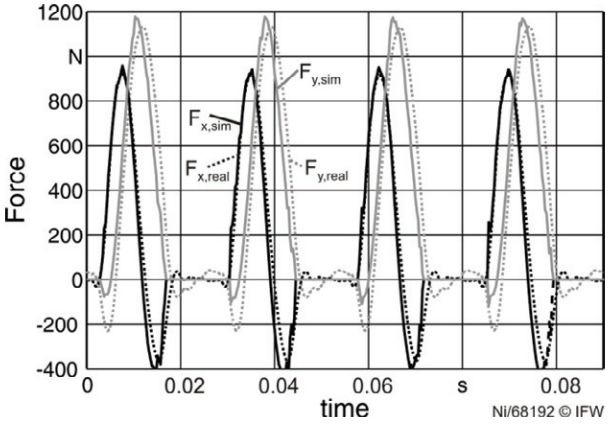

Figure 3: Simulated and Measured Forces

can be explained by the dynamic effects and vibrations of the real system that are not modeled within the simulation.

For calculation of the local heat generation, the differential cutting forces along the cutting edge have to be converted into the local dissipated power for each element (Equation 2).

$$\Delta\dot{Q} = \Delta P_c = \Delta F_c \cdot v_c \tag{2}$$

This generated heat can be projected onto the cut surface of the workpiece so that a heat flow via the angle of action can be determined and visualized (Figure 4).

The shown examples were computed using a standard desktop PC equipped with a conventional GPU. Necessary computational time is dependent in square relation on the discretization of the workpiece. Further influence lies in the accuracy of the triangulated tool and the length of the time slice. Choosing a resolution of the used dexel field between 256 and 1024 the calculation time varied from a few minutes up to 30 minutes. Additional potentials for faster performance could be received by optimizing the discretization of tool and workpiece.

7. Conclusion and Outlook

In the present paper a method for simulation based analysis of the tool-workpiece-contact area in cutting processes is presented. At first the tool-model was discretized into areas along the cutting edge as a basic preparation for the contact-zone-analysis. To perform contact zone analysis the discretized cutting geometry and the workpiece model are intersected. The intersection point of every dexel and the cutting geometry is calculated. Based on the local values of contact length and cross section area of the undeformed chip the characteristic values for the entire contact zone were calculated.

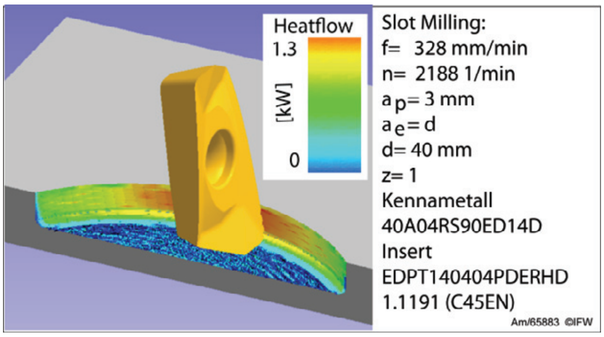

Figure 4: Local Heat Flow Distribution on Workpiece Surface

In further investigations the heat flow will be separated into workpiece, chips and tool to simulate the thermal behavior of these parts. The presented method will be adapted and validated for the drilling process.

Acknowledgements

The presented results have been obtained within the research project “Thermomechanical Deformation of Complex Workpieces in Drilling and Milling Processes” (DE 447/90-1) within the DFG Priority Program 1480 “Modeling, Simulation and Compensation of Thermal Effects for Complex Machining Processes”.

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