Simulation and Multi-Objective Optimization of Thermal Distortions for Milling Processes

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Abstract During a machining process, the produced heat results in thermomechanical deformation of the workpiece and thus an incorrect material removal by the cutting tool, which may exceed given tolerances.

We present a numerical model based on an adaptive finite element simulation for thermomechanics, which takes into account both the approximation of the temperature field as well as the approximation of the time dependent domain.

Control of the milling parameters and tool path can be used to minimize the final shape deviation. A multi-objective approach can try to additionally reduce the tool wear. We present results from a simulation-based optimization approach for a simplified workpiece.

1 Introduction

During a milling process, heat introduced by the cutting into the workpiece leads to thermoelastic deformation of the workpiece. As a consequence, the milling tool removes not the desired amount of material, but more or less. This can lead to a substantial shape error.

Mathematical modelling, simulation, and optimization can be used in order to predict and reduce this shape error. The time dependent shape of the workpiece adds another challenge to models and numerical methods. We present an approach based on a hybrid dexel/adaptive finite element model (Sect. 2) and a simulation-based multi-objective optimization method (Sect. 3). Applied to a model problem, we are able to reduce the shape error while additionally paying attention to the milling tool wear.

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2 Model and Numerical Method

With stress tensor σ depending on displacements u and temperature θ, $\sigma(u,\theta) = 2\mu(\theta)(\epsilon(u) + (\lambda(\theta)tr(\epsilon(u)) - 3\alpha(\theta - \theta_0))\,I$ with strain tensor $\epsilon(u) = \frac{1}{2}(\nabla u + \nabla u^T)$ and thermal expansion determined by α, the thermomechanical problem with quasi-stationary mechanics is given in strong form as: Find temperature θ and deformation u such that

$$\dot{\theta} - \operatorname{div}(\kappa\nabla\theta) = 0 \;\text{ in } \Omega(t), \tag{1}$$

$$-\operatorname{div}\sigma(u,\theta) = 0 \;\text{ in } \Omega(t) \tag{2}$$

for $t \in (0, t_{end})$ with initial condition $\theta(0) = \theta_0$ and boundary conditions

$$\kappa\nabla\theta\cdot\nu = g_N \text{ on } \partial\Omega(t), \quad \sigma(u,\theta)\cdot\nu = f_N \text{ on } \Gamma_N(t), \quad u = 0 \text{ on } \Gamma_D. \tag{3}$$

The heat flux g_N over the boundary is given by a cooling condition or by the flux produced during the milling process, as are the forces f_N. The workpiece is clamped at Γ_D and $\partial\Omega(t) = \Gamma_D \cup \Gamma_N(t)$.

The model is based on small deformations on a reference configuration with $\Omega(t) \subset \Omega(0)$ and uses the linearized elasticity tensor. The time dependent domain $\Omega(t)$ and its moving boundary $\Gamma_N(t)$ are given via the engagement of the milling tool. A macroscopic model is used here, where a boolean operation cuts in every time step the rotated tool sweep volume from the current, deformed workpiece geometry. For an efficient implementation, a dexel model is used here [2]. This results in a description of the domain $\Omega(t)$ which is independent of the numerical mesh of the finite element method. As microscopic effects like the creation and removal of single chips are not included in the macroscopic model, a suitable process model has to be used to compute heat fluxes and forces acting on the workpiece, resulting in the Neumann data g_N and f_N in (3).

Approximation of the Time-Dependent Workpiece Geometry A finite element discretization of the equations is used, based on a tetrahedral mesh and piecewise linear finite element spaces. Time discretization of the problem is done using an implicit Euler discretization, use of higher order methods would need further investigation due to the time dependent domain. As the model equations are given in the reference configuration, the domain is only getting smaller, $\Omega(t_2) \subseteq \Omega(t_1)$ for $t_2 \geq t_1$. Thus, data from the last time step t_{n-1} are always available in $\Omega(t_n)$. We approximate the time dependent domain $\Omega(t_n)$ by a discrete domain $\Omega_h(t_n)$ which is given by the union of all elements of a given triangulation $S_h(t_n)$ of $\Omega(0)$ which have a nonzero intersection with $\Omega(t_n)$,

$$\bar{\Omega}_h(t_n) := \bigcup\{S \in S_h(t_n) : S \cap \Omega(t_n) \neq \emptyset\}.$$

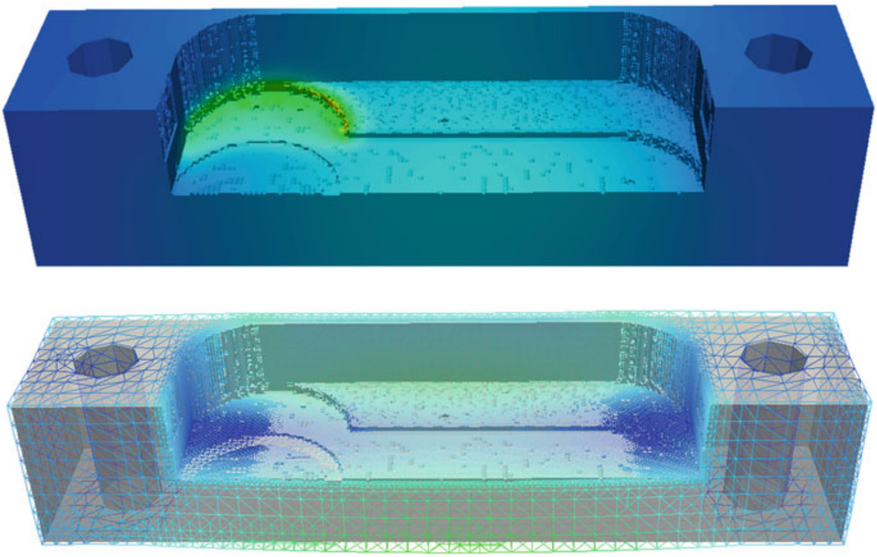

Fig. 1 Simulation of milling of a thin-walled reference workpiece. Temperature (top) and deformation (bottom, amplified by factor 100)

In order to get a convergent approximation of the solution, boundary conditions for flux and forces (3) need to be transferred suitably from $\partial\Omega(t_n)$ to the possibly rough discrete boundary $\partial\Omega_h(t_n)$. An adaptive mesh refinement for $S_h(t_n)$, based on error indicators for the solution of (1)–(3), combined with local refinement near $\partial\Omega_h(t)$, results in a good approximation of the domain as well as temperature and deformation [4, 5]. The numerical method for thermomechanics on the timedependent domain was implemented in the finite element toolbox ALBERTA [6].

Simulation of Milling Processes The numerical method was applied successfully to various milling and drilling scenarios [2, 4]. Figure 1 shows temperature, deformation and mesh at one timestep during the milling of a thin-walled workpiece from a rectangular block with holes for fixation. For this workpiece, comparisons with experiments were conducted by engineers from IFW Hannover, which show a good agreement of simulated temperatures, deformations and shape errors with experimental data [1].

3 Optimization

Based on the process simulation for given process parameters, we want to optimize the share error and tool wear with respect to some of the process' input parameters. As the simulation of the whole workpiece is rather computationally expensive, we restrict our model process further to a small part of the workpiece.

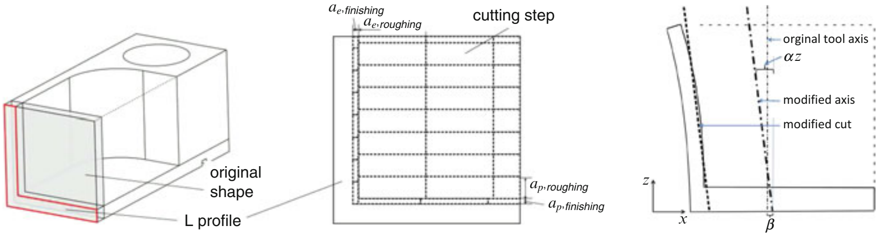

Fig. 2 Model process for optimization of L-shaped domain. Form and indication of adjustable process parameters

Reduced Workpiece and Process Model The left part of Fig. 2 depicts the reduced geometry, with a final L-shaped form, and indicates roughing and finishing steps of the milling process (middle part). Adjustable process parameters are milling parameters and the tool path.

Simulation-Based Optimization Traditional mathematical optimization methods try to use gradients of the cost functionals with respect to the adjustable parameters in order to find a descent direction. Computation of gradients can be done numerically, which results in correspondingly many evaluations of the cost functional, or by an analytic procedure which typically involves the additional solution of adjoint problems. Both approaches are very time consuming, when the control-to-state operator involves time dependent, nonlinear PDEs. Thus, a cheap approximation of the control-to-cost operator can save a lot of computing time. The "simulation-based optimization" method is able to derive approximations of the operator with only very few evaluations of the cost function [7]. It is used here in the following context for multi-objective optimization of the milling process.

Minimization of Shape Error and Tool Wear We choose the axial cutting depth $a_{p,roughing}$ as adjustable parameter, together with cutting velocity v_c, and an additional inclination α and displacement β of the tool axis for the finishing cuts, see Fig. 2 (middle and right). For all four adjustable parameters, suitable admissible ranges were selected.

We want to reduce the final shape error while having the tool wear under control. Thus, our objective functions for multi-objective optimization are given by the shape error

$$\delta_x := \max_{i,j} |L(d_{ij}) - L_d(i,j)|,$$

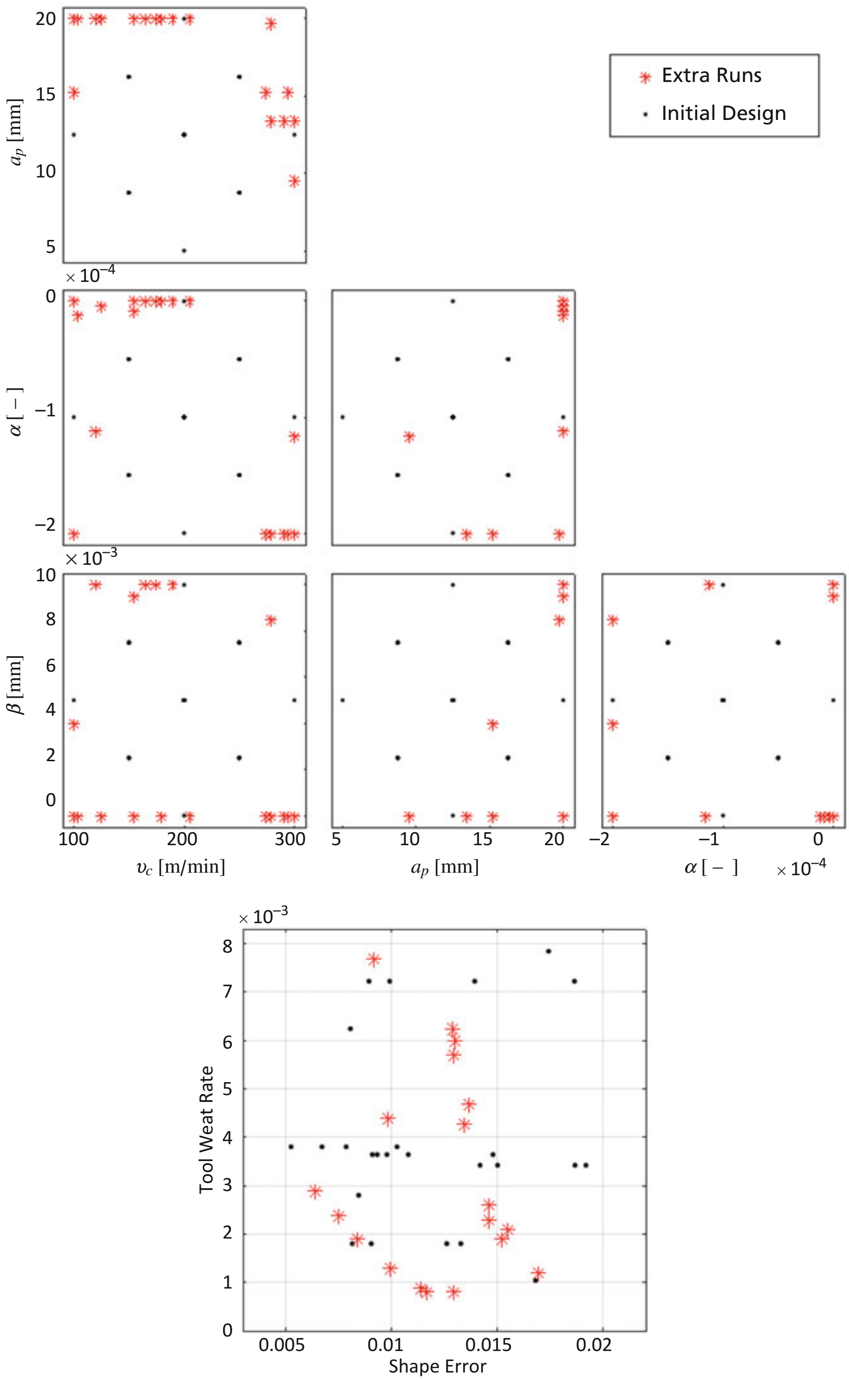

Fig. 3 2D projections of evaluated controllable process variables (top) and performance measure values of evaluated runs (bottom). Initial design (black dots) and extra runs (red stars)

computed by comparing the length of dexel d_{ij} and the corresponding desired length L_d for a 2-dimensional dexel field, and the tool wear rate is modeled by

$$\mathrm{TWR} = \frac{n_{cuts} L_{cut}}{L_f} = \frac{v_c - B}{A} \left(\left\lceil \frac{H}{a_p} \right\rceil \cdot \left(\left\lceil \frac{W}{a_e} \right\rceil + 1 \right) + \left\lceil \frac{W}{a_e} \right\rceil - 1 \right).$$

which is the inverse of the number of producible workpieces during tool life L_f, where H and W are the height and width of the removed pocket, from which the number of roughing and finishing steps are computed, and A, B are parameters.

Figure 3 shows control variables and results from the application of the simulation-based multi-objective optimization procedure. Black dots indicate initial parameter combinations which are selected in order to explore the set of admissible control parameters. Red stars indicate additional parameter combinations which were selected by the method in order to identify the Pareto set of parameters and Pareto front of objectives with values in the lower left corner of performance measure values in Fig. 3. These can be used to choose parameter sets for small shape error with acceptable tool wear, or small tool wear with acceptable shape error.

Details of the optimization method and the results are given in [3].

Conclusion The results presented above show, that a combination of modern and efficient approaches to simulation and optimization is able to improve rather complex production processes and thus is an important aspect of a digital factory environment.

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