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Modeling a Thermomechanical NC-Simulation

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Abstract

This paper presents a method for a NC-Simulation based prediction of shape errors caused by thermal expansions in machining of complex workpieces. In the first part of the paper the basic approach of modeling a thermomechanical NC-Simulation for a faster and more precise process simulation is shown. Therefore, a fast dexel based material removal simulation including process models for calculation of localized heat flux and forces is linked to a FE model for simulation of thermal conduction in the workpiece. Interdependencies of thermal process and workpiece conditions are considered by a closed simulation loop. In the second part of the paper the modeling of each component is explained. To consider thermomechanical effects in material removal simulation the dexel based workpiece model is extended by additional information like temperature and deformation in every dexel. An inverse projection of the workpiece deformation on a triangulated tool model allows consideration this effect by deformation of the tool model. Thereby, a realistic shape of the workpiece can be simulated. In addition, the current cutting conditions like area of undeformed chip-thickness or contact length are changed. This results in diversified cutting forces and heat fluxes. For a realistic simulation of the thermal conduction the dimensions of the FE model have to be adapted by a time dependent virtual domain method. In the last part of the paper, results of the simulation are compared to measured data. The comparison shows that process temperatures in different workpiece areas are predicted accurately.

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Keywords: NC-Simulation; thermomechanical effects; shape errors

1. Introduction

Shape errors caused by process induced thermal expansions are a major challenge for dry machining production of complex workpieces with close tolerances. Considering these thermomechanical effects in the pre-production NC-Simulation would be a great advantage for the optimization of cutting processes and reduction of shape errors. To achieve this goal a new method for modeling of cutting processes in a material removal simulation is presented. In this paper a thermomechanical extension of a dexel based workpiece model by linking it to a FE model is shown. In combination with a process model for prediction of cutting forces and heat flux density effects of temperature and deformation are taken into account. This creates a closed simulation loop (Fig. 1) that considers thermomechanical interdependencies.

2. State of the Art

A common structure for modeling the shape of a 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 updated in start and end point to modify the shape of the object. Earlier approaches used elements of only one direction, like for example the graphics rendering in graphics processor units (z-buffer) [1]. To decrease the dependency between the chosen dexel direction, the shape of the workpiece and the resulting accuracy, multi-dexel models have been introduced [2, 3]. Usually three grids are used oriented to the main axes of a cartesian coordinate system.

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Another representation from Computer Aided Design, the Computational Solid Geometry (CSG), is also used in cutting simulation [4]. It defines models by combination of primitive volumetric elements using geometric addition, difference or intersection.

The voxel model is another method for modeling cutting simulation that is deduced from a graphics body visualization technique. The material removal process is modelled by deleting cubes from the workpiece model. Based on an Octree-structure of cubes the workpiece is discretized by dividing the cubicles in smaller ones until an adequate accuracy of the workpiece is reached. Finally this modeling method was used for a thermal process simulation by linking it to a CSG-model for contact zone analysis [5].

An approach for modeling heat conduction and thermomechanical workpiece characteristics is the Finite-Element model (FE model). It was used in several investigations for modeling of machining processes [6, 7]. Analytical process models are used for defining a constant moving heat source that loads a predefined finished workpiece, not including material removal processes.

Depending on the data structure that is used for calculation of the part 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 calculation methods which reference to 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 pieces and calculating the values separately. This is comparable to nested intervals in approximating integrals.

3. Principle modeling approach

Deduced from the state-of-the-art the NC-Simulation has to be extended with several properties to emulate thermomechanical effects. These extensions can be divided analytically into two components, the process model and the workpiece model (Fig. 1).

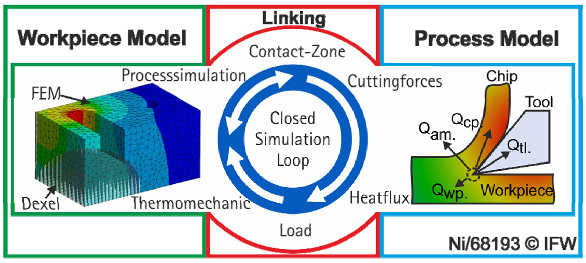

Fig. 1. Simulation Circle of Interactions.

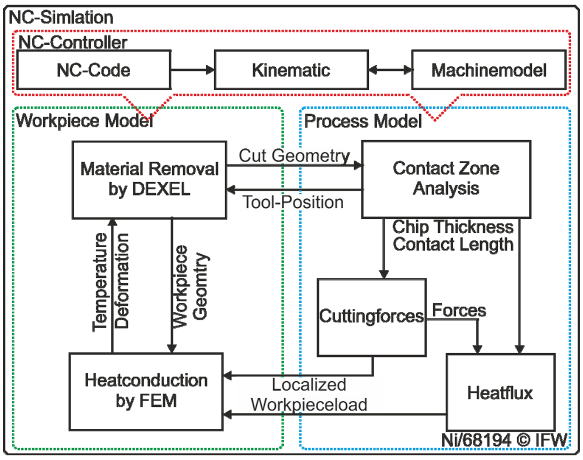

Fig. 2. Detailed Data Flow.

The workpiece model describes the actual state of the workpiece in geometrical and thermomechanical aspects (Fig. 2 left). Additional material removal algorithms allow changing the geometrical representation of the workpiece, while thermal conduction algorithms allocate modify the thermal condition of the workpiece.

The material removal process is controlled by a classical NC-Simulation, with kinematics and NC-Controller (Fig. 2 top) [8], for a realistic thermomechanical simulation the boundary conditions of the workpiece have to be changed by a process model. This process model has several sequences (Fig. 2 right). The local cutting conditions are calculated from the material removal process. With this data a cutting force and heat flux prediction is triggered that calculates the mechanical and thermal load. This changes the boundary conditions of the workpiece model.

The major aspect of this paper is the modeling of the workpiece model with its input and output parameters (Fig. 2 left). The contact zone analysis and cutting force had been shown in [9]. Linking a dexel model for the material removal process to an FE model for the heat conduction analysis allows considering both, volumetric changes and thermomechanical deformation, in the NC-Simulation. Thereby these components are considering the information of each other, so that the resulting effects can be modeled. Therefore, the dimensions of the FE model are changed by volume descriptions derived from material removal process for a more realistic heat conduction and workpiece deformation simulation. As input parameters for the FE model a moving heat source has to be extracted from the material removal process and cutting forces as mechanical load are calculated. Moreover the boundary conditions of the dexel model are changed by the current temperature distribution and thermomechanical deformation on the surface.

For the linking of all components a XML based communication system was implemented that is characterized by high flexibility and fault tolerance as shown in [10]. Thereby heat conduction simulation and NC-Simulation run and communicate in synchronized unequal time steps.

4. Thermomechanical extension of the Dexel Model

The component of the workpiece model used for the material removal simulation is discretized by a dexel model. To consider the thermomechanical effects in the material removal simulation the geometric representation of the workpiece by the dexel model has to be extended by thermomechanical information. Temperature and deformation of the workpiece are specific data have to been known when analyzing the information demand. The actual temperature of the workpiece has a major influence on the specific characteristics of the material like shear yield stress and therefore on the resulting cutting forces. The deformation of the workpiece changes the local (cross-section of undeformed chip A) and global (depth a_p and width a_e of cut) geometric contact conditions between tool and workpiece.

The data structure of the dexel model enables a geometric representation of the workpiece surface by discrete start and endpoints of the dexels (Fig. 3). In cutting operations only near-surface areas are machined. Caused by this fact information in these areas of the workpiece is relevant only for a material removal simulation. Therefore, an extension of the existing structure is only necessary in the start and endpoints of the dexel. To consider temperature and deformation a dexel point was extended by a temperature value and a deformation vector. Using a deformation vector instead of alternative methods like shortening and lengthening of the dexel or shifting of dexel points, gives essential advances. These advances are:

- keeping the consistency of the workpiece model
- easier linking to the FE model structure
- parallel representation of the chilled workpiece by the basic dexel structure

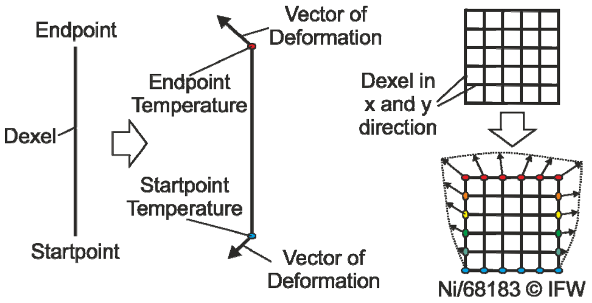

Fig. 3. Thermomechanical Extended Dexel-Structure

5. Modeling of the Moving Heat Source

One of the major components in the simulation circle is the modeling of the thermal workpiece load. Therefore, based on the material removal simulation the contact zone of tool and workpiece is analyzed like shown in [9], so that the cutting conditions like undeformed chip-thickness h, contact length b, cutting forces and cutting power are calculated related to the cutting face for every discrete simulation step (Fig. 4a). However, the moving heat source has to be modeled on the machined surface described as the sweep movement of the cutting edge between discrete simulation steps.

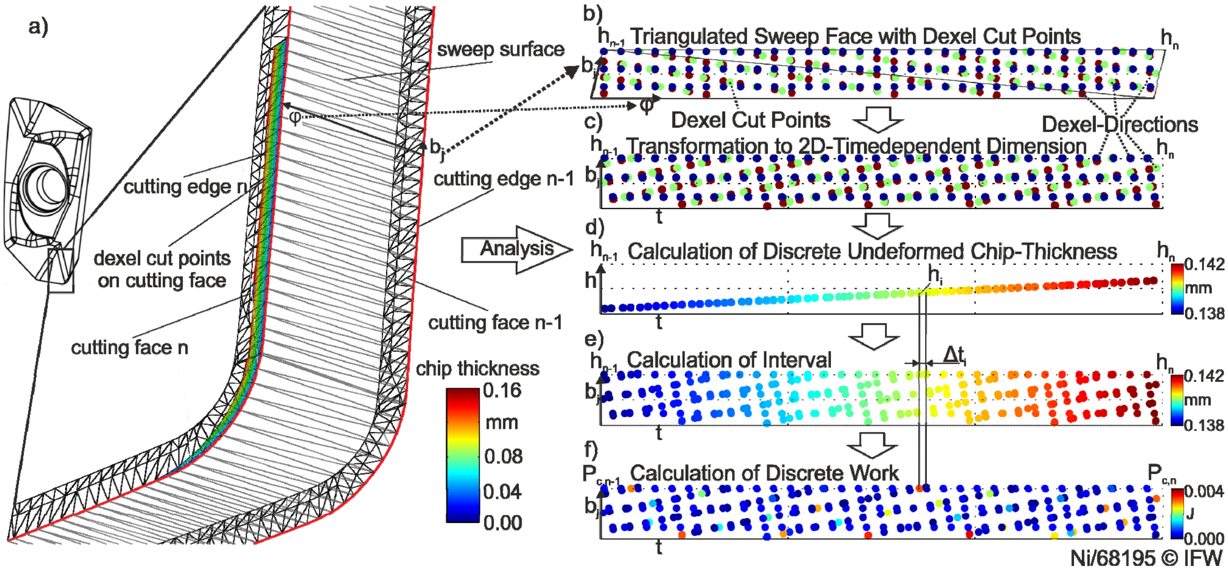

Fig. 4. Sweep Cutting Edge Face and Analysis

The first step in modeling the heat source is to sweep the segmented cutting edge of the cutting face along the movement defined by the NC-Controller. Thereby a new triangulated sweep surface is constructed that can be used to subtract the workpiece and thus detect dexel cut points (DCP) on it (Fig. 4a).

Afterwards, the 3D-DCPs have to be assigned to the tool coordinate system described by length of cutting edge segments b_j and rotational angle φ (Fig. 4b). In the next step the DCPs are transformed into a time dependent dimension for every cutting edge segment so that analysis of every point is possible (Fig. 4c). Then the DCPs are sorted by the instant time of contact to the cutting edge. The cutting conditions defined in the discrete simulation steps h_{n-1}, h_n are projected on the DCPs between these two moments by a linear interpolation (Fig. 4d). By the incremental information in every DCP and the fact that only one DCP is in contact in one point of time, it is possible to calculate the incremental work for a single DCP. Therefore the interval to the next DCP in contact Δt_{sim} has to be computed (Fig. 4e).

$$\Delta t_i = t_i - t_{i-1} \tag{1}$$

The cutting speed v_c is defined globally for every segment and can be calculated by the length of the segment φ_j tool diameter D and simulation time increment t_{sim}.

$$v_c = \frac{\varphi_j / 360 \cdot \Pi \cdot D}{t_{sim}} \tag{2}$$

Based on this Information the incremental work W_i for a DCP can be calculated using a cutting force model [11] with the cutting coefficients k_c, k_e (Fig. 4f).

$$W_i = (k_c \cdot b_j \cdot h_i + k_e \cdot b_j) \cdot v_c \cdot \Delta t_i \tag{3}$$

For a realistic simulation of the workpiece load the total dissipated work has to be divided into workpiece, tool and chip heat by a heat partition model. In the last step only the heat of the workpiece is transformed back to the 3D coordinates for every dexel point on every segment and used as a moving heat source input parameter for the FE model.

6. FEM for Heat Conduction and Thermomechanics

To compute heat conduction as well as thermomechanical elastic and plastic deformation of the workpiece in the dexel model, the equations of heat conduction and deformation are discetized and simulated by an FE model. The FE model is based on the adaptive finite element toolbox ALBERTA from Schmidt and Siebert [12]. This Toolbox is using unstructured simplicial meshes, like tetrahedrons in 3D, together with local adaptive mesh refinement and coarsening for appropriate approximation of domain and solutions, e.g. machining processes.

The coupled system of classical models of the heat equation

$$\begin{aligned} \rho c_e \frac{\partial \theta}{\partial t} - \mathrm{div}(\kappa \nabla \theta) &= f_\theta(u) && \text{in } \Omega(t) \\ -\kappa \nabla \theta \cdot n &= \delta(\theta - \theta_{ext}) && \text{on } \Gamma_\mathrm{R}(t) \\ -\kappa \nabla \theta \cdot n &= g(x,t) && \text{on } \Gamma_\mathrm{N}(t) \end{aligned} \tag{4}$$

for temperature θ and the quasi-stationary elasticity equation

$$\begin{aligned} -\mathrm{div}\,\sigma(u) &= \rho f_u(\theta) && \text{in } \Omega(t) \\ u &= g_D && \text{on } \Gamma_D(t) \\ \sigma(u) \cdot n &= g_N && \text{on } \Gamma_N(t) \\ \sigma(u) &= \lambda(\theta)(\mathrm{tr}(\varepsilon(u))\mathrm{I} + 2\mu(\theta)\varepsilon(u) \\ \varepsilon(u) &= \frac{1}{2}(\nabla u + (\nabla u)^T) \end{aligned} \tag{5}$$

for deformation u, both on a time-dependent domain, constitutes the FE model. Relevant aspects, like a moving heat source $g(x,t)$ on the boundary Γ_N in (4), of the machining process were modeled and implemented in this model. The Lame coefficients μ and λ of (5) depends on the temperature of (4). Current research focus mainly on the field of modeling machining processes engage in the microscopically view of chip formation simulation, where the effects had been investigated in the area of the shear zone especially. Here, is the focus on the macroscopical view of the machining process on the whole workpiece, like presented in [5, 6].

To consider the material removal of the dexel model also in the FE model, the two models are coupled. This coupling of the models is based on the interchange of parameters and values such as the geometry of the workpiece, the thermomechanical displacements of the workpiece as well as heat flux and forces produced by the cutting process.

The material removal and thus time dependent domain is realized in the FE model by using a time-dependent virtual domain, which will be described below in a bit more detail.

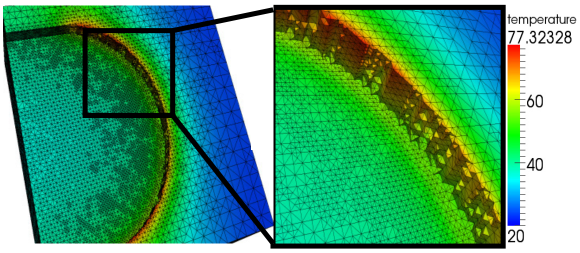

Fig. 5. Heat Equation of a Milling Process (left) and rough Boundary Surface (right)

Another approach to handle a time dependent domain might be a moving mesh approach, where the nodes are moved in every timestep in order to represent the current geometry. Due to large deformations by material removal, a frequent remeshing would be necessary in order to prevent distorted elements. Thus, the moving mesh approach is not used here.

By using here a fixed domain approach where the complete mesh always represents the full initial workpiece, so there is no need to generate a new mesh.

Determined by the current coordinates of the dexel endpoints from the dexel model, an interpolated surface defines the current boundary of the time dependent domain. For each element of the triangulation, it is then easy to decide whether the element is fully outside of the current domain or not. Such fully outside elements will not be considered anymore in the calculation and will thus be ignored during all following time steps of the simulation. In this way, the heat and deformation equations are solved only on a subset of the complete domain. Using an appropriate local adaptive refinement and coarsening of the mesh, the moving boundary can be approximated by the mesh as accurately as desired.

Boundary conditions given by the process model, like heat flux and forces, are now given on the boundary of the virtual domain, which is at least partly composed of interior sides of elements of the original mesh. The new boundary surface in the processing zone is typically not smooth but rough. For an example of this rough boundary surface see Fig. 5. In order to control the approximation error caused by the rough boundary approximation and the realization of boundary values on it, a suitable a posteriori error estimator will be derived and applied for the adaptive mesh control.

7. Considering the Thermomechanical Effects

Current thermomechanical data, continuously imported from the FE model in the dexel structure, now allows considering the thermomechanical effects in the NC-Simulation. These effects are caused by the local temperature and the local deformation of the workpiece in the cutting zone.

The local temperature of the workpiece mainly has an influence on the shear work and friction conditions in the cutting zone. Therefore, the process model, for the prediction of the cutting forces needs this information as input parameters. With the used method of projecting the intersected dexels on the tool surface it is now easily possible to detect the temperature of a discrete point on the cutting face and thus to describe a temperature field of the whole cross-section of undeformed chip *A* during the cutting process.

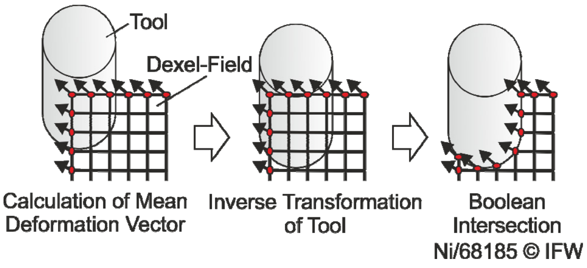

Fig. 6. Considering Thermomechanical Deformation

The deformation of the workpiece locally influences the dimension of the cross-section of undeformed chip *A* and globally influences the geometric representation of the workpiece. Therefore, the deformation determined by analyzing the sweep-surface DCPs is invers projected on the cutting edge (Fig. 6). By this method the thermomechanical deformation of the workpiece can be considered and the resulting shape errors can be predicted.

8. Results

The presented method initially was used for the prediction of the temperature distribution in milling of a simple workpiece. 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 and tool-runout the number of inserts was reduced to one. Slot milling has been chosen as a reference process. Fig. 7 shows the variation in time of both, measured and simulated workpiece in 5 different measuring positions.

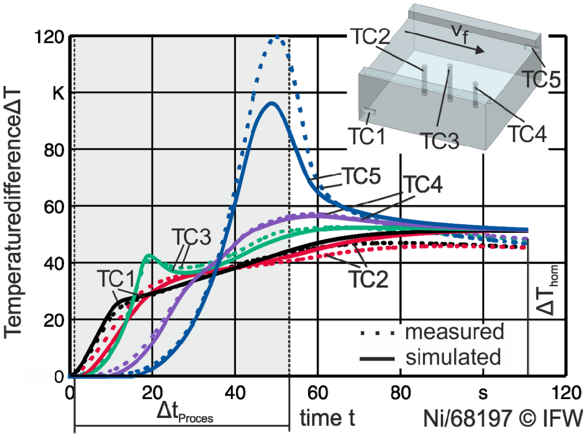

Fig. 7 Measured and Simulated Temperature

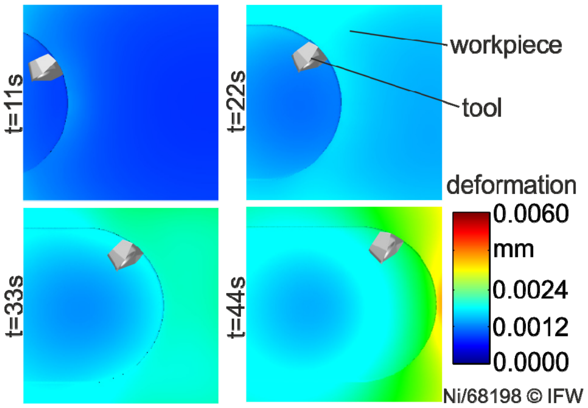

Fig. 8 Workpiece Deformation during Milling Process

The deviation can be explained by the less dynamic heat source and a mean heat load of the workpiece in the FE model. Hence with lower temperature gradients and therefore the maximum temperatures in the workpiece cannot be reached. In particular for thermocouple number 5 (TC5), that is the nearest one to the surface, this effects leads to differences in simulated and measured temperatures.

For this simple reference process the maximum thermomechanical induced deformation of the workpiece was less than 7 µm (Fig. 8). The resulting shape error of the machined surface is divided in two parts, an exponential decreasing shape error first order in feed direction and a symmetric concave shape error perpendicular to the feed direction.

The shown example was computed using a standard desktop PC equipped with a conventional GPU. Necessary computational time and accuracy of the method is dependent on the discretization of the workpiece by the dexels and FE-Elements. Choosing a resolution of the used dexel field between 256 and 1024 and 25000 to 300000 DOF in the FE model the time varied from a few minutes up to 2 hours.

9. Conclusion and Outlook

In the present paper a new method for the NC-Simulation of cutting processes considering thermomechanical effects is presented. A thermomechanical extended dexel based material removal model was linked to an FE model considering geometry changes as well as a process model for the thermomechanical load of the workpiece. It is shown that the temperature distribution in the workpiece can be predicted well. In future investigations workpieces with bigger size and complex cutting operations, like ramping or circular milling will be simulated and analyzed. Furthermore, the method will be adapted to the drilling process.

Acknowledgements

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